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STARDUST & SHORTCUTS

A fast, illustrated guide to astrophysics — written for people who intend to go further than a quick read.

38 chapters · 75 illustrations · one universe

Concepts · Case files · Worked numbers · Career map

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Stardust & Shortcuts

A fast, illustrated guide to astrophysics — for people who intend to go further.

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A fast, illustrated guide to astrophysics.
First edition, 2026.

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Set in Constantia and Bahnschrift. Trim 170 × 240 mm.

DEDICATION

For the early learner — the one who asks the next question after the lesson has ended.

This book began with my own son. He is fourteen, and he has decided he wants to be an astrophysicist. I went looking for something that would take that decision seriously — real physics, real numbers, an honest account of the work — and found plenty written down to him, and little written as though he might one day do it.

So we made this instead. Almost everything in these pages was discovered by someone who began exactly where you are: curious, under-equipped, and unwilling to accept “nobody knows” as the end of a conversation. Chandrasekhar was nineteen, on a boat from Madras. Jocelyn Bell read thirty metres of chart paper a day by eye. Cecilia Payne was told her greatest result was impossible, and published it anyway.

Alpha Web Innovations Pvt Ltd publishes it without charge, and means that literally. Copy it. Print it. Put it in a school library, or hand it to a student who cannot buy one. That is precisely what it is for.

And if somewhere in it you meet a question that will not leave you alone — follow it. That is how every discovery described here began.

Girish Manchanda

FOUNDER, ALPHA WEB INNOVATIONS PVT LTD

First edition · 2026

BEFORE YOU START

How To Use This Book

> There are two ways to read this. Both are legitimate. Pick one on purpose rather than by accident.

The **fast read** is the main text plus the black summary box at the end of each chapter. Thirty-eight chapters, no equations, roughly an evening and a half. You will finish knowing what astrophysicists actually claim, why they claim it, and which parts they are still arguing about. That is more than most adults ever get.

The **slow read** means you also stop at the coloured boxes, do the arithmetic yourself on paper, and try the observations. That takes weeks. It is the version written for somebody who intends to sit an olympiad paper, walk into a physics department, and one day add a line to the story rather than just read it.

Everything in the boxes is optional on the first pass and compulsory on the second. Here is what each one means.

CASE FILE

A real observation, mission or discovery — what was measured, by whom, and what it forced everyone to change their mind about. Astrophysics is not a set of facts; it is a set of arguments that got settled by evidence. These boxes are the evidence.

DO THE MATH

A calculation you can genuinely do with Class 9 algebra and a calculator. No calculus is used anywhere in this book. Every one of these has a worked answer in Appendix B — but the answer is worthless if you read it before trying.

```
Worked lines look like this.
Units are carried through every step, on purpose.
```

GET THIS STRAIGHT

A specific, common, confidently-repeated piece of nonsense — corrected. Some of these appear in school textbooks. Being able to spot them is one of the more reliable signs that you have understood a topic rather than memorised it.

TRY THIS

Something to do with your hands, your eyes, a phone, or a torch and a wall. Almost none of it needs a telescope. Astronomy is the only science whose main laboratory is freely visible from a terrace.

CAREER NOTE

Where the chapter's subject sits in a working life — which institutes in India and abroad do this, what the job is actually like day to day, and what you would need to have studied to get near it. Part IX collects all of this into one plan.

IN A HURRY?

- Every chapter ends with one of these — **five or six lines** holding the whole chapter.
- If you read only these, you have read a real, if very compressed, astrophysics course.
- If a summary line makes no sense, that is a signal to go back, not to move on.

Two habits worth building now

Carry your units. Most mistakes in physics — including expensive professional ones — are unit mistakes, not concept mistakes. NASA lost the *Mars Climate Orbiter* in 1999 because one team worked in pound-force-seconds and another in newton-seconds. Write the units into every line of every calculation and they will catch your errors for you.

Estimate before you compute. Guess the answer's order of magnitude first — is it closer to a thousand or a billion? Then calculate. If the two disagree wildly, one of them is wrong, and finding out which is where the learning happens. Enrico Fermi built a career on this and physicists still call the technique after him.

One last thing. This book states numbers with confidence because that is how the sentences read best, but a good fraction of them are measurements with error bars, and a few are actively disputed — the expansion rate of the universe most of all. Where the argument is live, the text says so. Treat anybody who tells you astrophysics is finished with the suspicion they deserve.

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I

The Stage

Before any physics, two things have to stop being abstractions: how big the universe is, and how old. Almost every misunderstanding in astronomy is really a failure to feel one of those two numbers.

CHAPTER 1 · THE STAGE

How Big Is Big?

> Your brain is excellent at distances up to about a kilometre and hopeless beyond that. Astronomy begins by admitting this and building a ladder instead.

Ask somebody how far away the Sun is and they will say "very far". Ask how far away the nearest star is and they will say "very, very far". The two answers feel one step apart. They are not. The Sun is 150 million kilometres away; the next nearest star is 40 trillion. One is roughly 270,000 times the other. If the distance to the Sun were the length of your thumb, the distance to Proxima Centauri would be the length of the Ganga.

This is the central difficulty of the subject, and it is a difficulty of psychology rather than physics. Human intuition treats "large" as a single category. Beyond a few kilometres, everything collapses into the same mental drawer marked *far*. Astrophysics does not work unless that drawer is opened and its contents spread out, and the tool for spreading them out is the **logarithmic scale**: a ruler on which each step is not one more, but ten times more.

The ladder

On the ladder below, every rung is ten times the one below it. A proton sits at the bottom, you sit somewhere in the middle, and the observable universe sits at the top — forty-two rungs from end to end. Notice where you fall. You are not close to the small end. In powers of ten, a human being sits almost exactly halfway between a proton and the edge of the visible universe, which is a genuinely strange fact and not a coincidence anyone has fully explained.

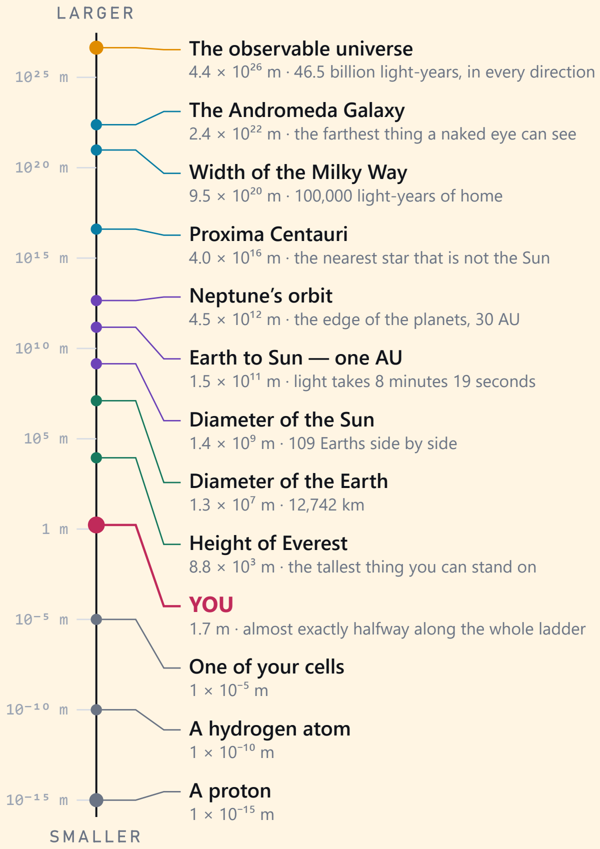


Figure 1.1 — The ladder of scale. Each rung is ten times the one below, so the whole of reality fits into forty-two steps. Dots mark true positions on the axis; labels are spread evenly and joined by leader lines. Colours group the rungs into the everyday (green), the Solar System (violet), the stellar and galactic (blue) and the cosmic (amber). Pink is you.

Three units, and why astronomers need all three

Kilometres run out fast. So astronomy uses a small set of larger units, each matched to a particular arena.

The **astronomical unit** (AU) is the average Earth–Sun distance, defined since 2012 as exactly 149,597,870,700 metres. It is the natural ruler for the Solar System: Mars is 1.52 AU from the Sun, Jupiter 5.2, Neptune 30. Use it for anything inside our own planetary family and the numbers stay conveniently small.

The **light-year** is the distance light covers in one year — about 9.46 trillion kilometres. It is not a unit of time, despite the word "year" in it, and the most reliable way to sound like you have not understood astronomy is to use it as one. Its virtue is that it silently encodes the most important fact in observational astronomy: distance is delay. Something four light-years away is being seen as it was four years ago.

The **parsec** is what professionals actually write in papers — 3.26 light-years. It comes from *par*allax *sec*ond, and it is defined so that a star one parsec away shifts by exactly one arcsecond against the background as the Earth moves from one side of its orbit to the other. It exists because it turns the messy business of measuring stellar distance into simple division, which you will meet in Chapter 32.

DO THE MATH · 1.1

Build the light-year from scratch. Do not look it up. You need only two numbers, both of which you should memorise today: the speed of light, c = 3.00 × 10^8 m/s, and the number of seconds in a year.

```
seconds in a year = 365.25 × 24 × 60 × 60
                  = 3.156 × 10⁷ s

1 light-year = c × t
             = (3.00 × 10⁸ m/s) × (3.156 × 10⁷ s)
             = ?  metres
```

Then push further: Proxima Centauri is 4.25 light-years away. How many *metres* is that? How many AU? And if the fastest object humans have ever launched — the Parker Solar Probe, at 690,000 km/h — flew straight there, how many years would the trip take?

The last answer is the one worth sitting with for a minute.

Shrinking the Solar System to a cricket pitch

Numbers on a page do not produce understanding. Scale models do. So shrink the Sun from its true 1.39 million kilometres across down to the size of a cricket ball — 7 centimetres. Everything else must shrink by the same factor, which works out to about 20 billion.

At that scale the Earth is a grain of sand two-thirds of a millimetre wide, sitting 7.5 metres from the ball. You could set the whole inner Solar System up in a school corridor. Neptune is 225 metres away — the far end of a large playing field. And Proxima Centauri, the very next star, is **2,000 kilometres** away: put the cricket-ball Sun in Delhi and the nearest neighbouring star is past Hyderabad, closing on Chennai.

That is the shape of the universe that matters most. Not "everything is far apart", but this: **solar systems are small, tidy places separated by staggering emptiness.** Every difficulty in interstellar travel, every reason we have not met anybody, and every reason astronomy is done with telescopes rather than spacecraft, follows from the gap between those 225 metres and those 2,000 kilometres.

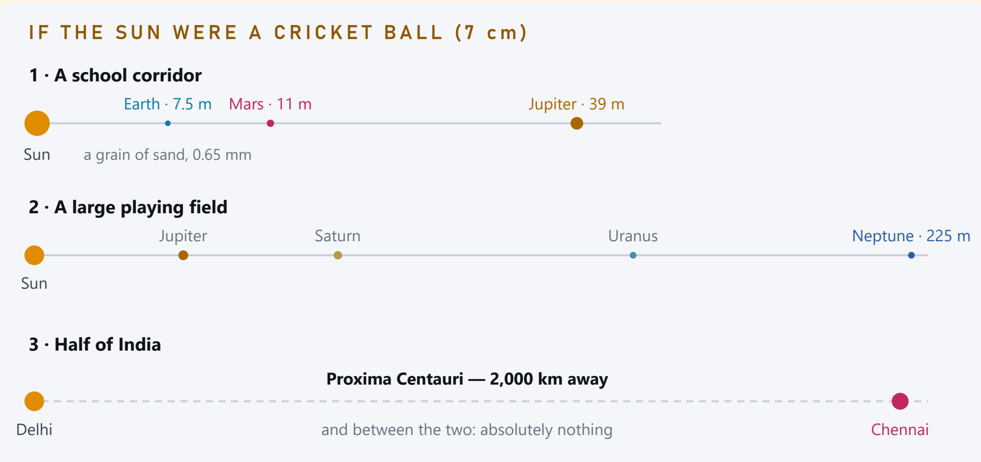


Figure 1.2 — The Solar System at one part in twenty billion. Panels 1 and 2 fit inside a school. Panel 3 does not fit inside a state. The emptiness between stars is the single most consequential fact in astronomy.

GET THIS STRAIGHT

"The asteroid belt is a dangerous, crowded place." Films require spacecraft to weave through tumbling rocks; reality does not. The belt holds perhaps two million asteroids over a kilometre across, spread through a doughnut of space some 300 million kilometres wide. The average separation between neighbours is close to a million kilometres — roughly three times the Earth–Moon distance.

Every one of the dozen-plus spacecraft that has crossed the belt was aimed straight through it without any avoidance manoeuvre, and none has been struck. Mission planners put the odds of a damaging collision at under one in a billion per crossing. The belt is not a minefield. It is an almost perfect vacuum with an occasional rock in it.

CASE FILE · VOYAGER 1

Launched on 5 September 1977, *Voyager 1* is the most distant human object in existence. It is currently around **167 AU** from the Sun and moving outward at about 17 kilometres every second — 61,000 km/h. Radio signals, travelling at the speed of light, now take over **23 hours** to reach it, so a round-trip conversation costs nearly two days.

It crossed the heliopause — the boundary where the Sun's wind gives way to interstellar gas — in August 2012, and by any sensible definition is now in interstellar space. Its instruments are powered by decaying plutonium, and the power budget has been shrinking for decades; NASA has been switching instruments off one at a time to keep the remainder alive into the 2030s.

Here is the part worth remembering. After nearly fifty years at 61,000 km/h, Voyager 1 has covered roughly **0.26 per cent** of the distance to Proxima Centauri. It is not aimed there, but if it were, the journey would take about 73,000 years. That is the honest scale of interstellar travel with current physics, and no amount of engineering enthusiasm changes the arithmetic.

TRY THIS · MEASURE THE SKY WITH YOUR HAND

Hold your arm straight out and stretch your fingers. Sky distances are angles, and your hand at arm's length is a surprisingly consistent protractor across almost all adults — big hands come attached to long arms.

- **Little finger**, width — about **1°**. Twice the width of the full Moon.
- **Three middle fingers** together — about **5°**.
- **Closed fist**, knuckle to knuckle — about **10°**.
- **Thumb to little finger**, fully spread — about **20°**.

Tonight, check one thing: hold your little finger up against the full Moon. The Moon will disappear behind half of it. Almost everybody, asked to draw the Moon's size on the sky, draws it three to five times too large — and now you know from your own hand that they are wrong. Nine fist-widths take you from the horizon to straight overhead. Learn this and you can follow any star chart without instruments.

CAREER NOTE

Scale estimation is not a warm-up exercise; it is a professional skill with a name. **Order-of-magnitude reasoning** is what lets a researcher decide, in ten seconds on a blackboard, whether a proposed idea is worth three months of work or is off by a factor of a million. Physics interviews at IISER, IIT and every graduate school abroad lean on it heavily — "how many piano tuners are there in Mumbai?" and its cousins are testing exactly this. Start the habit now: estimate first, calculate second.

One rung on the ladder

Earth from 36,000 km up — 1.3×10^7 m across, sitting on the green section of Figure 1.1. Everything that has ever happened to every human being happened here. On the cricket-ball scale of Figure 1.2 this entire world is a grain of sand two-thirds of a millimetre wide, and the nearest star is 2,000 kilometres away.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- Human intuition fails above about a kilometre, so astronomy uses **logarithmic ladders** — each rung ten times the last.
- Three units matter: the **AU** (Earth–Sun, 1.5×10^{11} m) for the Solar System, the **light-year** (9.46×10^{15} m) for stars, and the **parsec** (3.26 ly) for professional work.
- A light-year is a **distance**, not a time.
- Shrink the Sun to a cricket ball and Neptune is 225 m away — but the nearest star is 2,000 km away. **Systems are tiny; the gaps are enormous.**
- *Voyager 1*, after 49 years at 61,000 km/h, has crossed about a quarter of one per cent of the way to the nearest star.
- You sit roughly halfway, in powers of ten, between a proton and the observable universe.

CHAPTER 2 · THE STAGE

The Cosmic Calendar

> Squeeze 13.8 billion years into a single year and something becomes obvious that no list of dates can convey: almost everything you have ever heard of happened in the last few seconds.

Time is harder than distance. At least with distance you can walk some of it. Nobody has any experience of a million years, and "billion" is a word the brain treats as a synonym for "lots". So astronomers use a trick borrowed from cartography: change the scale until the whole thing fits on one page.

Compress the entire history of the universe — from the Big Bang to this afternoon — into one calendar year. The Big Bang goes at midnight on 1 January. Right now is midnight on 31 December. Everything in between gets squeezed proportionally.

On that scale, **one day is 37.8 million years**. One hour is 1.58 million years. One second is 437 years — long enough for the Mughal empire to rise, rule and fall while the second hand moves once.

THE UNIVERSE AS ONE YEAR

Figure 2.1 — Thirteen point eight billion years as one calendar year. Each day is 37.8 million years; each second is 437 years. Note how much of the year is over before the Sun even exists.

The part that should unsettle you

Look at the right-hand edge. The Sun does not appear until **31 August**. The Earth follows two days later. For eight months of cosmic history there was no Sun, no Earth, and no possibility of anyone reading this — just generations of other stars living and dying, manufacturing the raw material that would eventually become the two of us.

Then look closer. Life gets going on 21 September and then does almost nothing visible for three months. Animals with hard parts arrive on 17 December. Dinosaurs turn up on Christmas Day and are wiped out on the 30th. And every human being who has ever lived — all of them, all of history, all of art, all of physics — fits into the last **eleven minutes and twenty-six seconds** of 31 December.

Recorded history is the last **twelve seconds**. Aryabhata worked out that the Earth spins on its axis about three and a half seconds ago. Galileo pointed the first telescope at Jupiter one second ago. Everything we know about the universe was learnt in the final second of the final minute of the final day.

DO THE MATH · 2.1

Build your own calendar entry. The conversion factor is the whole trick:

```
1 calendar year  = 13.8 × 10⁹ real years
1 calendar day   = 13.8 × 10⁹ ÷ 365    = 3.78 × 10⁷ years
1 calendar sec   = 3.78 × 10⁷ ÷ 86400 = 437 years
```

Now place these yourself. Give the date and, where it matters, the time:

- The oldest known cave paintings, about 45,000 years old.
- The Indus Valley cities, about 4,600 years old.
- The founding of the Indian Institute of Science, 1909.
- Your own birth.

Then answer this: how long, on the cosmic calendar, is a human lifetime of 80 years?

How anybody knows the number

"13.8 billion years" is not a guess, and it is not one measurement. It is the point where four independent lines of evidence — each using different physics, different instruments and different assumptions — cross.

The oldest stars. Globular clusters contain stars that formed before the Milky Way had settled into a disc. Nuclear physics fixes how long a star of a given mass can burn, so the faintest surviving stars in these clusters put a floor under the age of the universe: around 13 billion years, with an uncertainty of a few hundred million.

Radioactive decay. Uranium-238 has a half-life of 4.47 billion years, thorium-232 one of 14.05 billion. Measuring the ratio in ancient stars and in meteorites dates material directly, the same way carbon-14 dates a piece of wood — just with a much longer clock.

Cooling white dwarfs. A white dwarf produces no new energy; it simply radiates away leftover heat on a schedule physics can calculate. Find the coolest white dwarfs in a cluster and you have a thermometer that reads in billions of years.

The microwave background. The strongest constraint. The pattern of hot and cold patches left over from the young universe encodes its expansion history. The Planck satellite's 2018 analysis returned **13.797 ± 0.023 billion years** — a precision of about one part in six hundred, which is roughly like dating a 60-year-old to within five weeks.

CASE FILE · THE STAR THAT WAS OLDER THAN THE UNIVERSE

In 2013, a team using the Hubble Space Telescope measured HD 140283 — nicknamed the Methuselah star, a metal-poor subgiant about 190 light-years away. The result: **14.5 ± 0.8 billion years**. The universe was 13.8. The star appeared to be older than everything.

This is exactly the sort of moment that makes science worth doing. Nobody announced that cosmology was overturned, and nobody quietly buried the result. Both possibilities were taken seriously and the error bars were examined. The ± 0.8 was doing real work: at the low end the star is 13.7 billion years old, which is fine. Refined distances from the Gaia satellite and improved models of how oxygen abundance affects stellar ageing have since pulled the estimate down to around 13.5 billion years.

The lesson is the one every working scientist internalises early: **a measurement without an uncertainty is not a measurement**. "14.5 billion years" is a headline. "14.5 ± 0.8 billion years" is a result.

GET THIS STRAIGHT

"The Big Bang was an explosion in space." It was not. An explosion has a centre, throws debris outward into surrounding space, and gets weaker as you move away from it. The Big Bang had none of these properties.

It was an expansion *of* space, happening everywhere at once. There is no point you could travel to and say "it started here", because it started *here* — and also at every other location, simultaneously. Galaxies are not flying apart through space like shrapnel; the space between them is getting larger. Chapter 27 takes this apart properly. For now, delete the word "explosion" from your vocabulary on this subject.

TRY THIS · YOUR OWN TIMELINE

Take a 10-metre length of string or a long corridor and mark one end "Big Bang", the other "now". Each metre is 1.38 billion years. Then place a sticker for:

- the first stars — 15 cm from the start;
- the Sun's birth — 6.67 m along, so 3.33 m from the end;
- the first animals — 39 cm from the end;
- the dinosaurs' extinction — 4.8 cm from the end;
- the whole of human existence — the final 0.2 mm.

You will need a needle for the last one. That is the point of the exercise.

IN A HURRY?

- The universe is **13.8 billion years** old, known to about ±0.02 billion.
- Scale it to one year and **1 day = 37.8 million years, 1 second = 437 years**.
- The Sun appears on **31 August**; the Earth on 2 September. Two-thirds of cosmic history happened before our Solar System existed.
- Humans occupy the last **11 minutes**; all recorded history the last **12 seconds**.
- The age comes from four independent methods — old stars, radioactive decay, cooling white dwarfs and the microwave background — that agree.
- The Big Bang was **not an explosion in space**. It was an expansion of space.

CHAPTER 3 · THE STAGE

Every Telescope Is a Time Machine

> Light is fast but not infinitely fast, and that single limitation turns astronomy from a survey of what is out there into an excavation of what used to be.

You have never seen the Sun. You have seen the Sun as it was eight minutes and nineteen seconds ago. If it were somehow switched off right now, you would carry on enjoying a perfectly ordinary afternoon for the next eight minutes, entirely unaware, because the news travels at 299,792,458 metres per second and no faster.

This is not a quirk. It is the organising principle of the entire science. Astronomers cannot visit anything, cannot run experiments on their subjects, and cannot ask a star to repeat itself. What they have instead is a peculiar compensation: because light takes time to arrive, **looking far away is identical to looking far back**. The universe helpfully archives its own history and posts it to us, slowly.

Lookback time

The delay has a name — **lookback time** — and it scales with distance in the simplest possible way. An object *d* light-years away is seen as it was *d* years ago. That is all there is to it.

WHAT YOU ARE ACTUALLY LOOKING AT

The Moon 1.3 light-seconds	as it was 1.3 seconds ago
The Sun 8.3 light-minutes	8 minutes 19 seconds ago
Saturn 1.3 light-hours	about 80 minutes ago
Sirius, the brightest night star 8.6 light-years	when you were about five
Betelgeuse 550 light-years	while Babur was invading India
The Andromeda Galaxy 2.5 million light-years	before any human being existed
GN-z11, seen by Hubble and Webb 13.4 billion years of lookback	400 million years after the Big Bang
The microwave background 13.8 billion years of lookback	the oldest light that exists

Figure 3.1 — The night sky is not a snapshot. Every object in it is being seen at a different moment in the past. The constellation Orion contains stars whose light left at dates centuries apart; the shape you see never existed all at once.

Sit with the consequence of the middle rows. When you look at Orion, one star's light left in 1780 and another's in 1450. You are looking at a composite photograph assembled from hundreds of different centuries. The constellation, as a simultaneous arrangement, has never existed.

The observable universe is not the universe

Because the universe has a finite age, there is a maximum distance from which light has had time to reach us. That boundary is the **particle horizon**, and the sphere inside it is the **observable universe**. Beyond it there is almost certainly more universe; we simply have no causal contact with it, and will not for a long time.

Here is where most people get tripped up. The universe is 13.8 billion years old, so the obvious guess is that the observable universe is 13.8 billion light-years in radius. It is not. It is about **46.5 billion light-years**.

The reason is that space itself has been expanding while the light was in transit. A photon that set out 13.4 billion years ago from what was then a nearby patch of gas has been swimming upstream against stretching space the whole way. By the time it arrives, the object that emitted it has been carried far further away than the distance the light actually travelled. The light has aged 13.4 billion years; the source is now 32 billion light-years off.

> DO THE MATH · 3.1
>
> **How stale is your information?** Compute the lookback time for each of these, given $c = 3.00 \times 10^8$ m/s:
>
> - Mars at closest approach, 5.5×10^{10} m. (Answer in minutes.)
> - Jupiter at 6.3×10^{11} m. Why does this number make live remote control of a Jupiter rover impossible?
> - Proxima Centauri at 4.0×10^{16} m. (Answer in years.)
>
> Then a harder one. The Voyager 1 spacecraft is 167 AU away. NASA sends a command and waits for confirmation. How long is the round trip? If an engineer spots a problem developing, how much has already happened by the time they can react?

Why this makes astronomy possible at all

A biologist studying evolution cannot watch a species change; they must infer it from fossils and genetics. An astronomer is in a much better position. Want to know how galaxies evolve over ten billion years? Do not wait ten billion years. Photograph galaxies at a range of distances, and each distance hands you a different epoch.

This is the whole logic behind the deep-field observations. Point a telescope at an apparently empty patch of sky and leave the shutter open for days. What emerges is a core sample drilled through cosmic history: nearby mature spirals in the foreground, and behind them, smaller, bluer, more chaotic objects — galaxies caught in the act of being young.

CASE FILE · THE DEEP FIELDS

In December 1995, Robert Williams, then director of the Space Telescope Science Institute, made a decision that a good many astronomers thought was a waste. He committed ten days of Hubble's director's discretionary time — the most competitively fought-over resource in astronomy — to staring at a patch of sky in Ursa Major about one-thirtieth the width of the full Moon, chosen specifically because it appeared to contain *nothing*.

342 exposures later, the Hubble Deep Field showed roughly **3,000 galaxies** in that empty speck. Extrapolated across the whole sky, it implied tens of billions of galaxies in the observable universe. It remains one of the most cited images in the history of the subject.

The technique has been repeated with steadily better instruments — the Ultra Deep Field in 2004, the eXtreme Deep Field in 2012, and since 2022 the JWST deep fields, which reach galaxies as they were roughly 300 million years after the Big Bang. Those Webb images have produced a genuine and unresolved problem: the early galaxies look too big, too bright and too well organised for the age of the universe at that point. Nobody yet knows whether the fix is in the galaxy-formation models, the mass estimates, or something more interesting.

GET THIS STRAIGHT

"If a star is 100 light-years away, it might have died and we would not know." True in principle, and almost always irrelevant in practice. A Sun-like star lives for about ten billion years. The chance that it happened to die within the last hundred years — a window of one part in a hundred million of its lifetime — is negligible.

The statement is only meaningful for stars that are genuinely near the end. Betelgeuse is 550 light-years away and will explode sometime in the next hundred thousand years, so it is entirely possible it has already gone. For an ordinary star, though, "it might be dead already" is a piece of pub philosophy, not astronomy.

TRY THIS · DATE THE LIGHT IN YOUR EYES

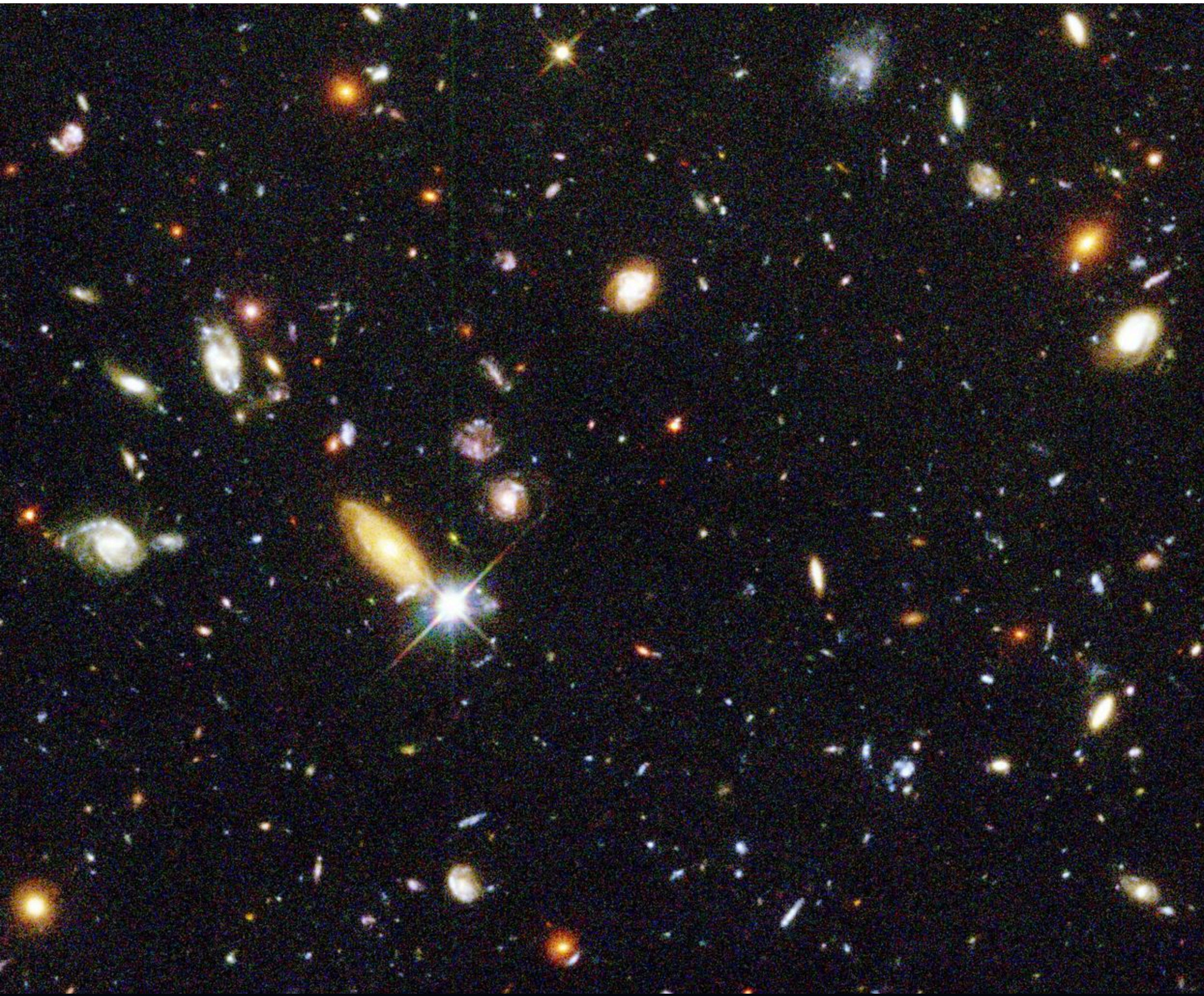
Pick a bright star tonight and look up its distance. Then subtract that many years from the current year. That is the date the photons hitting your retina departed. Write the date down. A short list to start with:

- **Sirius** — 8.6 ly · left roughly when you started primary school.
- **Vega** — 25 ly.
- **Polaris** — 448 ly · left during the reign of Akbar.
- **Rigel**, in Orion — 860 ly · left before the Delhi Sultanate.
- **The Andromeda Galaxy** — 2.5 million ly · left before *Homo sapiens*.

Andromeda is a smudge near the constellation Cassiopeia and is visible to the naked eye from a dark site. Finding it is the farthest any unaided human being can see.

CAREER NOTE

"Distance is time" makes **observational cosmology** possible as a career. The practical work involves photometric redshifts, survey catalogues and enormous amounts of Python. If it appeals, the institutes to know in India are IUCAA in Pune, the Raman Research Institute and the Indian Institute of Astrophysics in Bengaluru, and NCRA at the GMRT. All of them run summer programmes that take undergraduates — and the people who get selected are usually the ones who started reading papers years before they were qualified to understand them.



Ten days of looking at nothing

The Hubble Deep Field, 1995. Robert Williams pointed the telescope at a patch of apparently empty sky about one-thirtieth the width of the full Moon and left the shutter open for ten days. **Almost every object here is a galaxy**, not a star. The faintest are being seen as they were within a couple of billion years of the Big Bang. This single image implied tens of billions of galaxies in the observable universe.

Credit: NASA/JPL/STScI Hubble Deep Field Team. NASA — free to use with credit.

IN A HURRY?

- Light travels at **299,792,458 m/s** — fast, but finite.
- Therefore **looking far away is looking back in time**. An object *d* light-years away is seen as it was *d* years ago.
- The night sky is a composite of thousands of different dates. Constellations have never existed as simultaneous arrangements.
- The **observable universe** has a radius of ~46.5 billion light-years, not 13.8 — because space expanded while the light was in transit.
- Deep-field images work as core samples through cosmic history: distance on the image is age in the universe.
- JWST's earliest galaxies look more developed than the models predict. That argument is live right now.

II

The Rules

The universe runs on a startlingly short list of rules. Learn gravity, light and the spectrum properly and you can already read most of what the sky is telling you.

CHAPTER 4 · THE RULES

Gravity: The Weakest Force That Runs Everything

> A cheap fridge magnet beats the gravitational pull of the entire planet. And yet gravity, not magnetism, decides the shape of the universe.

Pick up a paperclip with a magnet the size of your thumbnail. In that moment a few grams of ferrite have out-muscled 6×10^{24} kilograms of Earth. Gravity is, by an enormous margin, the feeblest of the four fundamental forces — about 10^{36} times weaker than electromagnetism. A one followed by thirty-six zeroes.

So why does the universe look the way it does — spheres, orbits, discs, collapse — rather than being run by the vastly stronger electromagnetic force? Because of one asymmetry. **Electric charge comes in two kinds and cancels; mass comes in one kind and only ever adds up.**

Take any large object — a planet, a star, you — and count its charges. The positives and negatives balance almost exactly, so at a distance the electric force effectively vanishes. Nothing cancels gravity. Every gram of every object in the universe pulls on every other gram, always attractively, forever. Pile up enough grams and a force that is hopeless at small scales becomes the only thing that matters at large ones.

Newton's law, and why the exponent is exactly two

In 1687 Newton wrote down the rule, and for most purposes it is still the rule:

THE LAW OF UNIVERSAL GRAVITATION

$$F = \frac{G \cdot m_1 \cdot m_2}{r^2}$$

$$G = 6.674 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2} \quad \text{(the gravitational constant)}$$

The force between two masses is proportional to each mass and falls off as the *square* of the distance between their centres. Double the separation and the force drops to a quarter. Triple it and you are down to a ninth.

The exponent is not fitted to data; it is geometry. Imagine the gravitational influence of a body spreading outward like paint from a spray can. At distance *r* it is smeared over a sphere of area $4\pi r^2$. Go twice as far and the same fixed amount of influence has to cover four times the area, so its intensity is a quarter. Every effect that spreads out into three-dimensional space in this way — gravity, light, sound intensity, radio signals — obeys an inverse-square law for the same reason.

WHY THE INVERSE SQUARE?

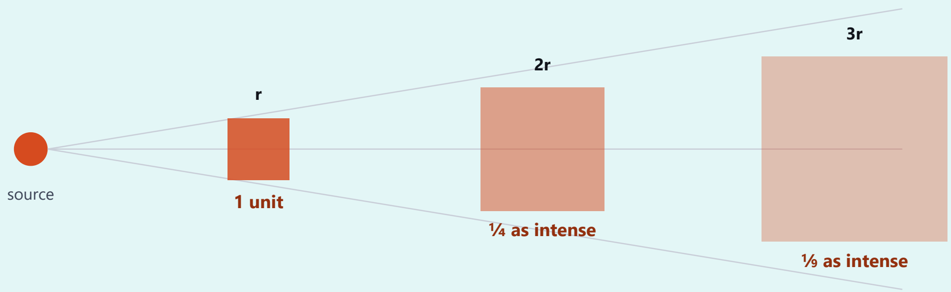


Figure 4.1 — Geometry, not physics. The same amount of influence must cover a larger and larger patch as it spreads. Area grows as the square of distance, so intensity falls as the square of distance. Light, sound, radio and gravity all obey this for the identical reason.

An orbit is just falling and missing

Newton's own explanation remains the best one ever written. Imagine a cannon on top of an impossibly high mountain, firing horizontally. Fire it gently and the ball arcs down and lands nearby. Fire harder and it lands further away, its path curving as the Earth's surface curves beneath it. Fire hard enough — and here is the whole idea — and the ball falls at exactly the rate the Earth's surface curves away from it. It never gets any closer to the ground. It is now in orbit.

An orbiting object is not being held up. It is falling, permanently, and missing. The International Space Station is falling towards the Earth at this moment at nearly the same 9.8 m/s^2 you experience — but it is also travelling sideways at 7.66 km/s, and the combination is a closed curve.

NEWTON'S CANNONBALL

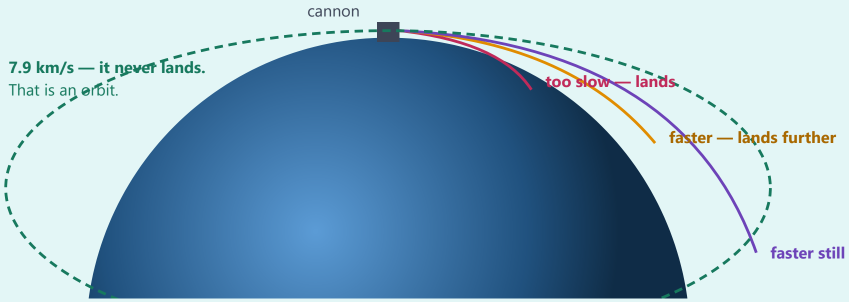


Figure 4.2 — Newton's thought experiment, 1687. There is no difference in kind between a thrown stone and the Moon. Only the sideways speed differs.

Two speeds fall out of the mathematics and are worth memorising in form if not in value. The **circular orbital speed** at distance r from a body of mass M is $v = \sqrt{(GM/r)}$. The **escape velocity** — the speed at which an object never comes back — is exactly √2 times larger: $v = \sqrt{(2GM/r)}$. For the Earth's surface that is 11.2 km/s.

Notice what is missing from both formulas: the mass of the orbiting object. A feather and a battleship, launched at the same speed from the same height, follow the same orbit. This is the first hint of something deep, and Chapter 5 is about what it turned out to mean.

DO THE MATH · 4.1

How fast is the space station going? Use $v = \sqrt{(GM/r)}$ with $G = 6.674 \times 10^{-11}$, the Earth's mass $M = 5.972 \times 10^{24}$ kg, and r measured from the Earth's *centre* — the ISS orbits 420 km up, so r = 6,371 km + 420 km.

```
r = (6371 + 420) × 10³ m = 6.791 × 10⁶ m

v = √( GM / r )
  = √( 6.674×10⁻¹¹ × 5.972×10²⁴ / 6.791×10⁶ )
  = ?  m/s
```

Convert to km/s. Then work out how long one orbit takes, using $T = 2\pi r/v$, and check your answer against the fact that astronauts on board see about sixteen sunrises a day.

Extension: repeat for the Moon, at $r = 3.84 \times 10^8$ m. You should recover a period close to 27.3 days.

CASE FILE · THE PLANET FOUND WITH A PENCIL

By the 1840s, Uranus was misbehaving. Its observed positions drifted from Newtonian predictions by about two arcminutes — small, but far larger than the observational error. Either Newton's law was wrong, or something unseen was tugging at it.

Urbain Le Verrier in Paris assumed the latter and did something audacious: he worked *backwards* from the discrepancy to the position of the disturbing body. On 31 August 1846 he published a predicted location. He sent it to Johann Galle at the Berlin Observatory, who received the letter on 23 September, pointed the telescope that same night, and found Neptune **within one degree** of the predicted spot — in under an hour of searching.

It remains the most spectacular prediction in the history of classical physics: a planet discovered by mathematics before anyone saw it. Le Verrier then tried the same trick on Mercury's orbital anomaly and proposed a planet called Vulcan. That one does not exist — and the failure turned out to be a doorway into Einstein, which is Chapter 5.

GET THIS STRAIGHT

"Astronauts float because there is no gravity in space." At the height of the ISS, Earth's gravity is about **89 per cent** as strong as at the surface. If the station stopped moving sideways it would drop out of the sky.

Astronauts float because they are in **free fall** — falling around the Earth together with their spacecraft, everything accelerating identically, so nothing pushes against anything else. You experience the same thing for a fraction of a second at the top of a jump. The correct term is *microgravity*, and the sensation is not the absence of gravity but the absence of a floor.

Tides: gravity's difference, not gravity's strength

Tides confuse people because they are caused not by gravitational pull but by **gravitational gradient** — the fact that the near side of the Earth is pulled a little harder than the far side.

The Moon pulls hardest on the ocean facing it, moderately on the Earth's centre, and least on the ocean on the far side. Relative to the centre, the near ocean is pulled towards the Moon and the far ocean is left behind — which produces **two** bulges, on opposite sides. As the Earth rotates beneath them you pass through both, which is why most coastlines get two high tides a day rather than one.

Because tidal effects depend on the difference across an object, they fall off as $\mathbf{1/r^3}$, not $1/r^2$. This is why the Sun, despite pulling on the Earth 178 times harder than the Moon does, produces a tide only about 46 per cent as large: it is far away, so its pull barely varies across the width of our planet. When Sun and Moon line up you get the extra-large spring tides; when they are at right angles you get the feeble neaps. The same $1/r^3$ arithmetic, applied close to a black hole, is what shreds infalling stars — see Chapter 20.

TRY THIS · MEASURE *G* WITH A SHOELACE

A pendulum's period depends only on its length and the local strength of gravity:

$$T = 2\pi \sqrt{L / g} \Longrightarrow g = 4\pi^2 L / T^2$$

Tie a small heavy object to a string exactly 1.000 m long, measured to the centre of the weight. Swing it through a small angle — under about 15° — and time **twenty** full swings with a phone stopwatch. Divide by 20 to get *T*. Timing twenty and dividing is not fussiness; it cuts your reaction-time error by a factor of twenty, and that trick is worth more marks in a practical exam than any amount of careful swinging.

You should land within a couple of per cent of 9.79 m/s^2 in northern India. If you are out by more than five per cent, your string length is probably measured to the top of the weight rather than its middle.

IN A HURRY?

- Gravity is **10^{36} times weaker** than electromagnetism but dominates the universe because **mass never cancels** while charge does.
- **$F = Gm_1m_2/r^2$**. The square is pure geometry — influence spread over a sphere of area $4\pi r^2$.
- An **orbit is free fall** with enough sideways speed to keep missing the ground.
- Orbital speed **$\sqrt{GM/r}$**; escape velocity **$\sqrt{2GM/r}$** — 11.2 km/s from Earth. Neither depends on the falling object's mass.
- Astronauts float from **free fall**, not absent gravity: at ISS height gravity is still 89% of surface strength.
- **Tides come from the gradient** of gravity and fall off as $1/r^3$, which is why the distant Sun loses to the nearby Moon.

Spacetime Has a Shape

> Newton said masses pull on each other across empty space. Einstein said there is no pull and the space is not empty. Astonishingly, the second man was right.

Newton himself was uneasy about his own theory. How does the Sun reach across 150 million kilometres of nothing and grab the Earth? Instantly? With what? He called action at a distance "so great an absurdity that no man who has a competent faculty of thinking can ever fall into it" — and then published the equations anyway, because they worked. It took 228 years for someone to explain what was actually happening.

The happiest thought

Einstein's route in was a thought experiment he later called the happiest thought of his life. Suppose you wake up in a sealed lift with no windows and find yourself pinned to the floor. Two explanations are available. The lift is sitting on Earth. Or the lift is in deep space, accelerating upwards at 9.8 m/s^2.

Einstein's claim — the **equivalence principle** — is that there is *no experiment you can do inside the lift* that distinguishes them. Not a clever one, not a subtle one. None. Gravity and acceleration are not merely similar; they are locally the same thing.

This immediately explains the curious fact from the last chapter — that the mass of a falling object drops out of every equation. Galileo's feather and hammer hit the lunar dust together not because of a coincidence in the numbers but because **neither of them is being pulled at all**. Both are simply moving straight ahead through a spacetime that is not flat.

What "curved" actually means

Here is the reframing. Newton: mass creates a force that deflects objects from straight lines. Einstein: **mass and energy curve spacetime, and objects follow the straightest available path through it.** There is no force. There is only geometry.

An analogy that works better than the usual one: two people set off from different points on the equator, both walking exactly due north, never turning. They start parallel. They meet at the North Pole. Did a force pull them together? No — they walked straight the whole way. The surface they walked on was curved. Gravity, in general relativity, is that: **convergence produced by geometry rather than by pulling.**

MASS TELLS SPACETIME HOW TO CURVE

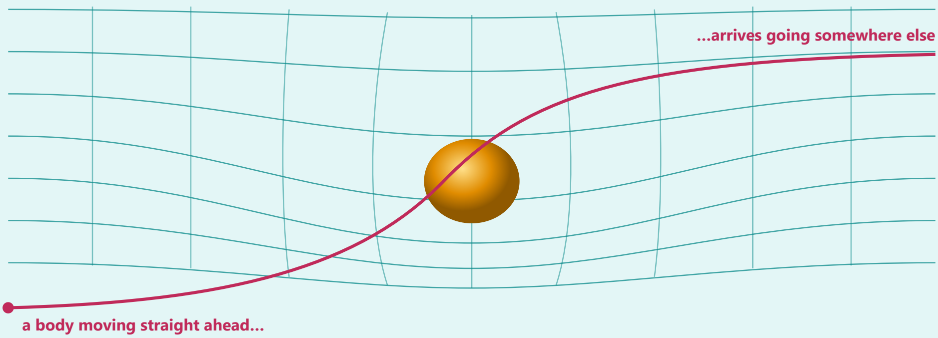


Figure 5.1 — Not a pull; a shape. The grid represents spacetime. The red path is a *geodesic* — the straightest line available. Nothing deflects the moving body; the geometry it is moving through is simply not flat. John Wheeler's summary is unimprovable: *spacetime tells matter how to move; matter tells spacetime how to curve.*

GET THIS STRAIGHT

The rubber sheet with a bowling ball on it. You have seen this picture. It is the standard illustration and it is badly flawed, in three ways worth knowing.

First, it is **circular**: the bowling ball only makes a dent because a downward gravity is pulling it into the sheet. The picture explains gravity using gravity. Second, it shows **only space**, and for everyday objects the curvature of *time* is by far the dominant effect — an apple falls mostly because time runs fractionally slower near the ground, not because space is bent. Third, real spacetime is four-dimensional and is not embedded in anything; there is no "outside" for it to sag into.

Keep the picture if it helps you remember that mass distorts geometry. Do not use it to reason with, and never offer it in an interview as an explanation.

Four tests, all passed

A beautiful theory that predicts nothing new is philosophy. General relativity made specific, risky, numerical predictions. Here are the four that matter.

1. Mercury's wandering orbit. Mercury's closest approach to the Sun slowly rotates around it. Newtonian mechanics, accounting for every other planet, explained all but **43 arcseconds per century** — a stubborn, tiny, well-measured leftover. Einstein's field equations produced 43 arcseconds per century with no free parameters to adjust. He later said the discovery gave him palpitations.

2. Starlight bends. General relativity predicted that light grazing the Sun would be deflected by **1.75 arcseconds** — precisely twice the value you get from naively applying Newtonian gravity to light corpuscles. The factor of two is the crux: it comes from space curvature contributing exactly as much as time curvature, so the measurement could tell the two theories apart cleanly.

3. Clocks run slow in gravity. Time itself passes more slowly deeper in a gravitational field. Pound and Rebka verified this in 1959 by measuring a frequency shift over a 22.5-metre drop in a Harvard tower — a change of about two parts in 10^{15}.

4. Your phone depends on it. GPS satellites orbit at 20,200 km. Their clocks run *fast* by 45 microseconds a day from weaker gravity, and *slow* by 7 microseconds a day from their orbital speed — a net gain of **38 microseconds daily**. Uncorrected, that would push your position error out by about **10 kilometres every day**. The correction is built into every GPS receiver on Earth. General relativity is not exotic; it is infrastructure.

CASE FILE · THE ECLIPSE OF 29 MAY 1919

To catch starlight grazing the Sun you must blot out the Sun, which means a total eclipse. Arthur Eddington led an expedition to Príncipe, off West Africa; a second team went to Sobral in Brazil. Príncipe was rained on almost the entire morning; the clouds parted for the last few minutes and Eddington got a handful of usable plates.

The results, announced on 6 November 1919: Sobral gave 1.98 ± 0.16 arcseconds, Príncipe 1.61 ± 0.40. Einstein predicted 1.75. Newton predicted 0.87. The next morning *The Times* of London ran the headline "Revolution in Science", and a German-Jewish physicist working in Berlin became, in the space of a week, the most famous scientist alive.

The honest footnote: the 1919 error bars were uncomfortably large, and historians have argued for decades about whether Eddington's data really excluded the Newtonian value or whether he leaned on it. It hardly matters now. The measurement has been repeated with radio interferometry to a precision of better than 0.02 per cent, and Einstein's number holds. But the episode is a useful reminder that famous confirmations are often messier at the time than they look afterwards.

Lensing: the effect that became a tool

If mass bends light, then a sufficiently massive object works as a lens. This is not a curiosity — it is now one of the most powerful instruments in astronomy, and the fact that it comes free is the best deal in the subject.

A galaxy cluster sitting between us and a more distant galaxy will smear the background object into arcs, multiple images, or — if the alignment is near-perfect — a complete **Einstein ring**. Three things follow. Because the distortion depends on *total* mass, lensing weighs objects including their invisible content, which is how dark matter was mapped (Chapter 26). Because a lens magnifies, clusters act as natural telescopes, letting JWST reach galaxies that would otherwise be far too faint. And because light takes different routes through the lens, the images arrive at different times — so a supernova behind a cluster can be seen exploding more than once, years apart.

DO THE MATH · 5.1

How much does gravity slow a clock? To a good approximation, a clock at distance r from a mass M ticks slower than a clock far away by the fraction

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Δt / t  ≈  GM / (r c²)
```

Compute this for a clock on the Earth's surface, using $M = 5.972 \times 10^{24}$ kg, $r = 6.371 \times 10^6$ m, $c = 3.00 \times 10^8$ m/s.

You should get roughly 7×10^{-10}. Now turn that into something concrete: how many seconds does an Earth-bound clock lose over an 80-year lifetime relative to one far out in space? And then the interesting question — is that a real, physical difference, or an illusion of measurement?

(It is real. Two atomic clocks separated by a 33 cm height difference have measurably different rates. This was demonstrated at NIST in 2010.)

CAREER NOTE

General relativity is normally met properly in the third or fourth year of a physics degree, because it needs tensor calculus and differential geometry. But the ideas need no such thing, and the people who go furthest with it almost always met the *ideas* years earlier. In India, the strongest gravity groups are at IUCAA Pune, ICTS-TIFR in Bengaluru, and the IITs at Madras, Bombay and Gandhinagar; ICTS in particular is a major partner in gravitational-wave astronomy (Chapter 33).

IN A HURRY?

- The **equivalence principle**: standing on Earth and accelerating in deep space are locally indistinguishable.
- Gravity is **not a force**. Mass and energy curve spacetime; objects follow the straightest available path — a **geodesic**.
- The rubber-sheet picture is circular, ignores curved *time*, and should not be used for reasoning.
- Four confirmations: Mercury's **43″ per century**, starlight deflection of **1.75″**, gravitational time dilation, and the **38 µs/day** GPS correction.
- **Gravitational lensing** turns the effect into an instrument — for weighing dark matter and for magnifying the early universe.
- Newton is not wrong, just incomplete. Use Newton for spacecraft; use Einstein near black holes, near light speed, and inside your phone.

CHAPTER 6 · THE RULES

Light: The Messenger That Arrives Late

> Almost everything humanity knows about the universe arrived as light. It pays to understand what light is, how it fades, and how astronomers turned a Greek ranking system into a precise measuring instrument.

Astronomy is a science conducted almost entirely by collecting photons. We cannot sample a star, weigh a galaxy on a balance, or heat a nebula to see what happens. What arrives is light — and, since about 2015, a trickle of neutrinos and gravitational waves. Everything else is inference from those photons.

Two descriptions, both correct

Light is a travelling disturbance in the electromagnetic field: an oscillating electric field generating an oscillating magnetic field generating the electric field again, leapfrogging through space at a speed Maxwell's equations fix without any reference to who is watching. It is a **wave**, with a wavelength λ and a frequency f, related by $c = \lambda f$.

Light is also a stream of indivisible packets called **photons**, each carrying energy $E = hf$, where $h = 6.626 \times 10^{-34}$ J·s is Planck's constant. A photon is not a small bullet; it has no mass and no rest frame. But it is countable, and it is either absorbed whole or not at all.

Both pictures are needed. Diffraction through a telescope aperture is a wave phenomenon; the response of the detector that records the image is a photon phenomenon. Nobody has a mental image that contains both comfortably, and after a while you stop wanting one. The mathematics is consistent, and consistency is what physics actually requires.

THREE WORDS PEOPLE MIX UP

Luminosity
How much energy the object actually emits per second, in watts. A property of the object alone. The Sun's is 3.828×10^{26} W.

Flux (or apparent brightness)
How much of that energy lands on each square metre of your detector. Depends on luminosity *and* distance.

Magnitude
A logarithmic ranking of flux, inherited from ancient Greece, still in daily use, and backwards.

Why distant things fade the way they do

Light obeys the same inverse-square law as gravity, and for the identical reason from Chapter 4: a fixed number of photons per second spreading over an expanding sphere.

THE RELATION THAT UNDERPINS ALL DISTANCE WORK

$$F = \frac{L}{4\pi d^2}$$

F = flux received (W/m^2)   L = luminosity (W)   d = distance (m)

Rearranged, it is the most useful equation in observational astronomy: measure *F*, work out *L* by some independent means, and you get the distance *d*. Every "standard candle" in Chapters 27 and 32 is an object whose *L* we believe we know.

THE SAME STAR AT FOUR DISTANCES

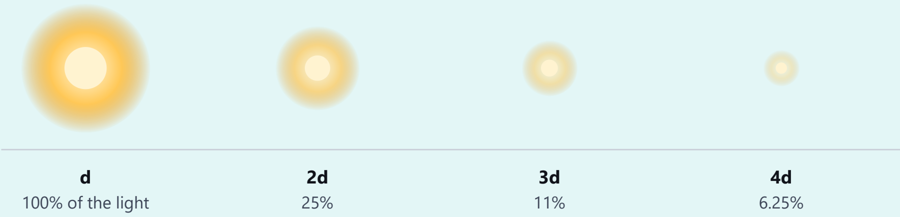


Figure 6.1 — Distance is brutal. Move a star four times further away and it delivers one-sixteenth the energy. This is why every telescope built since 1610 has been an argument about collecting area.

Magnitudes: a 2,100-year-old system nobody can get rid of

Around 130 BCE, Hipparchus sorted the visible stars into six classes: the brightest were "of the first magnitude", the faintest visible "of the sixth". Note the direction — **brighter means a smaller number**, which trips up every beginner and a fair number of professionals.

In 1856 Norman Pogson noticed that Hipparchus's six classes corresponded closely to a factor of about 100 in actual brightness, and formalised it: a difference of exactly **5 magnitudes = a factor of exactly 100 in flux**. One magnitude is therefore a factor of $100^{1/5}$ = **2.512**.

The scale had to be extended in both directions, so it now runs negative for bright objects. The Sun is magnitude −26.7. A full Moon is −12.7. Venus at best is −4.6. Sirius is −1.46. The faintest star a good naked eye can catch from a dark site is about +6.5, and JWST reaches past +34.

THE MAGNITUDE SCALE — SMALLER IS BRIGHTER

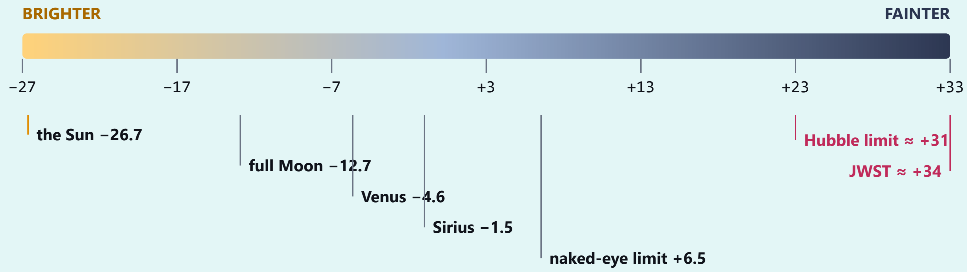


Figure 6.2 — Sixty magnitudes, and a scale that runs the wrong way. Each step of 5 magnitudes is a factor of 100 in brightness. From the Sun to JWST's limit is about 61 magnitudes — a brightness ratio of roughly 2×10^{24}.

There is a second flavour worth knowing. **Apparent magnitude** (written *m*) is how bright something looks from Earth. **Absolute magnitude** (*M*) is how bright it would look if placed at a standard distance of 10 parsecs. The difference $m - M$, the **distance modulus**, encodes the distance — which is how astronomers convert a photograph into a three-dimensional map.

DO THE MATH · 6.1

How much brighter, exactly? The flux ratio for a magnitude difference is

$$F_1 / F_2 = 2.512 ^ {(m_2 - m_1)}$$

- Sirius is m = −1.46; Polaris is m = +1.98. How many times brighter does Sirius appear?
- The Sun (−26.7) versus the full Moon (−12.7): a difference of 14 magnitudes. How many times brighter is daylight than moonlight? (The answer explains why you cannot read comfortably by moonlight even though the Moon looks perfectly bright.)
- Harder: Betelgeuse has m = +0.5 and lies 550 light-years away. Rigel has m = +0.13 at 860 light-years. They look almost equally bright. Which is genuinely more luminous, and by roughly what factor?

GET THIS STRAIGHT

"The brightest stars in the sky are the closest ones." Mostly false. Apparent brightness mixes up two completely independent things: how much light an object makes, and how far away it is.

Of the twenty brightest night-time stars, only a handful are genuine neighbours. Deneb, in Cygnus, is around 2,600 light-years away — some 300 times further than Sirius — and still ranks in the top twenty, because it pumps out roughly 200,000 times the Sun's power. Meanwhile Proxima Centauri, the *nearest* star of all, is magnitude +11 and completely invisible without a telescope. Brightness in the sky tells you nothing on its own.

CASE FILE · OLE RØMER TIMES THE SPEED OF LIGHT, 1676

Everyone before Rømer, including Descartes, assumed light was instantaneous. Galileo had tried to test it with lanterns on adjacent hilltops and, unsurprisingly, measured only human reaction time.

Rømer, working at the Paris Observatory, was studying eclipses of Io, Jupiter's innermost large moon, which disappears behind the planet every 42.5 hours with clockwork regularity. Except it did not. When Earth was moving away from Jupiter the eclipses ran progressively late; when approaching, progressively early. The total swing across the year was about **22 minutes**.

Rømer's insight: the eclipses are perfectly regular, and the "lateness" is the extra time light needs to cross the changing gap — the diameter of Earth's orbit. In 1676 he announced that light takes about 22 minutes to cross it. The modern value is 16 minutes 40 seconds, so he was around 30 per cent out, mostly because nobody yet knew the size of Earth's orbit accurately. But the physics was exactly right, and the qualitative conclusion — **light has a finite speed** — was the important part. It is a fine example of a result being valuable even when the number is wrong.

TRY THIS · ESTIMATE YOUR OWN LIMITING MAGNITUDE

Find the constellation Ursa Minor, which contains stars spanning magnitudes 2.0 to 5.0 in a compact pattern. On a clear night, away from direct lights, give your eyes a full **twenty minutes** to dark-adapt — no phone screen, or use a red filter — and count how many of its stars you can see.

The faintest one you can hold steadily is your limiting magnitude. In a city centre it is often 3 or worse. In a small town, 5. From a genuinely dark site, 6.5. Doing this from your terrace and then again on a trip out of the city is the most direct demonstration of light pollution you will ever get — and the numbers you collect are real data of the kind used in the global Globe at Night survey.

IN A HURRY?

- Light is both a **wave** ($c = \lambda f$) and a stream of **photons** ($E = hf$). Both are needed.
- **Luminosity** is what the object emits; **flux** is what you receive; they are linked by **$F = L / 4\pi d^2$**.
- The **magnitude scale runs backwards**: smaller is brighter. Five magnitudes is exactly a factor of 100; one magnitude is 2.512.
- **Apparent** magnitude is how it looks; **absolute** magnitude is how it would look at 10 parsecs. The difference gives distance.
- Bright in the sky ≠ nearby. Deneb is 2,600 ly away and outshines almost everything; Proxima is next door and invisible.
- Rømer proved light's speed is finite in **1676**, using the timing of Jupiter's moon Io.

CHAPTER 7 · THE RULES

Seeing With Invisible Eyes

> Human vision covers less than one ten-trillionth of the electromagnetic spectrum. Nearly everything interesting in the universe is broadcasting on a channel your eyes cannot receive.

Radio waves, microwaves, infrared, visible light, ultraviolet, X-rays and gamma rays are not seven different phenomena. They are one phenomenon — electromagnetic radiation — listed in order of wavelength. The only thing that makes the narrow band between 380 and 750 nanometres special is that our ancestors evolved eyes for it, because that happens to be where the Sun is loudest and where seawater is clear.

For most of history astronomy therefore studied one octave of an enormous keyboard. Every time a new band was opened — radio in the 1930s, X-ray in the 1960s, gamma-ray in the 1970s — the universe turned out to contain a category of object nobody had suspected. Pulsars, quasars, gamma-ray bursts and the microwave background were all found this way.

Hot things glow, and their colour gives away their temperature

Any object above absolute zero radiates. The spectrum it produces — a **blackbody curve** — has a characteristic hump, and the wavelength of that peak depends only on temperature. This is **Wien's displacement law**:

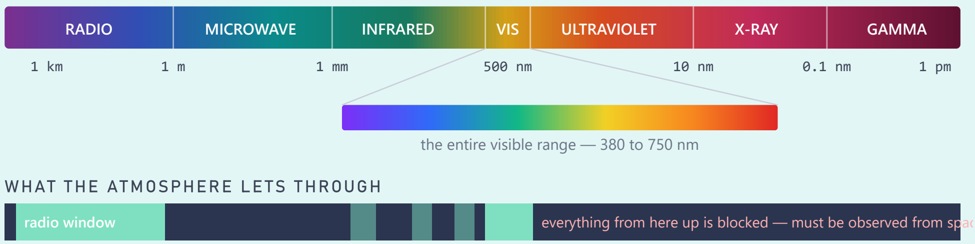
WIEN'S LAW

$$\lambda_{max} = \frac{2.898 \times 10^{-3}}{T} \text{ metres} \quad (T \text{ in kelvin})$$

Hotter means bluer. This single relation is why a star's colour is a thermometer, why cool dust must be hunted in the infrared, and why the leftover glow of the Big Bang, at 2.725 K, is found in the microwave band.

Work the law once and the whole spectrum organises itself. You, at 310 K, peak at about 9.3 micrometres — mid-infrared, which is why thermal cameras work. The Sun, at 5,772 K, peaks at 502 nm, which is green-blue, in the middle of the range our eyes evolved to use. A star at 25,000 K peaks in the ultraviolet and looks blue-white. Gas falling into a black hole at ten million kelvin peaks in X-rays.

ONE SPECTRUM, SEVEN NAMES



RADIO cold hydrogen gas · pulsars · jets from black holes · the 21 cm line
MICROWAVE the cosmic microwave background — the oldest light there is
INFRARED star-forming dust clouds · protostars · redshifted early galaxies · exoplanets
VISIBLE ordinary stars and galaxies — where the Sun is loudest
UV hot young massive stars · white dwarfs · the gas between galaxies
X & GAMMA accretion discs · supernova remnants · cluster gas · gamma-ray bursts

Figure 7.1 — The spectrum, the atmospheric windows, and the job each band does. Only radio and a narrow optical slot reach the ground. Everything else demanded rockets, which is why X-ray astronomy could not begin before 1962.

Why some telescopes must leave the planet

The atmosphere that keeps you alive is, for an astronomer, an obstruction. Water vapour absorbs most infrared. Ozone blocks ultraviolet. Nitrogen and oxygen stop X-rays and gamma rays completely. Only two wide windows are open: **radio**, from a few millimetres to about twenty metres, and **optical**, with a few infrared slots that survive if you go high and dry.

That single fact explains the geography of astronomy. Radio dishes can sit anywhere quiet — the GMRT is in farmland near Pune. Optical telescopes climb: Hanle in Ladakh at 4,500 m, Mauna Kea at 4,200 m, the Atacama at 5,000 m, chosen for thin, dry, still air. And ultraviolet, X-ray and gamma-ray astronomy simply cannot be done from the ground at all — every photon must be caught above the atmosphere, which is why AstroSat, Chandra, XMM-Newton and Fermi are satellites.

CASE FILE · THE ENGINEER WHO FOUND THE GALAXY BY ACCIDENT

In 1932 Karl Jansky was a 26-year-old engineer at Bell Telephone Laboratories with a dull assignment: find out what was causing static on transatlantic radio-telephone calls. He built a rotating 30-metre aerial on a set of Ford Model-T wheels — colleagues called it Jansky's merry-go-round — and catalogued the interference.

Two sources were nearby thunderstorms and distant thunderstorms. The third was a faint steady hiss that rose and set on a cycle of 23 hours 56 minutes. Jansky was careful enough to notice that this is *not* 24 hours: it is the **sidereal day**, the rotation period of the Earth relative to the stars rather than the Sun. The source was therefore not on Earth and not the Sun. It was fixed to the celestial sphere — and it lay in Sagittarius, towards the centre of the Milky Way.

Jansky had opened an entire new window on the universe. Bell Labs, satisfied that the static was nobody's fault, reassigned him to other work and he never returned to astronomy. The unit of radio flux density is now called the jansky. Radio astronomy would go on to deliver pulsars, quasars, the microwave background and the first image of a black hole.

GET THIS STRAIGHT

"Those beautiful nebula pictures show the real colours." Not usually, and the honest answer is more interesting than the myth.

Astronomical detectors are monochrome — they count photons and do not record colour. A colour image is built by taking separate exposures through different filters and assigning each to a channel. When the filters are roughly red, green and blue, you get something close to what a hypothetical eye with a huge pupil would see; this is called **natural colour**. But most famous images are **representative colour**: an infrared exposure mapped to red, another to green, another to blue, so that structures the eye cannot detect become visible.

The Hubble "Pillars of Creation" uses the Hubble palette, in which emission from sulphur, hydrogen and oxygen is mapped to red, green and blue. Those are real measurements of real gas, honestly labelled in the caption. They are not a photograph in the holiday-snap sense, and pretending otherwise does the science a disservice.

DO THE MATH · 7.1

Use Wien's law as a thermometer. $\lambda_{max} = 2.898 \times 10^{-3} / T$ metres. Find the peak wavelength, and name the band, for each:

- A human body at 310 K.
- The Sun's surface at 5,772 K.
- Betelgeuse at 3,600 K.
- Rigel at 12,100 K.
- The cosmic microwave background at 2.725 K.
- Gas in a galaxy cluster at 5×10^7 K.

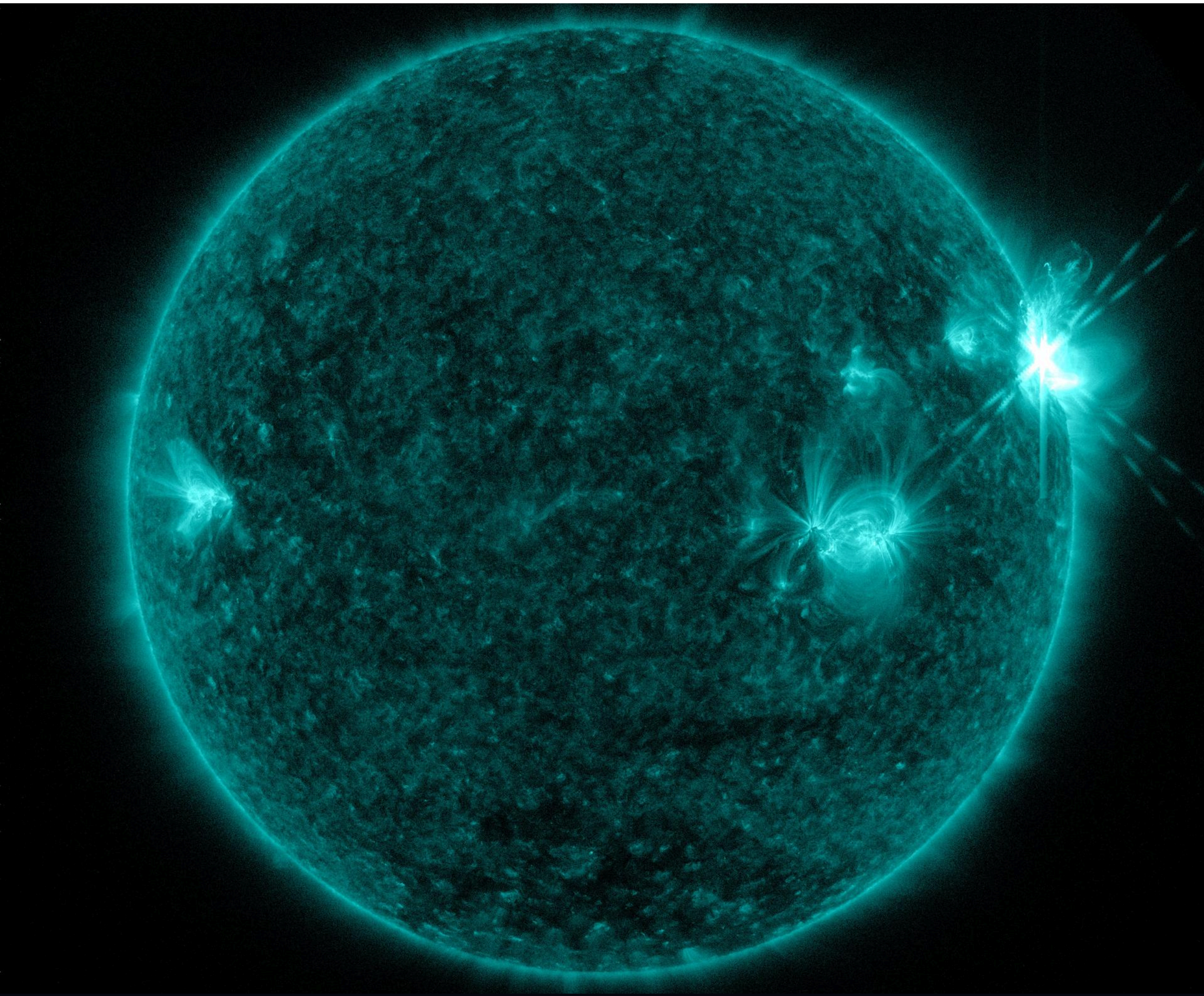
Then invert it. A newly forming star hidden inside a dust cloud radiates most strongly at 100 micrometres. How hot is it? And which of the world's telescopes could see it?

TRY THIS · FIND THE INVISIBLE WITH A PHONE CAMERA

Most phone camera sensors respond a little way into the near infrared, past what your eyes can do. Point any TV or air-conditioner remote at the camera, look at the screen, and press a button. The LED that appears blank to your eye flares pale purple or white on the display.

You are seeing about 940 nm — genuinely outside human vision. That is the entire principle of infrared astronomy in a five-second demonstration: build a detector sensitive where the eye is not, and information that was always arriving suddenly becomes data.

One caveat: newer phones often fit stronger infrared-cut filters on the rear camera. If the rear camera shows nothing, try the front-facing one, which is usually filtered less aggressively.



The Sun in light your eyes cannot detect

Three solar flares recorded by NASA’s Solar Dynamics Observatory in the **extreme ultraviolet**. Nothing in this picture is visible to the human eye, and none of this radiation reaches the ground — ozone stops it, which is why the image had to be taken from orbit. The false colours map different wavelengths to different temperatures of plasma, exactly as described on the previous pages.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- Radio through gamma rays are **one phenomenon** at different wavelengths. Visible light is a sliver.
- **Wien's law**: $\lambda_{max} = 2.898 \times 10^{-3}/T$. Hotter is bluer. Colour is a thermometer.
- The atmosphere opens only a **radio window** and an **optical window**. UV, X-ray and gamma astronomy must be done from space.
- Each band reveals different objects — cold gas in radio, newborn stars in infrared, accretion and explosions in X-ray.
- **Karl Jansky** founded radio astronomy in 1932 while chasing telephone static.
- Colour astronomical images are **constructed from filters**, not photographed. This is disclosed, not deceptive.

CHAPTER 8 · THE RULES

Spectroscopy: A Star's Barcode

> In 1835 a distinguished philosopher declared that the chemical composition of stars was permanently unknowable. Within thirty years it was routine laboratory work. This chapter is about the technique that did it.

Auguste Comte, founder of positivism, chose stars as his example of a question science could never answer. We could measure their positions and motions, he wrote, but never their chemistry. It was a reasonable claim. It was also, by 1860, spectacularly wrong — and the tool that demolished it, **spectroscopy**, remains the single most productive technique in astronomy.

Splitting light open

Newton showed in 1666 that a prism spreads sunlight into a band of colour. What he did not have was a slit narrow enough, or optics good enough, to see that the band is not smooth. In 1814 the Bavarian optician Joseph von Fraunhofer built a better instrument and found the solar spectrum crossed by **hundreds of sharp dark lines**. He mapped 574 of them and labelled the strongest A through K. He had no idea what they were.

The explanation came from Kirchhoff and Bunsen in Heidelberg around 1859, and reduces to three rules:

KIRCHHOFF'S THREE LAWS

1 · A hot dense object
— a solid, a liquid, or a dense gas — emits a smooth **continuous spectrum**, all colours blended.

2 · A hot thin gas
emits only at particular wavelengths: a set of bright **emission lines**, unique to the element producing them.

3 · A cool thin gas in front of a hot source
removes exactly those same wavelengths, leaving dark **absorption lines** in the continuous spectrum behind it.

Fraunhofer's dark lines were therefore case three. The Sun's dense interior makes a continuous spectrum; its cooler outer atmosphere absorbs specific wavelengths on the way out. And because the wavelengths absorbed depend on the energy levels available inside each kind of atom, the pattern is a fingerprint. Sodium always produces its pair at 589.0 and 589.6 nm — in a Bunsen flame in a laboratory, and in a star nine hundred light-years away.

That is the whole trick. **Atoms behave identically everywhere**, so a pattern measured on a bench in Heidelberg identifies the same element anywhere in the universe. It is difficult to overstate how much of astrophysics rests on this one assumption, and how well it has held up.

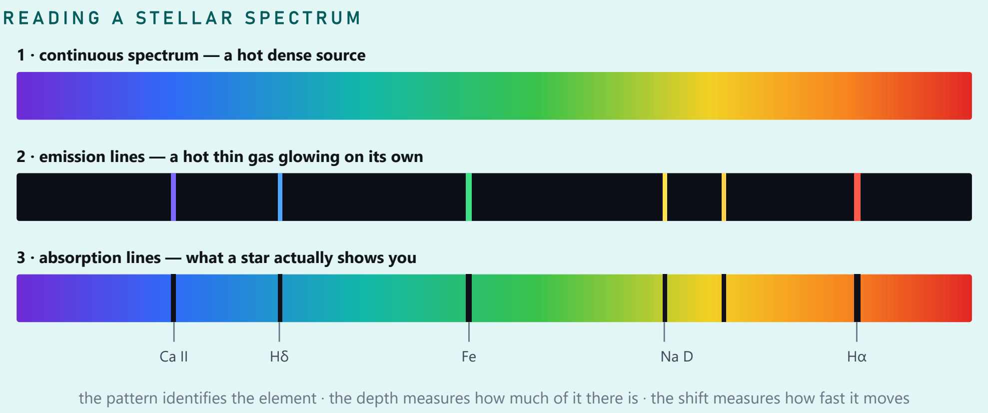


Figure 8.1 — Kirchhoff's three cases. The same element produces bright lines when glowing alone and dark lines at exactly the same wavelengths when backlit. Rows 2 and 3 are the same gas.

CASE FILE · AN ELEMENT DISCOVERED IN THE SUN BEFORE THE EARTH

On 18 August 1868 a total solar eclipse crossed India. Pierre Janssen, observing from Guntur in what is now Andhra Pradesh, trained a spectroscope on the prominences at the Sun's edge and recorded a bright yellow emission line at 587.6 nm. It sat close to the familiar sodium D lines but did not match them.

In October the same year, Norman Lockyer in London saw the same line and — with the chemist Edward Frankland — concluded it belonged to an element unknown on Earth. They named it after the Greek word for the Sun: **helium**.

For twenty-seven years, helium was an element that existed only in a star. It was not isolated on Earth until 1895, when William Ramsay extracted it from the uranium mineral cleveite. The second most abundant element in the universe was found in the sky first — a decisive answer to Comte, who had died only eleven years before Janssen's observation.

The Doppler shift: motion written into the lines

Spectroscopy does not stop at chemistry. If a source moves towards you, each successive wave crest is emitted slightly closer, so the wavelengths bunch up and the whole pattern shifts towards the blue. Moving away, it stretches towards the red. The frequencies change, but the *pattern* — the spacing and relative strength of the lines — is preserved, so you can always tell how far it has slid.

RADIAL VELOCITY FROM A SPECTRAL LINE

$$\frac{\Delta\lambda}{\lambda_0} = \frac{v}{c} \qquad \text{(for v much less than c)}$$

$\Delta\lambda = \lambda_{observed} - \lambda_{rest}$ λ_0 = laboratory wavelength

A positive Δλ (redshift) means receding; negative (blueshift) means approaching. This measures only motion *along the line of sight* — hence "radial" velocity. Sideways motion produces no shift at all.

This one relation is responsible for an implausible share of modern astronomy. It gives the rotation curves of galaxies that revealed dark matter (Chapter 26); the expansion of the universe (Chapter 27); the wobble of stars that betrays orbiting planets (Chapter 30); and the orbital speeds of stars around Sagittarius A* that proved the Milky Way has a black hole at its centre (Chapter 24).

What else a line will tell you if you look closely

A spectral line is not infinitely thin, and every way it deviates from thin carries information.

Temperature broadens lines, because hot atoms move faster and each contributes its own small Doppler shift; the line width is a thermometer. **Rotation** broadens them too — one limb of a spinning star approaches while the other recedes, smearing every line symmetrically, which is how stellar rotation rates are measured without resolving the star at all. **Pressure and density** in the atmosphere blur the atomic energy levels, which lets astronomers distinguish a bloated giant from a compact dwarf at the same temperature. And a **magnetic field** splits a single line into several components — the Zeeman effect — which is how George Ellery Hale proved in 1908 that sunspots are magnetic.

Composition, temperature, radial velocity, rotation, pressure, magnetism, and — from line strengths — abundances of individual elements down to trace levels. All of it from a smear of light too faint to see.

DO THE MATH · 8.1

How fast is it moving? Take the rest wavelength of the hydrogen-alpha line as λ_0 = 656.28 nm.

- A star shows Hα at 656.05 nm. Which way is it moving, and how fast in km/s?
- A galaxy shows Hα at 662.94 nm. Find its radial velocity.
- Using Hubble's law $v = H_0 d$ with H_0 = 70 km/s per megaparsec, how far away is that galaxy?

Then think about the limits. A telescope can measure a shift of about 0.0001 nm in a bright star. What radial velocity does that correspond to — and is it enough to detect the 0.09 m/s wobble the Earth induces in the Sun?

TRY THIS · BUILD A SPECTROSCOPE FROM A CD

A CD has tracks spaced 1.6 micrometres apart, which makes it an excellent diffraction grating — the same job a prism does, by a different mechanism.

1. Cut a narrow slit, about 1 mm wide, in one end of a cereal box or long carton.
2. Cut a viewing hole at the other end, angled roughly 60° from the slit.
3. Tape a CD (shiny side out) inside, behind the viewing hole, so light from the slit hits it and reflects to your eye.
4. Seal every other opening with tape. Stray light is the enemy.

Now look at different sources — and this is where it gets genuinely interesting. **Daylight from a patch of sky** gives a smooth continuous rainbow. A **fluorescent tube or CFL** gives sharp separated bright lines: mercury emission, Kirchhoff's second law in your hallway. A **sodium street lamp** shows an intense yellow line and almost nothing else. A **white LED** shows a blue spike with a broad smear — because that is exactly how it is made.

You have just distinguished three light sources by chemistry without touching any of them. That is astronomy.

CAREER NOTE

Spectroscopy is the workhorse skill of observational astronomy, and it is much less glamorous than the images suggest: most of the job is calibration, sky subtraction and fitting line profiles, all in Python with astropy and specutils. India runs serious spectroscopic facilities — the 2-m Himalayan Chandra Telescope at Hanle, the 3.6-m Devasthal Optical Telescope at ARIES Nainital, and the 2.34-m Vainu Bappu Telescope at Kavalur. If you can already reduce a spectrum before you finish a BSc, you are ahead of most postgraduates.

IN A HURRY?

- Every element absorbs and emits at a **unique set of wavelengths** — a fingerprint that works identically everywhere in the universe.
- **Kirchhoff's laws**: dense hot source → continuous; thin hot gas → emission lines; cool gas in front of a hot source → absorption lines.
- Stars show absorption lines, first mapped by **Fraunhofer in 1814**.
- **Helium was discovered in the Sun in 1868** — from an eclipse observed in India — twenty-seven years before it was found on Earth.
- The **Doppler shift**, $\Delta\lambda/\lambda_0 = v/c$, measures motion along the line of sight, and underpins dark matter, cosmic expansion and exoplanet detection.
- Line **width** gives temperature and rotation; line **splitting** gives magnetic field strength.

CHAPTER 9 · THE RULES

Four Forces and a Zoo of Particles

> Everything you have ever touched is built from three particles. Everything that happens to it is governed by four forces. The rest of the zoo is either rare, unstable, or hiding.

Astrophysics and particle physics are the same subject viewed from opposite ends. What a star does depends on how protons behave when squeezed; what the universe was doing in its first second depends on physics we can only test at CERN. You cannot get far in one without the other, so this chapter is the short version of the small end.

The forces, ranked by strength

Four interactions are known. Their relative strengths span forty orders of magnitude, which is why they each dominate a different arena.

THE FOUR FUNDAMENTAL INTERACTIONS

Force	Relative strength	Range	Carried by	What it does
Strong	1	10^{-15} m	gluons	binds quarks into protons and neutrons; holds nuclei together
Electromagnetic	10^{-2}	infinite	photons	atoms, chemistry, light, everything you can touch
Weak	10^{-6}	10^{-18} m	W and Z bosons	changes one kind of quark into another; starts fusion; radioactive decay
Gravity	10^{-38}	infinite	(graviton, undetected)	structure of the universe at every scale above a molecule

Two of them have infinite range and two die within a nuclear diameter, and this is why the world is organised as it is. The strong force is savagely powerful but cannot reach past the edge of a nucleus. Electromagnetism reaches forever but cancels itself out in bulk matter. Gravity is pathetic but never cancels — so at astronomical scales the weakest force is the only one left standing.

The particle inventory

Ordinary matter needs exactly three particles: the **up quark**, the **down quark** and the **electron**. A proton is two ups and a down; a neutron is two downs and an up; electrons orbit outside. That is you, this book, the Sun and every planet.

Nature then supplies two heavier copies of the same pattern, identical in every property except mass, for reasons nobody has explained. The joke attributed to Isidor Rabi on the discovery of the muon — "who ordered that?" — has never been answered.

Figure 9.1 — The complete known contents of the universe, excluding dark matter and dark energy, which fit nowhere on this chart. Everything in ordinary matter comes from the leftmost column. The other two generations decay within microseconds and are seen only in accelerators and cosmic rays.

Why a star needs the weak force to work

Here is where particle physics becomes astrophysics. The Sun fuses hydrogen into helium, and the very first step is two protons combining. But a proton–proton pair cannot simply stick: you need one of them to turn into a neutron, and that requires an up quark to become a down quark. Only the **weak force** can do that.

And the weak force is, as its name promises, feeble. The consequence is spectacular: in the Sun's core, a given proton waits on average about **nine billion years** before it undergoes this reaction. The bottleneck is not the temperature — it is that the weak interaction almost never fires.

This is why the Sun burns slowly and steadily for ten billion years rather than detonating. A star is not a bomb; it is a very badly designed nuclear reactor whose ignition switch sticks, and life on Earth exists because of it.

Neutrinos: the particles that ignore you

Every one of those weak reactions emits a **neutrino** — a particle with no charge, almost no mass, and essentially no interest in matter. About **65 billion solar neutrinos pass through every square centimetre of your body every second**, day and night. At night they arrive through the entire Earth, which is as transparent to them as glass is to light. Perhaps one neutrino in your lifetime will interact with an atom in your body.

They are maddening to detect and worth every rupee, because neutrinos escape from places photons cannot. Light from the Sun's core takes tens of thousands of years to random-walk to the surface; a neutrino leaves in 2.3 seconds. Neutrinos are the only direct look anyone will ever get at a stellar core.

CASE FILE · THE SOLAR NEUTRINO PROBLEM, 1968–2001

In the 1960s Raymond Davis Jr. filled a 380,000-litre tank with dry-cleaning fluid, buried it 1,500 metres down the Homestake gold mine in South Dakota, and set out to count solar neutrinos. The predicted rate, from John Bahcall's solar models, was a few atoms of argon produced per day. Davis measured about **one-third** of it.

The discrepancy survived thirty years of attack. Either Davis's fiendishly difficult experiment was wrong, or Bahcall's model of the Sun was wrong. Both men insisted their own work might be at fault; neither could find the error, because there wasn't one.

The answer, confirmed by the Sudbury Neutrino Observatory in Canada in 2001, was that neither was wrong and the particle physics was incomplete. Neutrinos come in three flavours and **oscillate** between them in flight. Davis's detector was only sensitive to electron-neutrinos; two-thirds of the Sun's output had converted to muon- and tau-neutrinos on the way. SNO could see all three, and found the total exactly matched Bahcall's prediction.

The consequence went far beyond the Sun: oscillation is only possible if neutrinos have **mass**, which the Standard Model had assumed they did not. A disagreement about a dry-cleaning tank became the first confirmed crack in the Standard Model. Davis shared the 2002 Nobel Prize; Takaaki Kajita and Arthur McDonald took the 2015 prize for the oscillations themselves.

DO THE MATH · 9.1

Count the neutrinos passing through you. The solar neutrino flux at Earth is about 6.5×10^{10} per cm^2 per second.

- Estimate your body's cross-sectional area facing the Sun in cm^2. (A rough rectangle is fine — this is an order-of-magnitude exercise.)
- How many neutrinos pass through you per second? Per day? Over 80 years?
- Compare that last number to the roughly 7×10^{27} atoms in your body.

Then the physics question: given that a neutrino's chance of interacting while crossing a human body is about one in 10^{13} per *lifetime's worth* of exposure, roughly how large would a detector have to be to catch a useful number? Look up Super-Kamiokande's size and see how close your estimate lands.

GET THIS STRAIGHT

"Atoms are mostly empty space." The familiar version — if a nucleus were a marble at the centre of a stadium, the electrons would be dust at the back of the stands — gets the sizes right and the physics wrong.

Electrons are not tiny specks orbiting through vacuum. They are spread out as standing waves that genuinely fill the atomic volume. The atom is not empty; it is *full of electron*. When your hand fails to pass through a table, that is not "electrical repulsion between distant charges" either — it is mostly the Pauli exclusion principle refusing to let two electrons occupy the same quantum state.

Solidity is a quantum effect, not an electrostatic one. The same principle, scaled up, is what holds a white dwarf against collapse in Chapter 17.

IN A HURRY?

- Four forces: **strong, electromagnetic, weak, gravity**, spanning 38 orders of magnitude in strength.
- Ordinary matter needs only **up quarks, down quarks and electrons**. Two heavier copies of each exist for unknown reasons.
- Fusion in the Sun is rate-limited by the **weak force** — a proton waits ~9 billion years for its first reaction. That is why stars last.
- **65 billion neutrinos per cm^2 per second** pass through you. They carry direct information from stellar cores.
- The **solar neutrino problem** was resolved in 2001 by neutrino oscillation — which proved neutrinos have mass and broke the Standard Model.
- Atoms are not empty; they are filled with electron wavefunction. Solidity comes from the **Pauli exclusion principle**.

III

The Beginning

The first second of the universe is the best-tested piece of ancient history we have. Here is what happened, how we know, and which parts are still guesswork.

CHAPTER 10 · THE BEGINNING

The First Three Minutes

> More happened in the universe's first second than in the 13.8 billion years since. Remarkably, we can reconstruct most of it — and check the answer.

The claim that anybody knows what happened one second after the beginning of time sounds like overreach. It is not, and the reason is worth understanding before the details: the early universe was **hot, dense and simple**. There were no galaxies, no chemistry, no geology — just particles, radiation and a temperature. Physics is extremely good at hot simple systems. It is complicated things like weather and biology that defeat it.

Better still, the early universe left behind physical evidence that can be checked today: the exact proportions of the lightest elements, and a photograph of the whole sky at 380,000 years old. Both match the calculations. That is why cosmologists talk about the first three minutes with a confidence that startles outsiders.

The sequence

Time in the early universe is best read logarithmically, because the interesting events cluster at the start. Each line below is a factor of roughly a thousand or a million in time, not an equal interval.

THE FIRST SECOND, AND A BIT AFTER

HOT

10^{-43} s · the Planck time
10^{32} K. Gravity and quantum theory both apply and contradict each other. Physics has nothing to say before this.

10^{-36} to 10^{-32} s · inflation
Space expands by a factor of at least 10^{26} in a sliver of a second. Chapter 11.

10^{-12} s · the forces separate
10^{15} K — the energy LHC collisions reach. Beyond here, everything is experimentally tested.

10^{-6} s · quarks are captured
10^{13} K. The quark–gluon soup condenses into protons and neutrons. Matter narrowly beats antimatter.

1 s · neutrinos go free
10^{10} K. Neutrinos stop interacting and stream away — they are still here, at 1.95 K, undetected.

3 to 20 minutes · nucleosynthesis
10^{9} K. Protons and neutrons fuse into helium and a trace of lithium — then it stops, for good.

380,000 years · recombination
3,000 K. Electrons finally stick to nuclei. The fog clears and light travels freely: the CMB.

≈ 200 million years · first light
The first stars ignite and end the cosmic dark ages.

13.8 billion years · you, reading this
2.725 K, and cooling.

COOL

Figure 10.1 — A logarithmic history. Note the boundary at 10^{-12} s: everything below it has been reproduced in accelerators. Above it the physics is extrapolation, and it gets more speculative the higher you go.

Where confidence ends

It is worth being precise about which parts of that list are solid.

From about a microsecond onwards, the physics involved is **ordinary, tested, laboratory physics**. The Large Hadron Collider routinely produces quark–gluon plasma at the conditions of 10^{-12} seconds. Nuclear reaction rates for the fusion at three minutes have been measured on benches. This is not speculation; it is applying known physics to a known temperature.

Before a microsecond, we are extrapolating beyond anything ever tested. Inflation is well motivated and well supported by indirect evidence, but the mechanism is not identified. And before the Planck time, at 10^{-43} seconds, we have *nothing at all* — quantum mechanics and general relativity give contradictory answers, and the honest position is that no theory currently exists. Anyone who tells you what happened "before the Big Bang" is doing philosophy or selling something.

The billion-and-one problem

At about a microsecond, matter and antimatter annihilated one another. Every quark met an antiquark and both vanished into photons. Had the numbers been equal, the universe would now contain radiation and nothing else — no atoms, no stars, no reader.

They were not equal. For roughly every **billion antiquarks there were a billion and one quarks**. Everything that exists is that leftover one part in a billion; the other 999,999,999 pairs became the photons of the microwave background, which is why there are about two billion photons in the universe for every atom.

Why the imbalance? Nobody knows. Andrei Sakharov set out in 1967 the three conditions any explanation must satisfy, and the Standard Model satisfies all three — but by quantities far too small, off by about ten orders of magnitude. **The existence of matter is an unsolved problem in physics**, and it is one of the most promising places for a new discovery. Chapter 38 comes back to it.

CASE FILE · ALPHER, BETHE, GAMOW — AND A PHYSICS JOKE

In 1948 Ralph Alpher, a PhD student, and his supervisor George Gamow worked out what nuclear fusion in a hot early universe would produce. Gamow, who found the physics literature insufficiently amusing, added Hans Bethe's name to the author list purely so the paper would read **Alpher, Bethe, Gamow** — alpha, beta, gamma. Bethe had not written a word of it and cheerfully agreed. It was published on 1 April.

The joke has overshadowed the result, which was excellent. The paper predicted that about a quarter of the universe's ordinary matter, by mass, should be helium — a number that had no other explanation and that observation later confirmed almost exactly.

Later that year Alpher and Robert Herman went further and predicted that the leftover heat should still be detectable today as a faint microwave glow at about 5 K. Nobody looked. The prediction was forgotten for seventeen years until two radio engineers stumbled onto it by accident — which is Chapter 12.

GET THIS STRAIGHT

"At the Big Bang, the entire universe was compressed into a single point." This is the most persistent error in popular cosmology, and it quietly misleads people for years.

What was compressed into a very small volume was **the part of the universe we can now observe**. The universe as a whole may well be infinite in extent — and if it is infinite now, it was infinite then, just very much denser everywhere. An infinite space can get denser without shrinking to a point.

So the correct statement is not "everything was in one place" but "**everything was much closer to everything else**". There was no centre and no edge, then or now. Every observer anywhere in the universe sees the same expansion and could equally well believe they are at the middle of it.

DO THE MATH · 10.1

When can a photon make matter? A photon can create a particle–antiparticle pair if it carries at least twice that particle's rest energy, $E = 2mc^2$. Roughly, the universe was hot enough to make a particle freely while $k_B T > mc^2$, with $k_B = 1.381 \times 10^{-23}$ J/K.

```
electron mass  m = 9.109 × 10⁻³¹ kg
mc²   =  ?  joules
T     =  mc² / k_B  =  ?  kelvin
```

Compute the temperature above which electron–positron pairs pop freely out of the radiation field. Then repeat for the proton, at 1.673×10^{-27} kg. Compare both to Figure 10.1 and check that your answers land where the timeline says they should — this is exactly how the epochs in that figure were worked out.

CAREER NOTE

Early-universe cosmology sits at the junction of particle physics and astrophysics, and the entry route is a physics degree with heavy emphasis on statistical mechanics, quantum field theory and computation — not on telescopes. In India the places doing it are IUCAA Pune, TIFR and ICTS in Mumbai and Bengaluru, HRI Allahabad, IISERs, and the theory groups at the IITs. Almost all of them recruit through the **JEST** and **GATE** examinations after a BSc or BS–MS, and almost all run summer projects that accept second-year undergraduates who ask.

IN A HURRY?

- The early universe was **hot, dense and simple** — which is precisely the kind of system physics handles well.
- From **10^{-12} s onwards** the physics has been reproduced in accelerators. Before that we extrapolate; before 10^{-43} s we have nothing.
- At ~10^{-6} s, matter beat antimatter by **one part in a billion**. Everything that exists is the leftover. Nobody knows why.
- At 1 second, neutrinos decoupled — a cosmic neutrino background at **1.95 K** still fills space, so far undetected.
- Between 3 and 20 minutes, **nucleosynthesis** made the helium.
- The Big Bang was **not a point**. Everything was closer together, everywhere. There is no centre.

CHAPTER 11 · THE BEGINNING

Inflation: The Growth Spurt

> Three separate things about the universe made no sense at all. One idea, lasting less than a trillionth of a trillionth of a second, fixed all three — and threw in an explanation for galaxies as a bonus.

By the late 1970s the Big Bang model was in good shape and quietly embarrassing. It explained the expansion, the helium abundance and the microwave background. What it could not explain was why the universe looked the way it did in three specific respects — and in each case the model needed the initial conditions to be fine-tuned to an absurd degree.

Problem one: the sky is too uniform

The microwave background has the same temperature — 2.725 K — in every direction, to about one part in 100,000. That sounds unremarkable until you ask how it got that way. Things reach a common temperature by exchanging energy, and nothing travels faster than light.

Take two patches of sky on opposite sides. Light from one has taken 13.8 billion years to reach us. It has never reached the other patch. In the standard Big Bang, those regions have **never been in causal contact** — not once, not ever. Yet they agree on their temperature to five decimal places. This is the **horizon problem**, and the only answer available was "they just started out that way", which is not an answer.

THE HORIZON PROBLEM

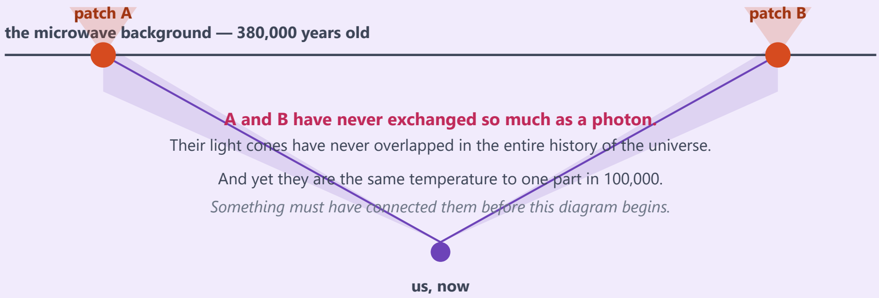


Figure 11.1 — Two strangers who agree exactly. Every pair of points on the microwave sky separated by more than about 2 degrees has this problem. Inflation solves it by putting the whole visible universe inside one tiny causally-connected patch before blowing it up.

Problem two: the universe is too flat

Spacetime as a whole can have positive curvature (a closed universe, like a sphere), negative curvature (open, saddle-shaped), or zero (flat). Measurements say the universe is flat to within about 0.4 per cent.

The trouble is that flatness is *unstable*. Any small deviation from perfect flatness grows rapidly as the universe expands, the way a pencil balanced on its point falls faster the further it tips. For the universe to be within 0.4 per cent of flat today, it must have been within about one part in 10^{60} at the Planck time. Numbers like that are not explanations; they are confessions.

Problem three: the missing monopoles

Grand unified theories of particle physics predict that the early universe should have produced enormous numbers of **magnetic monopoles** — heavy, stable particles carrying an isolated magnetic north or south pole. They should be common enough to dominate the mass of the universe. Not one has ever been detected.

One idea, three solutions

In December 1979, Alan Guth — then a young postdoc without a permanent job — wrote in his notebook the words "SPECTACULAR REALIZATION". His proposal: for a brief interval around 10^{-36} seconds, the universe underwent **exponential** expansion — growing by a factor of e = 2.718 roughly every 10^{-37} seconds, for at least sixty such **e-foldings**.

Sixty e-foldings is a factor of $e^{60} \approx 10^{26}$. That is the equivalent of inflating something the size of a **proton** to roughly the size of the **Earth's orbit around the Sun** — and that patch then becomes everything we can see.

Watch all three problems dissolve. **Horizon:** the entire observable universe was once a patch small enough to have equalised its temperature comfortably, before being stretched apart. **Flatness:** stretch any curved surface by a factor of 10^{26} and the piece you are standing on becomes indistinguishable from flat — the same reason a field looks level on a spherical planet. **Monopoles:** they were made before inflation, and the expansion diluted them so severely that the expected number inside the observable universe is now around one.

The bonus that made people believe it

Solving three problems you were designed to solve is respectable but not compelling. What made inflation persuasive was something it was *not* designed to do.

On the tiny scales at which inflation began, quantum mechanics guarantees that the energy field driving it could not be perfectly smooth — the uncertainty principle requires random fluctuations. Inflation then stretched those subatomic quantum wobbles to astronomical size and froze them in as slight variations in density.

Those density variations are the seeds. Slightly denser regions pulled in more matter, became denser still, and eventually collapsed into galaxies. **Every galaxy in the sky, including ours, is a quantum fluctuation that got very large.**

This is a testable claim, because it predicts the statistical pattern of the fluctuations: nearly the same strength at all scales, but very slightly stronger at larger ones. That "very slightly" is quantified by a number called the spectral index, n_s, which inflation says should be a little below 1. Planck measured $\mathbf{n_s = 0.965 \pm 0.004}$ — below one, by about nine standard deviations, and in the predicted range. It is one of the more impressive predictions in physics.

CASE FILE · BICEP2, AND HOW SCIENCE CORRECTS ITSELF IN PUBLIC

On 17 March 2014, the BICEP2 collaboration announced from Harvard that they had detected a specific swirl pattern — **B-mode polarisation** — in the microwave background. If real, this was the imprint of gravitational waves generated by inflation itself: direct evidence, and an almost certain Nobel Prize. Andrei Linde was filmed being told the news on his doorstep. The signal was quoted at more than five sigma.

Within weeks, other cosmologists raised a concern. B-modes can also be produced by **polarised dust** in our own galaxy, and BICEP2 observed at a single frequency, which made it hard to separate the two. By September, Planck's dust maps of that patch of sky were released. A joint BICEP2–Planck analysis published in early 2015 concluded that the signal was **consistent with being entirely galactic dust**.

The result was retracted. No fraud, no misconduct — a hard measurement at the edge of what was possible, with an underestimated foreground. What matters is what happened next: the team published the refutation of their own result, the search continued with better instruments, and nobody's career ended.

Primordial B-modes remain undetected. Finding them would be the closest thing to direct proof that inflation happened. It is one of the great open prizes, and the experiments hunting it now — BICEP Array, Simons Observatory, LiteBIRD — will report within your working lifetime.

GET THIS STRAIGHT

"Nothing can travel faster than light, so inflation is impossible." The speed limit in relativity applies to objects moving *through* space. It says nothing about how fast space itself may expand.

During inflation, two points separated by more than a certain distance were carried apart faster than light — and this is entirely permitted, because neither was moving through space relative to its own neighbourhood. It is still happening: galaxies beyond about 14.5 billion light-years are receding from us faster than c right now, and no physical law is being broken. Chapter 27 returns to this.

DO THE MATH · 11.1

Sixty doublings. Exponential growth is hard to feel, so compute it.

- Sixty e-foldings means growth by e^{60}. Compute it, and express it in scientific notation. (Compare with 2^{60}, which is the answer to the different question of sixty *doublings* — the two differ by eight orders of magnitude.)
- A proton is about 10^{-15} m across. Multiply by your factor. What everyday object is that size?
- Inflation is estimated to have lasted about 10^{-32} s. If it managed 60 e-foldings in that time, how long was each one?

Then a check on the flatness argument. The Earth's radius is 6,371 km, and its surface curves away by roughly 8 cm over 1 km. If you inflated the Earth by a factor of 10^{26}, how much would its surface deviate from flat over that same kilometre? This is exactly why inflation makes the universe look flat.

IN A HURRY?

- Three problems: the sky is **too uniform** (horizon), space is **too flat** (flatness), and predicted **monopoles are missing**.
- **Inflation** — proposed by Alan Guth in 1979 — expands space by $\geq 10^{26}$ between about 10^{-36} and 10^{-32} seconds.
- That one event solves all three: contact before stretching, curvature flattened, monopoles diluted away.
- The unplanned bonus: **quantum fluctuations stretched to cosmic size became the seeds of every galaxy**.
- Prediction: nearly scale-invariant fluctuations, slightly tilted. Planck measured **n_s = 0.965**, as predicted.
- Primordial **B-mode polarisation** would be direct proof. BICEP2's 2014 claim turned out to be galactic dust. The search is live.
- Space may expand faster than light. Only motion *through* space is limited.

CHAPTER 12 · THE BEGINNING

The Baby Photo of the Universe

> About one per cent of the static on an untuned analogue television was light from the Big Bang. Read carefully, that noise gives the age, shape and composition of the universe.

For its first 380,000 years the universe was an opaque plasma — free electrons everywhere, scattering photons the way fog scatters headlights. Light could not travel more than a short distance before being knocked sideways. There was nothing to see, because seeing requires light to travel in straight lines.

Then the expansion cooled things to about 3,000 K, and electrons could finally be captured by protons without being immediately knocked loose again. Neutral atoms formed. The fog lifted — and the photons that happened to be in flight at that instant have been travelling, unobstructed, ever since.

That light is still arriving. Stretched by a factor of about 1,100 by the expansion of space, its blackbody temperature has fallen from 3,000 K to **2.72548 K**, putting it in the microwave band. It comes from every direction, it is the oldest thing anyone can observe, and it is called the **cosmic microwave background**.

CASE FILE · THE PIGEONS OF HOLMDEL, 1964

Arno Penzias and Robert Wilson had a 6-metre horn antenna at Bell Labs in New Jersey and a plan to use it for radio astronomy. First they needed to eliminate the noise. There was a persistent hiss, equivalent to about 3.5 K, that would not go away.

They checked everything. It was the same in every direction, so not from a source. It did not vary with time of day or season, so not the Sun, and not New York City. They dismantled and rebuilt joints. They found a pair of pigeons nesting in the horn, evicted them, and cleaned out what Penzias delicately called "a white dielectric material". The hiss remained.

Thirty miles away at Princeton, Robert Dicke's group was building a detector to hunt for exactly this radiation, having independently rederived Alpher and Herman's 1948 prediction. A phone call was made. Dicke put the receiver down and said to his team: "Boys, we've been scooped."

The two papers appeared back to back in 1965 — Penzias and Wilson reporting an unexplained excess temperature, Dicke's group explaining what it was. Penzias and Wilson took the 1978 Nobel Prize. It is the most consequential piece of accidental noise in the history of science, and it converted the Big Bang from one contending model into the established one within about two years.

The most perfect blackbody ever measured

In 1989 NASA launched COBE, and within nine minutes of opening its cover it had measured the CMB spectrum. The result, presented to the American Astronomical Society in January 1990, produced something unheard of at a scientific meeting: a standing ovation for a graph.

The data points fitted a perfect blackbody curve so exactly that the error bars had to be drawn at 400 times their real size to be visible. No astrophysical process other than thermal equilibrium in a hot early universe can produce that. It is the single strongest piece of evidence that the universe had a hot dense phase.

The lumps, and what they encode

The CMB is uniform to about one part in 100,000 — but not perfectly. COBE found the variations in 1992, WMAP mapped them from 2001, and the European Planck satellite measured them to the limit set by the foregrounds between 2009 and 2013.

Those hundred-thousandth-level hot and cold spots are the density seeds from Chapter 11, caught at the moment the fog lifted. And they are not random: the plasma had been ringing. Gravity pulled matter into the denser regions, radiation pressure pushed it back out, and the competition set up standing sound waves — genuine acoustic oscillations in the early universe, with a fundamental tone and overtones.

Plot how much variation appears at each angular scale and you get the **CMB power spectrum**, a curve with a series of peaks. Each peak's position and height is sensitive to a different property of the universe, which is why one graph can pin down half of cosmology at once.

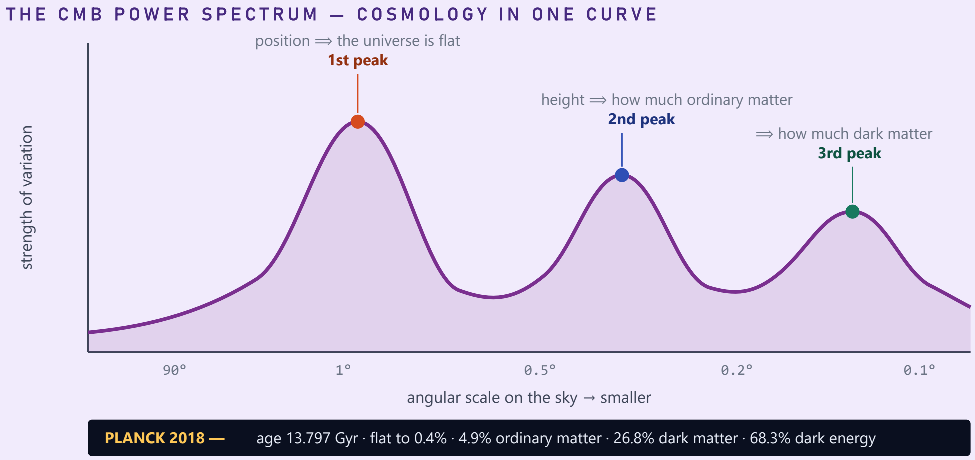


Figure 12.1 — The most information-dense graph in astrophysics. Sound waves in the plasma of the young universe, frozen at 380,000 years. The first peak's angular position fixes the geometry of space; the relative peak heights weigh ordinary and dark matter separately.

What one graph delivered

The universe is flat. The first peak sits at about 1 degree, which is where it belongs only if space has zero overall curvature. If space were curved, the light from those hot spots would have been focused or defocused on its way here, and the peak would sit at a different angle.

The inventory. Ordinary matter — atoms, everything on the periodic table — is **4.9 per cent** of the universe. Dark matter is **26.8 per cent**. Dark energy is **68.3 per cent**.

Part VI is about the other ninety-five.

The age. 13.797 ± 0.023 billion years.

Confirmation of inflation's fingerprint. The spread of fluctuation strength across scales is nearly, but not exactly, uniform — precisely as Chapter 11 predicted.

TRY THIS · YOU HAVE ALREADY SEEN IT

If you can find an old analogue television — the kind with an aerial rather than a cable box — tune it to a channel with no station. About **1 per cent** of the flickering snow is the cosmic microwave background: photons that have travelled 13.8 billion years and finished their journey in a set-top aerial in your house.

Digital sets will not do it, since they display nothing rather than noise. Nor will an FM radio, which is at the wrong frequency. If no analogue TV is available, the honest substitute is to look up the Planck all-sky map and sit with it for a minute: every speck of colour on it is a density variation of one part in 100,000 that grew, over billions of years, into a supercluster of galaxies.

GET THIS STRAIGHT

"The CMB is coming from the edge of the universe." There is no edge, and the CMB is not a place. It is a *time*.

The microwave background is arriving from every direction because 380,000 years after the Big Bang, *everywhere* was glowing at 3,000 K, including the exact spot where you are sitting. What we call the surface of last scattering is simply the sphere at the distance from which that light is reaching us right now.

Wait a million years and the sphere will be larger — you would be seeing light from material that is now further away. An observer in a galaxy ten billion light-years off sees their own microwave background, centred on themselves, made of photons that were once close to where we are.

DO THE MATH · 12.1

Stretch the light yourself. Cosmological redshift stretches every wavelength by the factor (1 + *z*), and temperature falls in exactly the same proportion:

```
T_then  =  T_now × (1 + z)
```

- The CMB was emitted at *z* = 1,100 and is now 2.725 K. What was its temperature at emission? Does your answer match the 3,000 K quoted above?
- Use Wien's law from Chapter 7 on both temperatures. What band was this light in when it was emitted, and what band is it in now?
- The universe has expanded by a factor of 1,101 since then. Volume goes as the cube of that. By what factor has the density of matter dropped?

Finally: at what redshift was the CMB at a comfortable 300 K — room temperature everywhere in the universe, with no stars yet formed?

IN A HURRY?

- For 380,000 years the universe was an **opaque plasma**. When it cooled to 3,000 K, atoms formed and light broke free.
- That light is the **CMB**, now stretched to **2.725 K** microwaves, arriving from every direction.
- Found **by accident** by Penzias and Wilson in 1964 while chasing antenna noise.
- It is the **most perfect blackbody ever measured** — proof of a hot dense early phase.
- Its one-part-in-100,000 lumps are **frozen sound waves**; their power spectrum gives the age, the flatness and the full inventory of the universe.
- Planck 2018: **4.9% atoms, 26.8% dark matter, 68.3% dark energy**, age 13.797 billion years.
- The CMB is not a place at the edge. It is a moment, visible in all directions.

CHAPTER 13 · THE BEGINNING

Where the Atoms in You Were Made

> The hydrogen in your body is 13.8 billion years old. The carbon was cooked in a dying star. The iron in your blood came from an exploding one, and the gold in a wedding ring from two neutron stars colliding.

The Big Bang was a poor chemist. Twenty minutes after it began, the universe contained hydrogen, helium, a whisper of lithium, and essentially nothing else. No carbon, no oxygen, no iron, no silicon — none of the ninety-odd elements that make planets, chemistry or people possible.

Everything heavier had to be manufactured afterwards, inside stars, and delivered by their deaths. This is the single most personal result in astrophysics, and it is worth stating precisely rather than poetically: **every atom in your body heavier than hydrogen was assembled inside a star that no longer exists.**

Why the Big Bang stopped at helium

Between three and twenty minutes, the universe was at the right temperature for fusion — around a billion kelvin. Protons and neutrons combined into deuterium, then helium-4. Roughly 25 per cent of ordinary matter by mass became helium, and this proportion, worked out by Alpher and Gamow in 1948, matches observation almost exactly.

Then it stopped, for a specific and rather elegant reason: **there is no stable nucleus with 5 or 8 nucleons**. Add a proton to helium-4 and you get lithium-5, which falls apart in 10^{-22} seconds. Stick two helium-4 nuclei together and you get beryllium-8, which survives for about 10^{-16} seconds. Both are dead ends. The path upward is blocked, and by the time the universe might have found a way around it, expansion had cooled everything below the ignition temperature.

So the universe was left with a hydrogen-and-helium inventory for its first couple of hundred million years. Getting past the gap needed something the early universe did not have: **density, and time**. Stars supply both.

How stars climb the periodic table

The trick that gets past beryllium-8 is the **triple-alpha process**, and it works only because of a coincidence so precise that its discovery is one of the great stories in physics. In the core of a red giant at 100 million kelvin, helium nuclei are packed so tightly that a third one can strike a beryllium-8 within its 10^{-16}-second lifetime. Three helium-4 nuclei become carbon-12.

From carbon onwards a massive star burns through successive shells, each hotter and faster than the last: carbon to neon, neon to oxygen, oxygen to silicon, silicon to iron. The final stage is startling — a star that has spent ten million years burning hydrogen gets through its silicon-burning phase in about **one day**.

And there the ladder ends. Iron-56 has the highest binding energy per nucleon of any nucleus. Fusing anything into iron releases energy; fusing iron into anything *consumes* it. A star that reaches an iron core has run out of fuel in the most fundamental sense available, and Chapter 18 describes what happens next, which is not gentle.

Above iron: two ways to add neutrons

Everything heavier than iron is made by adding neutrons rather than fusing, and there are two speeds.

The **s-process** — "slow" — happens over thousands of years in the calm interiors of dying low-mass stars. Neutrons are captured one at a time, with long gaps in which any unstable nucleus can decay before the next arrives. It builds slowly up the valley of stability and produces strontium, barium, lead and about half of everything heavier than iron.

The **r-process** — "rapid" — needs a neutron flux so extreme that nuclei absorb neutrons faster than they can decay, in a matter of *seconds*. This produces the heaviest and most neutron-rich elements: gold, platinum, uranium, europium. For decades nobody was certain where conditions that violent existed. The answer arrived in 2017.

WHERE EVERY ELEMENT WAS MADE

Colour shows the dominant cosmic source of each element. Most have more than one.

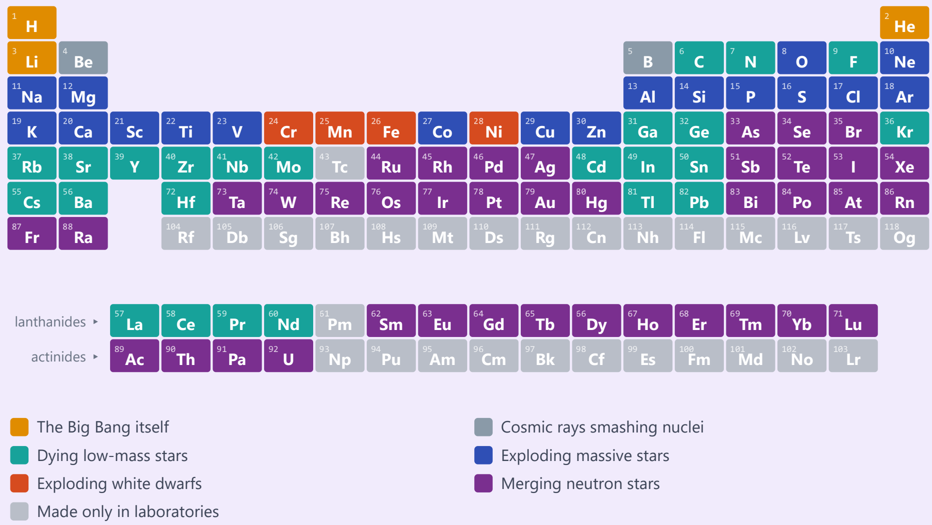


Figure 13.1 — The periodic table, coloured by birthplace. Only the first three elements come from the Big Bang. Everything else was manufactured by stars, over billions of years, and scattered by their deaths. Most elements have more than one source; the colour shows the dominant one.

CASE FILE · HOYLE PREDICTS A NUCLEAR ENERGY LEVEL USING BIOLOGY

In 1953 Fred Hoyle had a problem. His calculations said the triple-alpha process was far too slow to produce the carbon the universe visibly contains — off by orders of magnitude.

His argument for why it must work anyway was unlike anything in physics. Carbon exists. I am made of carbon. Therefore some mechanism must produce it in quantity. Therefore — and this was the leap — the carbon-12 nucleus must possess an excited state at almost exactly the combined energy of beryllium-8 plus helium-4, creating a **resonance** that boosts the reaction rate enormously. He predicted the level at about 7.7 MeV.

Hoyle was visiting Caltech at the time and pestered the nuclear physicist Willy Fowler into looking for it. Fowler thought the reasoning was nonsense — you cannot deduce nuclear structure from your own existence — but ran the experiment to be rid of him. Within ten days his group found the state, at **7.65 MeV**.

It is the most celebrated use of anthropic reasoning in physics, and it remains controversial as a method precisely because it worked so spectacularly once. Fowler won the Nobel Prize in 1983 for the resulting body of work. Hoyle, who had made the prediction, did not — a decision still argued about.

CASE FILE · GW170817 — WATCHING GOLD BEING MADE

On 17 August 2017 at 12:41 UTC, LIGO and Virgo detected a gravitational-wave signal lasting about 100 seconds — far longer than any black-hole merger, and exactly the signature of two **neutron stars** spiralling together. Two seconds later, the Fermi satellite recorded a short gamma-ray burst from the same direction.

Within eleven hours, telescopes had pinned the source to the galaxy NGC 4993, 130 million light-years away. Roughly seventy observatories on every continent and in orbit followed it for weeks across every band of the spectrum. It was the most intensively observed event in the history of astronomy.

The optical glow faded from blue to red over days in exactly the way models of a **kilonova** predicted — the signature of freshly made, radioactive, very heavy elements decaying. Spectroscopy confirmed r-process material. The estimated yield from that single collision was several Earth-masses of gold and platinum, and something like ten Earth-masses of heavy elements overall.

A forty-year-old question about the origin of the heaviest elements was settled in one afternoon. It also launched multi-messenger astronomy as a working field — Chapter 34.

DO THE MATH · 13.1

Audit your own atoms. A 50 kg human is roughly 65% oxygen, 18% carbon, 10% hydrogen, 3% nitrogen, 1.4% calcium and 1.1% phosphorus by mass, with about 4 g of iron.

- What mass of you is hydrogen — that is, material that has existed unchanged since the first twenty minutes of the universe?
- What mass came from stellar fusion (everything else)? What percentage is that?
- Your 4 g of iron is mostly from exploding white dwarfs. Given that a Type Ia supernova produces about 0.6 solar masses of iron and the Sun is 2×10^{30} kg, what fraction of one supernova's iron output are you?

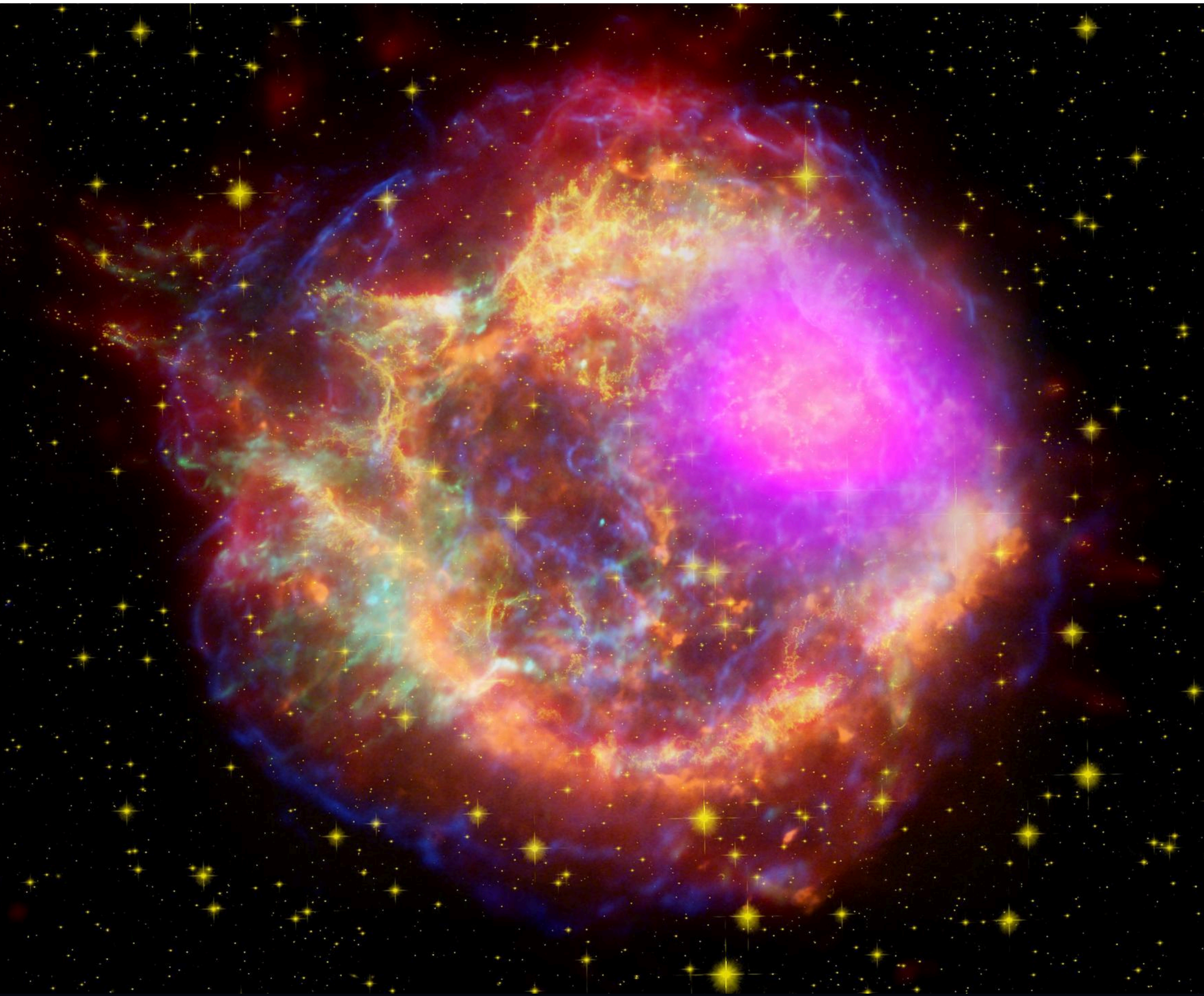
Finally, an estimate worth doing carefully: if the r-process elements in your body came from neutron-star mergers, and the Milky Way hosts roughly one such merger every 100,000 years, how many mergers have occurred since the galaxy formed — and is that enough to explain the gold in circulation?

GET THIS STRAIGHT

"We are all made of stardust — all of us, entirely." The sentiment is right and the physics is slightly off, in a way worth getting straight.

By mass you are about 10 per cent hydrogen, and essentially none of that hydrogen was made in a star. It was made in the first twenty minutes of the universe and has been passed along ever since. By *number of atoms* the effect is even more pronounced: roughly 62 per cent of the atoms in your body are hydrogen, which makes the majority of you — atom by atom — older than any star that has ever existed.

The accurate version: you are about 90 per cent stardust by mass, and about 38 per cent stardust by atom count. The rest is Big Bang.



The factory, photographed mid-explosion

Cassiopeia A — the shredded remains of a massive star that exploded about 340 years ago, 11,000 light-years away. The expanding shell is roughly ten light-years across and still moving at thousands of kilometres per second. **Everything in this cloud used to be inside a star**: the oxygen, silicon, sulphur and iron visible in its spectrum are the products of the burning shells in Figure 18.1, now being returned to the galaxy to build the next generation of planets.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- The Big Bang made only **hydrogen, helium and a trace of lithium** — blocked by the absence of stable nuclei with 5 or 8 nucleons.
- Stars get past the gap with the **triple-alpha process**, which works only because of a resonance **Hoyle predicted from his own existence** in 1953.
- Massive stars fuse up to **iron** and stop — iron has the highest binding energy per nucleon, so fusing it costs energy.
- Beyond iron: the **s-process** in dying low-mass stars, and the **r-process** in violent events.
- **GW170817** (2017) proved neutron-star mergers make gold, platinum and uranium — several Earth-masses of gold from one collision.
- You are ~90% stardust by mass, but the majority of your *atoms* are primordial hydrogen, older than any star.

IV

Stars

A star is a very simple object having a very long argument with itself. Gravity pulls in; pressure pushes out. Everything else — colour, size, lifetime, death — follows from who is winning.

CHAPTER 14 · STARS

Star Birth: Collapse in the Cold

> Stars are not lit. They are crushed until they catch. And the coldest, emptiest places in the galaxy are where it happens.

The nursery of stars is a **giant molecular cloud**: a vast, ragged region of gas and dust tens of light-years across, containing anything from a thousand to ten million times the mass of the Sun. It is dark, because dust blocks visible light. It is nearly empty, at a few hundred to a few thousand molecules per cubic centimetre — a far better vacuum than any laboratory on Earth can produce. And it is desperately cold, around 10 to 20 kelvin.

From these unpromising materials come every star, every planet and every reader.

Why nothing collapses on its own

A cloud sits in a standoff. Gravity pulls it inward. Gas pressure, turbulence, magnetic fields and rotation all resist. Which side wins is decided by a criterion James Jeans worked out in 1902: if the cloud's mass exceeds a threshold — the **Jeans mass** — set by its temperature and density, gravity wins and collapse begins.

Cold helps enormously, because cold gas has feeble pressure. A cloud at 10 K can collapse at masses hundreds of times smaller than the same cloud at 100 K. This is why stars form in the coldest places rather than the hottest: heat is the enemy of star formation, not its cause.

Most clouds sit just on the stable side of the line, and stay there indefinitely. They need a shove. The known triggers are all violent: the **shock wave from a nearby supernova**, the **compression as a cloud drifts through a galaxy's spiral arm**, a **collision between two clouds**, or the fierce radiation and winds from massive stars that have already formed nearby. Star formation is contagious — one generation's deaths set off the next generation's births.

The sequence, from cloud to star

FROM COLD CLOUD TO NEW SUN

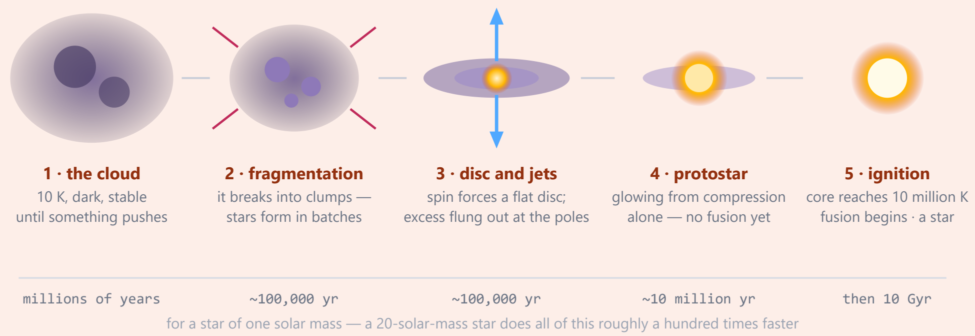


Figure 14.1 — The making of a star. Note stage 3: rotation is unavoidable, and its consequence — a flat disc of leftover material — is where planets come from. Every planetary system is a by-product of a star's failure to swallow all its own raw material.

Why stars come in litters

A collapsing cloud does not produce one star. As it contracts, the denser sub-regions reach their own Jeans threshold and collapse independently, so the cloud fragments — typically into hundreds or thousands of pieces. The result is an **open cluster**: a group of stars all born within a few million years of each other, from the same material, at the same distance.

This is enormously useful, and Chapter 16 explains why: a cluster is a controlled experiment. Everything is the same age and composition, so any differences between its stars must come from mass alone.

The fragments are not evenly sized. For every star of 20 solar masses, roughly 500 of one solar mass form, and several thousand red dwarfs below half a solar mass. This distribution is the **initial mass function**, and it appears to be remarkably similar everywhere anyone has looked — which is itself an unsolved puzzle. Small stars are the norm; the Sun is already in the top 10 per cent by mass, and giants are freaks.

The angular momentum problem

Every cloud rotates a little. As it shrinks, conservation of angular momentum makes it spin faster — the skater pulling in their arms, over a factor of 10^7 in radius. Taken naively, the young star should be spinning so violently that it tears itself apart long before it can ignite. Something must dump the spin.

Nature's solution is spectacular and only became clear in the 1980s. The infalling material flattens into a **disc**, and the star launches **bipolar jets** — narrow beams of gas fired out along the rotation axis at hundreds of kilometres per second, carrying angular momentum away with them. Where those jets slam into surrounding gas they light up as glowing knots called Herbig–Haro objects, which is how a star announces its own birth to anyone watching.

CASE FILE · HL TAURI, AND PLANETS THAT FORMED TOO FAST

In November 2014 the ALMA array in Chile released its first image at full resolution: the disc around **HL Tauri**, a star roughly 450 light-years away in a nearby star-forming region.

The picture was a shock. The disc was carved into a series of sharp concentric rings and gaps — exactly what forming planets do as they sweep their orbits clear. The problem was the star's age: **under one million years**. Planet-formation models of the time said building bodies large enough to open gaps like that should take several million years at least.

The image forced a substantial rethink. Planet formation is now understood to begin far earlier and proceed far faster than the standard core-accretion timeline allowed, with mechanisms like pebble accretion and streaming instabilities doing the work. It is a good example of how a single sufficiently sharp image can overturn a field — and of why resolution, not sensitivity, is often the thing worth paying for.

DO THE MATH · 14.1

How long does a cloud take to fall in? If pressure were removed entirely, a cloud of density ρ would collapse in the free-fall time

```
            3π
t_ff   =  √ ──────────
          32 G ρ

G = 6.674 × 10⁻¹¹ ,  ρ in kg/m³
```

- A molecular cloud has about 10^4 hydrogen molecules per cm^3. Convert this to kg/m^3, given the mass of H_2 is 3.35×10^{-27} kg. (Careful with the $cm^3 \rightarrow m^3$ factor — it is 10^6, not 10^2.)
- Compute t_{ff} in seconds, then in years.
- Observed clouds survive far longer than your answer. What does that tell you about how much support pressure, turbulence and magnetic fields are actually providing?

TRY THIS · LOOK AT A STAR NURSERY WITH YOUR OWN EYES

The **Orion Nebula** is the nearest large star-forming region — 1,344 light-years away, and forming stars right now. It is genuinely visible without any equipment.

Find Orion, unmistakable in the winter sky across India from about November to March. Locate the three stars of the belt, then look below them for the fainter line of three that forms the "sword". The middle object of the sword is not a star. To the naked eye it looks slightly fuzzy; through any pair of binoculars it becomes a distinct grey-green cloud.

Inside it are the four bright stars of the Trapezium cluster, all under a million years old — younger than the human species. Their ultraviolet light is what makes the whole nebula glow. You are looking at stage 2 of Figure 14.1, in progress.

GET THIS STRAIGHT

"Nebulae are the dust clouds left over when stars explode." Some are — the Crab Nebula genuinely is a supernova remnant. But most of the famous glowing nebulae are the opposite: **birth places, not graveyards**.

The Orion Nebula, the Eagle Nebula and the Carina Nebula are all star-forming regions. They glow for a specific reason: newly formed massive stars flood the surrounding gas with ultraviolet light, stripping electrons from hydrogen atoms. When the electrons recombine they emit at 656.3 nm — the red hydrogen-alpha line from Chapter 8. That characteristic red is the signature of hydrogen being ionised by hot young stars, and it is why so many nebula photographs look pink.

The Orion Nebula. 1,344 light-years away and visible to the naked eye as the fuzzy middle "star" of Orion’s sword. The four hot young stars of the Trapezium cluster, all under a million years old, are ionising the surrounding hydrogen and making it glow. This is the nearest place in the galaxy where massive stars are being made right now.

Credit: NASA and the Hubble Heritage Team STScI/AURA. NASA — free to use with credit.

Stars being born, right now

The “Cosmic Cliffs” of the Carina Nebula, photographed by the James Webb Space Telescope in the infrared. The ridge is the edge of a gas cavity being carved out by the radiation of young massive stars above the frame. The peaks are denser clumps resisting erosion — and inside several of them, protostars are collapsing. The tiny jets visible at the tips are stage 3 of Figure 14.1, caught in the act.

Credit: STScI (Webb). NASA — free to use with credit.

IN A HURRY?

- Stars form in **giant molecular clouds** — 10–20 K, dark, and a better vacuum than any laboratory.
- Collapse begins when mass exceeds the **Jeans mass**. **Cold favours collapse**, because cold gas has little pressure.
- Clouds usually need a **trigger**: a supernova shock, a spiral arm, or a collision. Star formation is contagious.
- Clouds **fragment**, so stars are born in clusters — which makes clusters perfect natural experiments.
- Rotation forces a **disc** (future planets) and **bipolar jets** (which carry away the excess spin).
- The **initial mass function** makes small stars overwhelmingly common. The Sun is above average.
- Ignition happens when the core hits **10 million K** — about 10 million years after collapse begins, for a Sun-like star.

CHAPTER 15 · STARS

The Nuclear Furnace

> The Sun converts four million tonnes of itself into pure energy every second, and has done so for four and a half billion years without varying by more than a tenth of a per cent. Here is how that is possible.

A star is a sphere of gas engaged in a permanent argument. Gravity presses every layer inward, trying to crush the whole thing to a point. Pressure from the hot gas below pushes outward. Where the two balance exactly — at every depth, simultaneously — the star is stable. This condition is called **hydrostatic equilibrium**, and it is the entire structural theory of stars in one idea.

The pressure has to come from somewhere, and it has to be replenished, because the star is radiating energy away constantly. That is what the fusion is for. The nuclear reactor in the core is not what makes a star shine so much as what stops it from collapsing.

Where the energy actually comes from

Four hydrogen nuclei go into the reaction. One helium nucleus comes out. Weigh them carefully and the books do not balance:

THE MASS THAT GOES MISSING

```
4 protons         4 × 1.6726 × 10⁻²⁷ kg  =  6.6904 × 10⁻²⁷ kg
1 helium-4 nucleus                         =  6.6447 × 10⁻²⁷ kg
                                              ─────────────────
missing                                    =  0.0457 × 10⁻²⁷ kg

That is 0.7% of the original mass — released as energy, E = mc².
```

Seven-tenths of one per cent does not sound like much. Multiply by $c^2 = 9 \times 10^{16}$ and it becomes the most concentrated energy source in the universe short of matter–antimatter annihilation. The Sun fuses about **600 million tonnes of hydrogen every second** and converts roughly **4 million tonnes** of that into energy — the mass of a small mountain, every second, for billions of years.

The reaction chain, and the quantum loophole that allows it

In stars of about the Sun's mass, the route is the **proton–proton chain**. Two protons fuse into deuterium, releasing a positron and a neutrino; the deuterium captures another proton to make helium-3; two helium-3 nuclei combine to make helium-4 and return two protons.

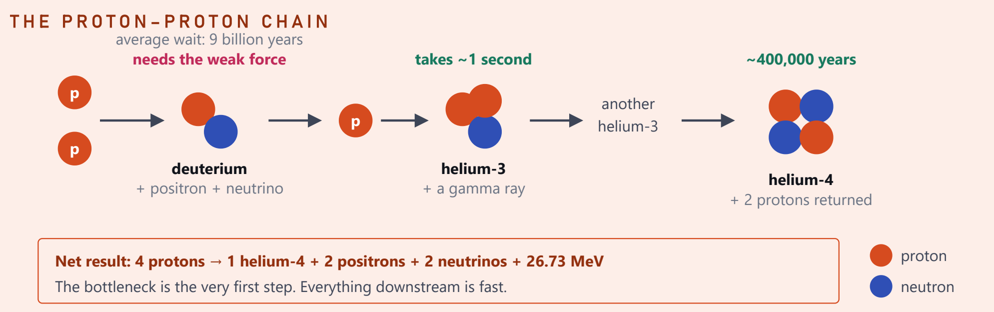


Figure 15.1 — The Sun's main reaction, and why it is slow. The first step requires a proton to become a neutron, which only the weak force can arrange. In the Sun's core, a given proton waits an average of nine billion years for it to happen.

There is a serious problem with all of this. Protons are positively charged and repel each other fiercely. At the Sun's core temperature of 15.7 million kelvin, the average proton simply does not have enough energy to overcome that barrier — not by a factor of about a thousand. Classical physics says the Sun should not shine.

The rescue is **quantum tunnelling**. A proton is a wave as well as a particle, and its wavefunction extends a little way into the forbidden region. There is a small but non-zero probability of it appearing on the far side of a barrier it could never climb. The probability is tiny — but the Sun's core contains around 10^{56} protons and they collide constantly, so tiny multiplied by enormous is sufficient.

Stars run on a quantum-mechanical loophole. Without tunnelling, no star in the universe would ignite.

The thermostat

Fusion rate rises very steeply with temperature — roughly as T^4 for the pp chain. That should be catastrophically unstable: a small heating produces much more fusion, which produces more heating. Why does the Sun not run away?

Because of hydrostatic equilibrium. If the core heats slightly, pressure rises, the core **expands** — and expansion cools it, which brings the fusion rate back down. If the core cools, it contracts, which heats it, and fusion increases. The star holds itself at exactly the temperature where energy generated equals energy radiated.

This negative feedback is why the Sun's output has varied by only about 0.1 per cent over the eleven-year solar cycle, and why life on Earth has had four billion years of stability to work with. It also explains what goes wrong in Chapter 17: when a star's core becomes so dense that pressure stops depending on temperature, the thermostat breaks, and the result is an explosion.

Mass decides everything

The single most useful relation in stellar astrophysics is the **mass–luminosity relation**. For main-sequence stars, luminosity scales as roughly the 3.5th power of mass:

```
L / L⊙ ≈ ( M / M⊙ )³·⁵
```

Now combine that with the fuel supply. A star has fuel proportional to its mass, and burns it at a rate proportional to its luminosity, so its lifetime goes as $M/L \propto M^{-2.5}$.

More massive stars are catastrophically more extravagant. Double the mass and you get eleven times the luminosity but only about a sixth of the lifetime.

WHAT MASS BUYS YOU

Mass (Suns)	Luminosity (Suns)	Surface temp	Main-sequence lifetime	Example
40	400,000	40,000 K	1 million yr	the most massive O stars
10	3,200	22,000 K	20 million yr	Bellatrix
3	47	10,700 K	400 million yr	Fomalhaut
1	1	5,772 K	10 billion yr	the Sun
0.5	0.03	3,800 K	80 billion yr	Lacaille 8760
0.1	0.0008	2,800 K	6 trillion yr	Proxima Centauri

Read the last row again. A red dwarf can burn for **six trillion years** — four hundred times the current age of the universe. Not one red dwarf has ever died. Every one that has ever formed is still shining, and will still be shining long after the last Sun-like star has gone out.

CASE FILE · KELVIN, DARWIN, AND THE AGE OF THE SUN

In the 1860s Lord Kelvin — the most authoritative physicist in Britain — calculated how long the Sun could shine. The only energy sources known were chemical burning and gravitational contraction. Chemical burning gave a few thousand years, which was obviously wrong. Gravitational contraction gave a maximum of about **20 to 100 million years**.

This was a serious problem, because geologists reading rock strata and Darwin computing rates of evolutionary change both needed *hundreds* of millions of years at minimum. Kelvin was emphatic that they were wrong, and his physics was, as far as it went, correct. Darwin found the objection genuinely troubling and removed some age estimates from later editions of *On the Origin of Species*.

The resolution came only in the 1920s, when Arthur Eddington proposed that the Sun ran on subatomic energy, and Hans Bethe worked out the actual reactions in 1939. The Sun is 4.6 billion years old and has enough hydrogen for about five billion more.

The lesson is one every scientist should carry. Kelvin's arithmetic was flawless. His conclusion was wrong because his list of possible energy sources was incomplete — and he had no way of knowing it was incomplete. **Confidence should scale with the completeness of your assumptions, not with the elegance of your calculation.**

DO THE MATH · 15.1

Weigh the Sun's fuel bill. The Sun's luminosity is 3.828×10^{26} W and its mass is 1.989×10^{30} kg.

- Using $E = mc^2$, how many kilograms of mass does the Sun convert to energy each second? Each year?
- Fusion converts 0.7% of the hydrogen mass into energy. How many kg of hydrogen are consumed per second?
- Only the inner 10% of the Sun's mass is hot enough to fuse. Estimate the total main-sequence lifetime, and compare it to the 10 billion years quoted above.

Then a check on the mass–luminosity relation: a star of 2 solar masses should have $L = 2^{3.5}$ Suns. Compute it, then compute the lifetime, and confirm the $M^{-2.5}$ scaling by comparing with the Sun.

GET THIS STRAIGHT

"The Sun is burning." Burning is chemistry — electrons rearranging between atoms. If the Sun were made of coal and oxygen and burning at its present rate, it would be entirely consumed in about **5,000 years**.

Fusion is nuclear: it rearranges the nuclei themselves and releases roughly a million times more energy per kilogram than any chemical reaction can. The Sun is not on fire. It is a gravitationally confined fusion reactor whose containment vessel is its own weight — which is, incidentally, exactly the problem that makes fusion so difficult on Earth, where we have to build a containment field instead of having one for free.

IN A HURRY?

- A star balances gravity against pressure — **hydrostatic equilibrium**. Fusion exists to maintain the pressure.
- Fusing 4 H → 1 He loses **0.7% of the mass**, released as energy via $E = mc^2$. The Sun converts **4 million tonnes per second**.
- Protons should not be able to fuse at 15.7 million K. They do it by **quantum tunnelling**.
- The first step of the pp chain needs the **weak force** and takes ~9 billion years per proton. That is why stars are slow.
- A **thermostat** — expand and cool, contract and heat — keeps output steady to 0.1%.
- **$L \propto M^{3.5}$**, so lifetime ∝ **$M^{-2.5}$**. Massive stars live millions of years; red dwarfs trillions.
- **No red dwarf has ever died.** The universe is not old enough.

CHAPTER 16 · STARS

The H–R Diagram

> Plot two easily measured properties of stars against each other and they do not scatter randomly. They fall into narrow, sharply defined regions — and the pattern turns out to be the life story of every star that exists.

Around 1911, the Danish chemist-turned-astronomer Ejnar Hertzsprung plotted stellar brightness against colour. Two years later, and independently, the American Henry Norris Russell did the same. Both found the same thing, and it was not what anyone expected: the points were not scattered across the graph. Roughly ninety per cent of them lay along a single sweeping diagonal band.

The **Hertzsprung–Russell diagram** is the most important chart in stellar astronomy, and learning to read it is the closest thing this subject has to a rite of passage.

THE HERTZSPRUNG–RUSSELL DIAGRAM

Every star ever measured falls into one of these regions. Note the temperature axis runs backwards.

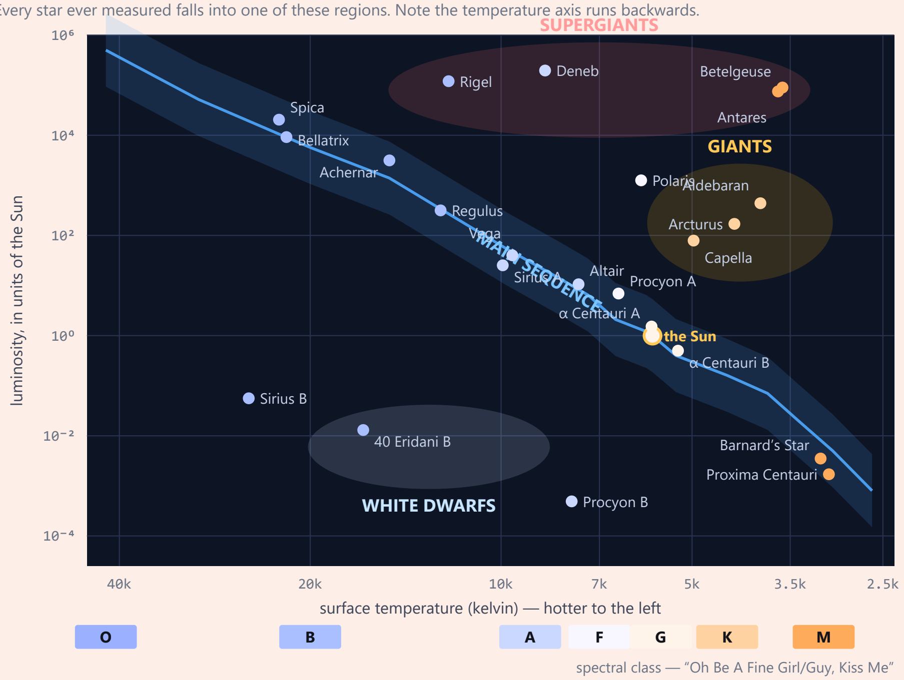


Figure 16.1 — The H–R diagram, with real stars plotted. Horizontal axis: surface temperature, running *backwards* for historical reasons. Vertical axis: luminosity, logarithmic, spanning a factor of ten billion. The Sun is marked in gold, and sits unremarkably in the middle of the main sequence.

Reading the regions

The main sequence is the diagonal band, and it holds about 90 per cent of all stars — including the Sun. It is not a track that stars travel along. It is the place a star sits, essentially motionless, for the whole of its hydrogen-burning life. Position along it is set by **mass alone**: hot luminous O stars at the top left run to 40 solar masses; cool faint M dwarfs at the bottom right are under a tenth of one.

The giants, up and to the right, are cool but enormously bright. Since a cool surface radiates poorly per square metre, the only way to be both cool and luminous is to have an extraordinary number of square metres. Aldebaran is 44 times the Sun's diameter; Arcturus 25 times. These are dying stars, and Chapter 17 explains what has happened to them.

The supergiants along the top are the extreme version — Betelgeuse is roughly 900 times the Sun's diameter. Placed where the Sun is, its surface would engulf the orbit of Mars. They are rare, short-lived, and destined for Chapter 18.

The white dwarfs, bottom left, are hot but almost invisible: an intense surface attached to an object about the size of the Earth. Sirius B is hotter than Sirius A and ten thousand times fainter. These are stellar corpses.

THE RELATION THAT MAKES THE DIAGRAM READABLE

The Stefan–Boltzmann law

$L = 4\pi R^2 \sigma T^4$, with $\sigma = 5.67 \times 10^{-8}$ W m^{-2} K^{-4}.

Luminosity depends on surface area *and* on temperature to the **fourth power**. Because temperature is so dominant, a star that is cool and yet luminous must be vast — which is why "up and to the right" is exactly the same statement as "enormous". Every position on the H–R diagram implies a radius, and lines of constant radius run diagonally across it.

The spectral classes, and how they got their strange order

The sequence **O B A F G K M** — hottest to coolest — is not alphabetical, and the reason is a good story. Nineteenth-century astronomers at Harvard classified stars A, B, C and so on by the strength of their hydrogen absorption lines. When the physics was later understood, it turned out hydrogen line strength peaks at intermediate temperatures rather than increasing with heat, so the classes had to be reordered and several dropped. Nobody wanted to relabel decades of catalogues, so the surviving letters were simply rearranged into temperature order and left alone.

Three more classes have been added below M for the very coolest objects: **L**, **T** and **Y**, covering brown dwarfs — objects too light to sustain hydrogen fusion. Y dwarfs can be under 300 K, which is to say roughly room temperature. There are stars you could, in principle, touch.

CASE FILE · CECILIA PAYNE FINDS OUT WHAT STARS ARE MADE OF

In 1925, a 25-year-old British graduate student at Harvard submitted a doctoral thesis applying new quantum ionisation theory to stellar spectra. Cecilia Payne's conclusion was that the differences between spectral classes are almost entirely differences of **temperature**, not composition — and that when you correct for this, stars turn out to be overwhelmingly **hydrogen and helium**, with everything else a trace contaminant.

This contradicted the settled consensus that stars had roughly the same composition as the Earth. Henry Norris Russell — of H–R diagram fame, and the most powerful astronomer in America — reviewed the thesis and told her the result was "clearly impossible". Payne added a sentence describing her own central finding as probably spurious, and published.

Four years later Russell reached the same conclusion by a different route and published it himself. He credited Payne, but the result is often attributed to him anyway. Otto Struve later called her thesis "the most brilliant PhD thesis ever written in astronomy".

Payne-Gaposchkin went on to become the first woman promoted to full professor at Harvard, and the first to head a department there — in 1956, thirty-one years after the thesis. The fact that the universe is 74 per cent hydrogen by mass, which underpins every chapter in this part of the book, is her result.

The diagram as a clock

Here is where the H–R diagram becomes genuinely powerful. Plot a **star cluster** — where every member formed at the same time from the same material — and you get something no single star can give you.

At the moment of formation, all of them lie on the main sequence. But massive stars burn out fast (Chapter 15: lifetime $\propto M^{-2.5}$). So the top-left end of the main sequence empties first, then the next section down, then the next — like a candle burning from one end. The point where the cluster's main sequence stops is called the **turn-off point**, and its position gives the cluster's age directly.

This works beautifully. The Pleiades turn off high on the main sequence, so they are young — about 100 million years. The globular cluster M13 has a turn-off barely above the Sun's position, so almost everything more massive than the Sun has already died: age around 11.6 billion years. This is one of the four independent age measurements from Chapter 2, and it is done by looking at where a line stops.

DO THE MATH · 16.1

Work out a star's size without resolving it. Rearranging Stefan–Boltzmann and dividing by the same relation for the Sun gives a form with no constants at all:

$$\frac{R}{R_\odot} = \sqrt{\frac{L}{L_\odot}} \times \left(\frac{T_\odot}{T}\right)^2$$

Take $T_\odot$ = 5,772 K. Find the radius, in solar radii, of:

- **Betelgeuse** — L = 90,000 $L_\odot$, T = 3,600 K.
- **Sirius B** — L = 0.056 $L_\odot$, T = 25,000 K.
- **Proxima Centauri** — L = 0.0017 $L_\odot$, T = 3,042 K.

The Sun's radius is 696,000 km. Convert all three answers to kilometres. Then compare Sirius B with the Earth's radius of 6,371 km, and Betelgeuse with the 228-million-km radius of Mars's orbit. Both comparisons should produce a reaction.

TRY THIS · SEE STELLAR COLOUR WITH YOUR OWN EYES

Star colours are real and visible, but the eye's colour receptors work poorly at low light, so you have to help them. Two tricks work.

Compare, don't judge alone. In Orion, look at **Betelgeuse** in the top-left shoulder and **Rigel** in the bottom-right foot, in quick succession. Betelgeuse is distinctly orange-red at 3,600 K; Rigel is blue-white at 12,100 K. Seen side by side the difference is unmistakable; seen alone, either looks white.

Defocus. Look at a bright star through binoculars and turn the focus wheel until it becomes a small disc. Spreading the light over more retinal cells makes the colour far easier to register.

Then find **Albireo** in Cygnus, visible through the monsoon months and after. Any small telescope splits it into a gold star and a blue one in the same field — the finest colour contrast in the sky, and an H–R diagram with two data points.

GET THIS STRAIGHT

"Stars move along the main sequence as they age, sliding from blue to red." No. A star's position on the main sequence is fixed by its mass, and stars do not lose meaningful mass while burning hydrogen.

The Sun will not slide down the main sequence and become a red dwarf. It will sit almost exactly where it is for another five billion years, then move **off** the main sequence entirely — up and to the right, into the giant region, in a matter of a few hundred million years. Evolution across the H–R diagram is fast and happens at the end; the long stable middle of a star's life is a single stationary dot.

CAREER NOTE

If you want one concrete project that will teach you more than a term of reading: download the **Gaia** catalogue — the European Space Agency has measured distances and colours for nearly two billion stars, and the data is free and public — and plot your own H–R diagram in Python. It takes perhaps forty lines of code with astroquery and matplotlib. Watching the main sequence, the giant branch and the white dwarf sequence emerge from raw data you fetched yourself is the moment astronomy stops being a subject you read about.

IN A HURRY?

- The **H–R diagram** plots luminosity against surface temperature. Temperature runs backwards.
- About **90% of stars lie on the main sequence**, positioned by **mass alone**, where they sit for their entire hydrogen-burning life.
- Giants and supergiants are cool but luminous, so they must be **enormous** ($L = 4\pi R^2 \sigma T^4$). White dwarfs are hot but faint, so they must be **tiny**.
- Spectral classes **OBAFGKM** (plus L, T, Y) run hottest to coolest; the odd order is a historical accident.
- **Cecilia Payne** showed in 1925 that stars are mostly hydrogen — against the consensus, and she was right.
- A cluster's **main-sequence turn-off point** gives its age directly, because massive stars die first.

CHAPTER 17 · STARS

The Quiet Death: White Dwarfs

> Ninety-seven per cent of stars, including the Sun, end without an explosion. They swell, shed their outer layers, and leave behind an Earth-sized ember held up by a quantum rule.

A star spends its life burning hydrogen in its core because that is where the temperature and pressure are highest. What happens next is entirely determined by a problem of supply: the core runs out first, and the star has no way to stir fresh fuel down into it.

What will happen to the Sun

In about five billion years the Sun's core will be pure helium and no longer able to fuse. Without energy generation, the core cannot maintain its pressure, so it contracts — and contraction heats it. That heat ignites hydrogen in a **shell** around the dead core, and shell burning is far more vigorous than core burning was.

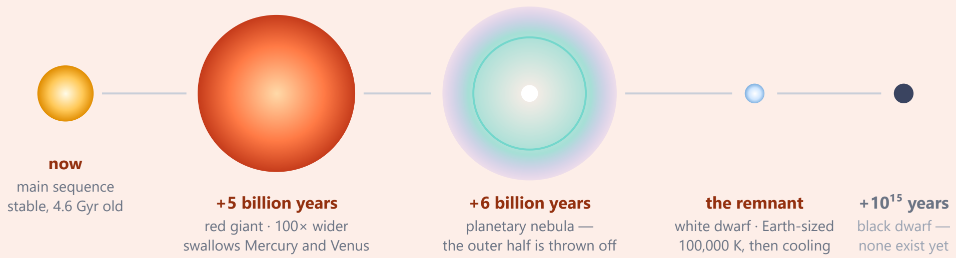
The result is counterintuitive and worth pausing on: **the core shrinks while the outer layers expand enormously**. The Sun will swell to over a hundred times its present radius, its surface cooling to around 3,000 K as the same energy is spread over a vastly greater area. It becomes a **red giant**, moving up and to the right on the H–R diagram.

Mercury and Venus will certainly be swallowed. The Earth's fate is genuinely uncertain — the Sun will lose about a third of its mass as a wind, which lets Earth's orbit drift outward, and the calculation is close enough that the answer flips depending on assumptions. It is academic in any case: the Earth's oceans will have boiled away roughly a billion years from now, long before the giant phase, as the Sun's steady brightening finally overwhelms the carbon cycle.

When the core reaches 100 million kelvin, helium ignites — in a Sun-like star, all at once, in a runaway called the **helium flash** that releases as much power in seconds as an entire galaxy, and is completely invisible from outside because it is absorbed by the overlying layers. The star settles, burns helium to carbon and oxygen for about a hundred million years, then repeats the whole crisis when the helium runs out.

This time the star cannot get hot enough to fuse carbon. The outer layers, now loosely bound, are pushed off by pulsations and radiation pressure, drifting away as a glowing shell. What remains is the naked core: a **white dwarf**.

THE REST OF THE SUN'S LIFE



Everything above happens to any star below about 8 solar masses.
That is roughly 97% of all stars. The other 3% are Chapter 18.

Figure 17.1 — Five billion years, compressed. The giant phase lasts only about a billion years and the planetary nebula perhaps twenty thousand — a blink against ten billion years of stability.

GET THIS STRAIGHT

"Planetary nebulae have something to do with planets." Nothing whatsoever. The name is an eighteenth-century mistake that stuck. William Herschel, observing through the telescopes of the 1780s, thought these small round greenish objects resembled the disc of Uranus, which he had just discovered. He called them planetary nebulae, and astronomy has been apologising ever since.

They are dying stars shedding their atmospheres. Astronomers have periodically proposed renaming them and have always lost, because two centuries of literature use the old term. It is a good example of how naming in science is usually settled by inertia rather than accuracy.

What holds a white dwarf up

A white dwarf has no fusion. Nothing is generating energy, so nothing is generating thermal pressure. By the logic of Chapter 15 it should collapse under its own weight.

It does not, because of the Pauli exclusion principle from Chapter 9. No two electrons may occupy the same quantum state. Squeeze matter hard enough and the electrons are forced into ever higher momentum states simply because the low ones are full — and that resistance produces a genuine outward pressure. It is called **electron degeneracy pressure**, and it is not a thermal effect at all: it would be just as strong at absolute zero.

The numbers that result are unreasonable. A typical white dwarf holds about 0.6 solar masses in a sphere the size of the Earth. Density is around a tonne per cubic centimetre — **one teaspoonful weighs about as much as a small car**. Surface gravity is roughly 100,000 times Earth's.

And degenerate matter behaves backwards: **the more massive a white dwarf is, the smaller it gets**. Add mass and it shrinks. Push that far enough and something has to give.

CASE FILE · A NINETEEN-YEAR-OLD ON A BOAT FROM MADRAS

In the summer of 1930, Subrahmanyan Chandrasekhar boarded a ship from Madras to England to take up a scholarship at Cambridge. He was nineteen. To pass the eighteen-day voyage he worked on the structure of white dwarfs, and did something nobody had done: he combined degeneracy pressure with **special relativity**.

The correction matters because in a sufficiently massive white dwarf, the electrons are pushed to speeds approaching that of light — and a relativistic electron gas is "softer" than a non-relativistic one. It cannot stiffen indefinitely. Chandrasekhar found that above a critical mass, degeneracy pressure **fails completely**. The modern value of that **Chandrasekhar limit** is **1.44 solar masses**.

The implication was radical: a sufficiently massive star has no stable endpoint at all. It must collapse to something else.

On 11 January 1935, Chandrasekhar presented the result to the Royal Astronomical Society in London. Arthur Eddington — the most eminent astrophysicist alive, and Chandrasekhar's own mentor — rose immediately afterwards and dismissed it publicly, saying there should be a law of Nature to prevent a star behaving in such an absurd way. The room, deferring to Eddington's authority, largely accepted this. Chandrasekhar, then 24, was humiliated in front of the field he was trying to enter.

He was right and Eddington was wrong, and it took the community the better part of two decades to say so plainly. Chandrasekhar left stellar structure entirely, moved to Chicago, and spent a remarkable career changing subject every ten years. He received the Nobel Prize in 1983 — **fifty-three years** after the calculation on the boat. NASA's great X-ray observatory is named *Chandra* after him.

Two lessons. The first: eminence is not evidence. The second, harder one: Eddington was not stupid or malicious — he simply could not accept a conclusion he found aesthetically intolerable, which is a failure mode available to anybody, including you.

DO THE MATH · 17.1

How dense is degenerate matter? A white dwarf of 0.6 solar masses (1.19×10^{30} kg) has a radius of about 7,000 km.

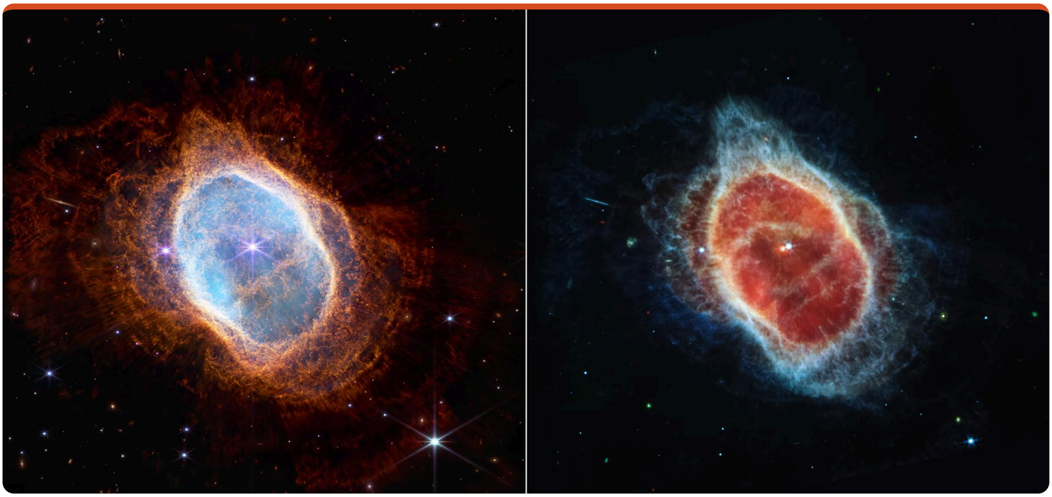
- Compute its volume, then its average density in kg/m^3.
- Convert to tonnes per cubic centimetre. How does that compare to the densest ordinary material, osmium, at 22.6 g/cm^3?
- Compute the surface gravity, $g = GM/R^2$, and express it as a multiple of Earth's 9.81 m/s^2.
- How much would a 50 kg person weigh there, in tonnes?

Now the interesting one. Use $v_{esc} = \sqrt{(2GM/R)}$ from Chapter 4. What is the escape velocity from a white dwarf, as a fraction of the speed of light? Keep the answer — Chapters 19 and 20 repeat this calculation for progressively smaller objects, and you will watch it climb to 1.

The long cooling

A newly exposed white dwarf is around 100,000 K. It has no fuel, so from that moment it does exactly one thing: radiate away its stored heat, getting fainter and redder over billions of years. Eventually it should become a cold, dark **black dwarf**, emitting nothing.

None exists. The cooling time to that state is of order 10^{15} years, and the universe has managed 1.4×10^{10}. The universe is about one hundred-thousandth of the way to producing its first black dwarf. The coolest white dwarfs found so far are around 3,000 K and roughly as old as the galaxy — which, as Chapter 2 noted, makes them one of the four independent clocks used to age the universe.



The Southern Ring Nebula, seen twice by JWST. On the left in near-infrared, on the right in mid-infrared — where the dying central star, invisible on the left, becomes obvious. The same object photographed in two bands answers different questions, which is the whole argument of Chapter 7.

Credit: STScI. NASA — free to use with credit.

A star that has just finished dying

The Helix Nebula, 650 light-years away — one of the nearest planetary nebulae, and among the best-studied. The glowing ring is the outer atmosphere of a Sun-like star, thrown off over roughly ten thousand years and now expanding into space. The faint blue point at the centre is the exposed core: **a white dwarf**, around the size of the Earth, and the fate of our own Sun.

IN A HURRY?

- When core hydrogen runs out, the core **contracts** and the envelope **expands**: a red giant.
- The Sun will do this in ~5 billion years, swallow Mercury and Venus, and shed its outer layers as a **planetary nebula** — which has nothing to do with planets.
- The remnant is a **white dwarf**: ~0.6 solar masses in an Earth-sized sphere, about a tonne per cubic centimetre.
- It is held up by **electron degeneracy pressure** — the Pauli exclusion principle, not heat.
- Degenerate objects shrink as they gain mass, and above the **Chandrasekhar limit of 1.44 solar masses** they cannot exist at all.
- That limit was derived by **Chandrasekhar at nineteen**, publicly rubbished by Eddington in 1935, and vindicated with a Nobel Prize in 1983.
- White dwarfs cool forever. **No black dwarf exists** — the universe is far too young.

CHAPTER 18 · STARS

The Loud Death: Supernovae

> For a few weeks, one dying star can outshine the hundred billion stars of its own galaxy combined. Everything in you heavier than iron owes its existence to events like this.

Above about eight solar masses, a star cannot end quietly. It has enough gravity to force fusion past carbon, and each successive fuel buys it less time than the last. The end, when it arrives, takes less than a second.

The onion, and the day it collapses

A massive star near the end has organised itself into concentric shells, each burning a different fuel, hottest at the centre. The timings are the striking part. A 20-solar-mass star burns hydrogen for about 8 million years, helium for a million, carbon for a thousand years, neon for about a year, oxygen for a few months — and **silicon for roughly one day**.

Silicon burning produces iron, and iron is the end of the line: fusing it consumes energy instead of releasing it (Chapter 13). Once the iron core reaches the Chandrasekhar limit of 1.44 solar masses, electron degeneracy pressure fails, exactly as Chandrasekhar said it must.

What follows takes about a quarter of a second.

The core collapses at roughly a quarter of the speed of light. Two processes accelerate it: gamma rays tear iron nuclei apart into helium, absorbing energy, and electrons are crushed into protons to make neutrons and neutrinos, removing the very pressure that was holding things up. In a fraction of a second, an object the size of the Earth becomes a ball 20 kilometres across.

Then the collapse stops, hard. Neutron degeneracy pressure and the strong nuclear force bring the inner core to an abrupt halt, and the infalling material above it

bounces. A shock wave races outward — and stalls, because it costs energy to tear apart the iron it is ploughing through.

What revives it is the neutrinos. The collapsing core releases about 10^{46} joules in neutrinos in ten seconds, and although neutrinos barely interact with anything, the density here is so extreme that a small percentage is absorbed. That is enough to reheat the stalled shock and blow the star apart.

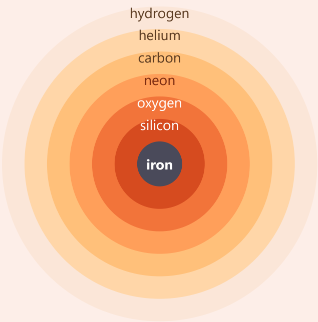
THE ENERGY BUDGET OF A CORE-COLLAPSE SUPERNOVA

99 per cent
escapes as **neutrinos** — invisible, and gone in seconds.

about 1 per cent
becomes **kinetic energy** of the expanding debris.

about 0.01 per cent
is emitted as **light** — and that fraction alone outshines an entire galaxy.

TWO WAYS TO EXPLODE



TYPE II — core collapse
a massive star runs out of fuel

TYPE II	TYPE Ia
Massive star, > 8 $M_\odot$ dies alone, of old age	**White dwarf in a binary** steals gas from a companion
Trigger: iron core exceeds 1.44 $M_\odot$ and collapses	**Trigger: accretion** pushes it past 1.44 $M_\odot$
Leaves behind a neutron star or a black hole	**Leaves behind** nothing at all
Spectrum: hydrogen present brightness varies widely	**Spectrum: no hydrogen** **always the same brightness**

Because Type Ia always detonates at the same mass,
it always releases the same energy — a standard candle.

Figure 18.1 — Two unrelated events with the same name. Type II is a massive star dying of old age. Type Ia is a white dwarf being pushed over the Chandrasekhar limit by a companion. They were classified together in the 1940s purely because both look like a star suddenly appearing.

Type Ia: the explosion that measures the universe

The second kind has nothing to do with massive stars. Take a white dwarf in a close binary system. It pulls gas from its companion, and its mass creeps upward. At **1.44 solar masses** — always the same number, because it is set by physics rather than circumstance — carbon fusion ignites throughout the degenerate interior at once.

Degenerate matter cannot expand to cool itself, so the thermostat from Chapter 15 is absent. The result is a runaway that consumes the entire star in about two seconds and leaves nothing behind. It releases roughly 10^{44} joules — comparable to the total energy the Sun will emit over its entire ten-billion-year life.

Because the trigger mass is always identical, the peak brightness is always nearly identical. That makes Type Ia supernovae **standard candles**: measure how bright one appears, compare with how bright it must actually be, and equation $F = L/4\pi d^2$ from Chapter 6 hands you the distance to its galaxy. This is the single most important distance tool in cosmology, and in 1998 it produced the discovery of dark energy (Chapter 27).

CASE FILE · SN 1987A — THREE HOURS OF WARNING

On 23 February 1987, at 07:35 UTC, three neutrino detectors on three continents — Kamiokande-II in Japan, IMB in Ohio, and Baksan in Russia — each recorded a brief burst of neutrinos. Twenty-five events in about thirteen seconds. It was, and remains, the only time neutrinos have been detected from beyond the Solar System.

Roughly three hours later, observers in the southern hemisphere saw a new star in the Large Magellanic Cloud, 168,000 light-years away. It was the nearest supernova since 1604 and the first ever observed with modern instruments.

The three-hour delay is the beautiful part, and it is not a measurement error. The neutrinos left the collapsing core immediately, because almost nothing can stop them. The *light* could not escape until the shock wave had fought its way out through the star's outer layers. The gap was predicted before it was observed, and it confirmed the entire theoretical picture of core collapse in one stroke.

Two dozen neutrinos, from a star 168,000 light-years away, validated a theory. It also launched a working alarm system: SNEWS, the SuperNova Early Warning System, now links neutrino detectors worldwide so that if a nearby star collapses, optical astronomers get a few hours of notice before there is anything to see.

DO THE MATH · 18.1

Put a supernova in perspective. The Sun's luminosity is 3.828×10^{26} W. A Type Ia supernova releases about 10^{44} J of light over roughly a month.

- How much total energy will the Sun emit over 10 billion years?
- Compare with the supernova's 10^{44} J. What does that tell you?
- Average power of the supernova = energy ÷ time (take one month = 2.6×10^{6} s). How many Suns is that?
- The Milky Way holds roughly 10^{11} stars, most fainter than the Sun. Does the supernova genuinely outshine its whole galaxy?

Then: a core-collapse supernova releases about 10^{46} J in neutrinos. If a supernova went off 10 parsecs (3.1×10^{17} m) away, what neutrino energy would cross each square metre at Earth? This is the calculation behind the estimate that a supernova within about 25 light-years would be a mass-extinction event.

TRY THIS · FIND A SUPERNOVA REMNANT, AND A FUTURE ONE

In July 1054, Chinese court astronomers recorded a "guest star" in Taurus, bright enough to be visible in daylight for 23 days. What they saw is now the **Crab Nebula** — a shredded cloud 6,500 light-years away, still expanding at 1,500 km/s, with a pulsar spinning 30 times a second at its centre. It sits near the tip of Taurus's lower horn and is visible in a small telescope as a faint grey smudge. Its official designation, M1, is the first entry in Messier's catalogue.

Then look at **Betelgeuse** in Orion. It is roughly 15 to 20 solar masses, about 10 million years old, and already fusing elements well beyond helium. It will explode — the only questions are when, and whether it already has. Estimates run from tomorrow to a hundred thousand years from now.

When it does, at 550 light-years, it will reach about magnitude −11: bright enough to read by, visible in daylight, casting shadows at night, for several months. It is far too distant to harm us. Somebody will see it. It might be you.

GET THIS STRAIGHT

"A supernova is a very big explosion, like a bomb going off." A Type II supernova is better understood as an *implosion* that rebounds. The energy does not come from any chemical or nuclear burning of the outer layers; it comes from **gravitational potential energy** released as the core falls inward.

And the mechanism is stranger still: the star is blown apart by **neutrinos**, the particles from Chapter 9 that pass through the entire Earth without noticing. Only because the collapsing core is briefly so dense that even neutrinos cannot ignore it does a fraction of them deposit enough energy to reverse the collapse. Getting this to work in computer simulations took the field about fifty years, and three-dimensional models only began exploding reliably in the 2010s.

What the Chinese saw in 1054

The Crab Nebula, 6,500 light-years away in Taurus. On 4 July 1054, court astronomers recorded a “guest star” here bright enough to be seen in daylight for 23 days. This is what is left: debris still expanding at about 1,500 km/s, wrapped around a neutron star that rotates 30 times a second. It is the only supernova remnant whose explosion date is known from written records.

Credit: NASA/ESA/JPL/Arizona State Univ. NASA — free to use with credit.

IN A HURRY?

- Stars above **8 solar masses** fuse to iron, then collapse in about a quarter of a second when the core passes 1.44 $M_\odot$.
- The core bounces, and the stalled shock is **revived by neutrinos**. **99% of the energy leaves as neutrinos**; 0.01% as light — and that outshines a galaxy.
- **Type Ia** is unrelated: a white dwarf pushed past the Chandrasekhar limit by a companion, detonating completely.
- Because Ia always ignites at the same mass, its brightness is **standard** — making it cosmology's most important distance measure.
- **SN 1987A** delivered neutrinos **three hours before the light**, exactly as predicted, confirming the core-collapse theory.
- Supernovae distribute the elements from Chapter 13. Without them there would be no planets and no chemistry.

CHAPTER 19 · STARS

Neutron Stars and Pulsars

> An object heavier than the Sun, twenty kilometres across, spinning seven hundred times a second, with a magnetic field a quadrillion times the Earth's. It is the densest thing that can exist without becoming a black hole.

When the core of a massive star collapses and the bounce blows away everything above it, what remains — provided it is under roughly 2.2 solar masses — is a **neutron star**. Electrons and protons have been crushed together into neutrons, and the whole object is held up by neutron degeneracy pressure: the same Pauli exclusion principle as a white dwarf, but applied to particles nearly two thousand times heavier and packed far tighter.

The numbers are the least believable in astronomy. About 1.4 solar masses — 2.8×10^{30} kg — inside a sphere roughly 20 km across, the size of a city. Density around 4×10^{17} kg/m³, which is the density of an atomic nucleus. A neutron star is, in effect, **a single atomic nucleus the size of Delhi**.

A teaspoon of it would weigh about a billion tonnes. Surface gravity is roughly 200 billion times Earth's; escape velocity is over half the speed of light. An object dropped from one metre above the surface would hit it at about 2,000 km/s.

Why they spin so absurdly fast

Angular momentum is conserved. When a stellar core shrinks from something the size of the Earth to something the size of a city — a factor of several hundred in radius — its rotation rate increases by the square of that factor.

A core rotating once a month becomes a neutron star rotating many times a second. The fastest known, PSR J1748–2446ad, spins **716 times per second**. Its equator is moving at roughly a quarter of the speed of light, and the star is very close to flying apart.

The magnetic field is compressed in the same way. Magnetic flux is conserved as the core shrinks, so field strength rises by the square of the compression factor. Typical neutron stars carry fields of 10^8 tesla — a hundred million times a hospital MRI scanner. **Magnetars** reach 10^{11} tesla, strong enough to distort atoms into needles and, from a thousand kilometres away, to erase every magnetic stripe on every card in your wallet.

THE LIGHTHOUSE MODEL

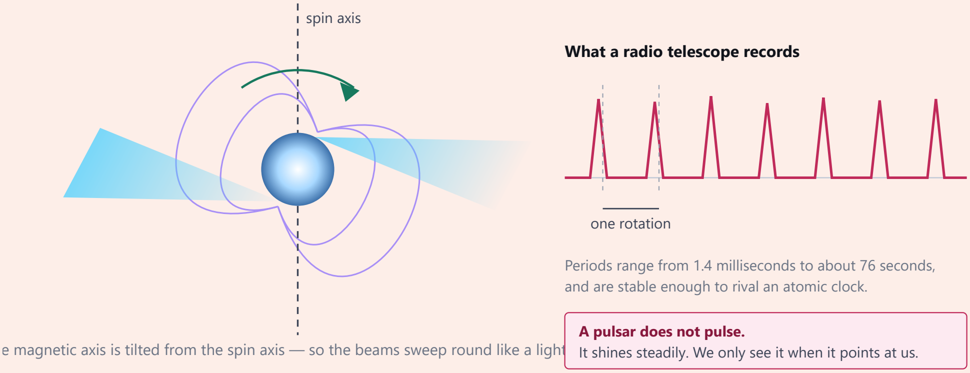


Figure 19.1 — Why a steady beam looks like a heartbeat. Radiation streams continuously from the magnetic poles. Because the magnetic axis is tilted away from the rotation axis, the beams sweep across space, and a detector in their path registers a pulse once per rotation.

CASE FILE · JOCELYN BELL AND LGM-1

In July 1967, Jocelyn Bell was a 24-year-old PhD student at Cambridge. She had spent two years helping build a radio telescope out of 1,000 wooden posts and 120 miles of wire, and was now analysing its output — which arrived as ink on paper, roughly 30 metres of chart per day, read by eye.

She noticed what she called "a bit of scruff" occupying about a quarter-inch of chart, recurring in the same patch of sky. Running the recorder faster, she found it resolved into pulses of astonishing regularity: one every **1.337 seconds**, stable to better than one part in ten million.

Nothing known could do that. The signal was so artificial-looking that the team seriously discussed an extraterrestrial origin and labelled the source **LGM-1**, for Little Green Men. Bell was, by her own account, mostly annoyed — she was trying to finish a thesis and aliens were an inconvenience. Then, within weeks, she found a second pulsing source in a completely different part of the sky. Two independent civilisations both signalling Cambridge on the same frequency was not plausible. It had to be a natural object.

The 1974 Nobel Prize in Physics went to her supervisor Antony Hewish and to Martin Ryle. Bell Burnell was not included. The omission was controversial then and is regarded as indefensible now; Fred Hoyle objected publicly at the time.

Her own response has been consistently gracious and pointed. In 2018 she was awarded the $3 million Breakthrough Prize — and donated **the entire sum** to the Institute of Physics to fund graduate scholarships for students from under-represented backgrounds. "I don't need the money myself," she said, "and it seems to me this is perhaps the best use I could put to it."

Clocks accurate enough to test general relativity

Pulsar rotation is so stable that pulsars function as clocks — and anything that disturbs the timing becomes measurable. This has made them one of the most productive instruments in physics.

In 1974 Russell Hulse and Joseph Taylor found **PSR B1913+16**, a pulsar orbiting another neutron star. General relativity predicts such a system must radiate energy as gravitational waves and spiral inward, shortening its orbital period by a very specific amount: 76.5 microseconds per year.

They measured it. Over three decades of timing, the observed orbital decay matched the prediction to better than 0.2 per cent. This was the **first evidence that**

gravitational waves exist — forty-one years before LIGO detected one directly — and it won the 1993 Nobel Prize. Chapter 33 picks up the story.

Pulsars are also used for navigation, for probing the interstellar medium, and — through pulsar timing arrays like the Indian Pulsar Timing Array, which uses the GMRT — to hunt for the gravitational-wave background from supermassive black hole binaries across the whole sky at once.

DO THE MATH · 19.1

Spin up a stellar core. Angular momentum $I\omega$ is conserved, and for a sphere $I \propto MR^2$. With mass unchanged:

$$\omega_2 / \omega_1 = (R_1 / R_2)^2 \qquad \text{equivalently} \qquad T_2 = T_1 \times (R_2/R_1)^2$$

- A stellar core of radius 10,000 km rotates once every 30 days. It collapses to 10 km. What is the new rotation period?
- Convert to rotations per second. Compare with the Crab pulsar's 30 per second.
- Compute the equatorial speed of a 20 km neutron star spinning 716 times a second. What fraction of *c* is that?

Then continue the escape-velocity series from Chapter 17. For a neutron star, $M = 2.8 \times 10^{30}$ kg and $R = 10{,}000$ m, find $v_{esc} = \sqrt{(2GM/R)}$ as a fraction of *c*. Then work out what radius would make it exactly equal to *c* — you will have derived the Schwarzschild radius, which is Chapter 20.

GET THIS STRAIGHT

"A pulsar is a star that pulses on and off." It does nothing of the kind. A pulsar emits a steady, continuous beam from its magnetic poles. The apparent pulsing is entirely a **geometric effect** — the beam sweeps past our line of sight once per rotation, exactly like a lighthouse.

One consequence is worth appreciating: we can only detect a pulsar whose beam happens to sweep across the Earth. Most neutron stars are pointing somewhere else and are completely invisible to us. Of the roughly 100 million to a billion neutron stars thought to exist in the Milky Way, about 3,500 have been catalogued.

CAREER NOTE

Pulsar astronomy is one of the fields where India is genuinely world-leading. The **Giant Metrewave Radio Telescope** near Pune — thirty 45-metre dishes spread over 25 km, designed and built in India under Govind Swarup — is among the best instruments in the world at metre wavelengths, precisely the band where pulsars are brightest. It is operated by NCRA-TIFR, which runs a well-regarded summer programme and takes on students from any BSc physics background. If radio astronomy appeals, this is a facility you can realistically work at.

IN A HURRY?

- A **neutron star** is ~1.4 solar masses in a 20 km sphere — nuclear density, a billion tonnes per teaspoon.
- Held up by **neutron degeneracy pressure**; the maximum mass is about **2.2 solar masses**. Above that: a black hole.
- Conservation of angular momentum makes them spin up to **716 times a second**; conservation of magnetic flux gives fields up to 10^{11} T.
- A **pulsar** does not pulse — a steady beam sweeps past us like a lighthouse.
- Discovered by **Jocelyn Bell** in 1967; her supervisor received the Nobel Prize and she did not.
- The **Hulse–Taylor binary pulsar** proved gravitational waves exist in 1974, four decades before they were directly detected.

CHAPTER 20 · STARS

Black Holes

> Not a thing so much as a region — a boundary in space beyond which every possible path leads inward. The physics is far stranger, and far better established, than the films suggest.

Run the escape-velocity calculation from Chapter 4 backwards. For a body of mass *M*, ask what radius would make the escape velocity exactly equal to the speed of light. Set $\sqrt{(2GM/R)} = c$ and solve:

THE SCHWARZSCHILD RADIUS

```
          2 G M
R_s  =  ─────────
           c²

For the Sun:     3.0 km
For the Earth:   8.9 mm
For a person:    about 10⁻²³ m
```

Compress anything below its Schwarzschild radius and nothing — not light, not information, not any conceivable rocket — can leave. Karl Schwarzschild derived this from Einstein's field equations in 1916, while serving on the Russian front in the First World War. He sent the solution to Einstein by post and died of illness a few months later, aged 42.

The event horizon is not a place

The **event horizon** at R_s is the most misunderstood object in physics. It is not a surface. There is nothing there. If you fell through the horizon of a sufficiently large black hole you would notice nothing at all at the moment of crossing — no membrane, no jolt, no flash. Space would look normal.

What it is, is a **boundary of causality**: the set of points from which no future path leads outward. Inside it, the geometry of spacetime is so distorted that the direction "towards the centre" becomes as inescapable as "towards the future" is for you now. You cannot avoid the singularity for the same reason you cannot avoid next Tuesday.

ANATOMY OF A BLACK HOLE

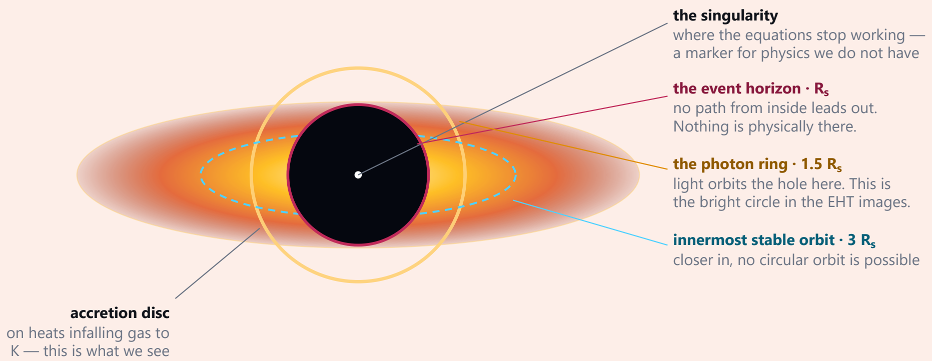


Figure 20.1 — A black hole is invisible; its surroundings are not. Everything we observe comes from material outside the horizon. The black hole itself contributes only a shadow.

Three sizes, two of them explained

Stellar-mass black holes, from about 3 to 150 solar masses, form when a massive star's core exceeds the neutron-star limit. Around fifty are known in the Milky Way from X-ray binaries, and gravitational-wave detectors have now catalogued over a hundred more.

Supermassive black holes, from millions to tens of billions of solar masses, sit at the centre of essentially every large galaxy. Ours, Sagittarius A*, is 4.3 million solar masses. How they got so big so early is an open problem — Chapter 24.

Intermediate-mass black holes, between 100 and 100,000 solar masses, were long a conspicuous gap. A handful of candidates now exist, including GW190521, a merger that produced a 142-solar-mass remnant.

One point deserves emphasis because films get it exactly wrong. A black hole's gravity at a distance is **completely ordinary**. If the Sun were replaced by a black hole of identical mass, the Earth's orbit would not change at all. It would get very cold, and nothing else would happen. Black holes do not suck. They have no special reach; they are simply extremely compact, which lets you get very close to a lot of mass.

Being pulled apart lengthwise

Getting close is where it becomes unpleasant, via the $1/r^3$ tidal effect from Chapter 4. Falling in feet-first towards a stellar-mass black hole, the pull on your feet vastly exceeds the pull on your head. The difference stretches you vertically and squeezes you horizontally. The technical term, coined by Stephen Hawking and now used in journals without embarrassment, is **spaghettification**.

The scaling is counterintuitive: **bigger black holes are gentler**. Tidal force at the horizon falls as $1/M^2$. At a 10-solar-mass black hole you would be torn apart thousands of kilometres before reaching the horizon. At Sagittarius A*, 4.3 million solar masses, you would cross the horizon entirely intact and have several minutes to consider your situation before the tides became a problem.

Watching someone fall in

Gravitational time dilation from Chapter 5 becomes extreme near the horizon. Watching a friend fall in, you would see their clock run slower and slower, their light redshift further and further towards the infrared and then radio, and their image fade and freeze just above the horizon — never quite crossing it, from your point of view, taking infinite time to arrive and becoming undetectably dim within a fraction of a second.

From *their* point of view, they cross the horizon at a perfectly ordinary moment, notice nothing, and reach the centre in a finite and rather short time. Both descriptions are correct. There is no fact of the matter about who is "really" right, because simultaneity between distant observers is not a well-defined concept in general relativity.

CASE FILE · HAWKING RADIATION, AND THE BET HAWKING LOST

In 1974 Stephen Hawking showed that black holes are not entirely black. Applying quantum field theory near the horizon, he found that black holes should emit thermal radiation and slowly evaporate. The temperature is inversely proportional to mass:

$$T = \hbar c^3 / (8\pi\ G\ M\ k\_B)$$

For a stellar-mass black hole this is about 6×10^{-9} K — far colder than the 2.725 K microwave background, so such a hole absorbs vastly more than it emits and is currently growing, not shrinking. Only once the universe has expanded and cooled below that temperature, in perhaps 10^{100} years, will evaporation begin in earnest. A solar-mass black hole would take roughly 10^{67} years to evaporate.

Hawking radiation raised a deeper problem. If a black hole evaporates into pure thermal radiation, the information about whatever fell in appears to be destroyed — which quantum mechanics forbids. This is the **black hole information paradox**, and Hawking bet John Preskill in 1997 that information really was lost.

In 2004 Hawking publicly conceded the bet and paid up with an encyclopaedia of baseball, "from which information can be retrieved at will". Most theorists now believe information is preserved, though exactly how remains unsettled — the leading approaches involve holography, entanglement islands and the AdS/CFT correspondence. It is one of the liveliest open problems in theoretical physics, and Chapter 38 returns to it.

DO THE MATH · 20.1

Shrink things until they disappear. Use $R_s = 2GM/c^2$, with $G = 6.674 \times 10^{-11}$ and $c = 3.00 \times 10^8$.

- The Sun, 1.989×10^{30} kg. (Answer in km.)
- The Earth, 5.972×10^{24} kg. (Answer in mm.)
- Sagittarius A*, 4.3 million solar masses. Express in AU and compare with Mercury's orbit at 0.39 AU.
- Yourself. Take 50 kg. Compare with a proton at 10^{-15} m.

Now something genuinely surprising. Average density is M divided by the volume $(4/3)\pi R_s^3$. Compute it for a 1-solar-mass hole, and then for a 4.3-million-solar-mass one. The second answer comes out close to the density of *water* — about 1,000 kg/m^3. Explain why density falls as mass rises — the answer is that R_s scales as M while volume scales as M^3.

GET THIS STRAIGHT

"Black holes suck everything in, like cosmic vacuum cleaners." This is the most persistent misconception in astronomy, and it is simply false. Gravity follows GMm/r^2 whether the mass is a star, a planet or a black hole.

To fall into a black hole you must aim at it with considerable precision. Material with any sideways velocity goes into orbit instead — which is exactly why accretion discs exist and why anything is visible at all. Stars orbit Sagittarius A* stably for millions of years without incident. The galaxy is not being drained.

The related myth — that black holes "eat everything nearby" — has the causation backwards. Black holes grow slowly and mostly by mergers with other black holes. Feeding on gas is inefficient, because infalling material heats up and the resulting radiation pressure pushes further material away.

IN A HURRY?

- **$R_S = 2GM/c^2$**. Sun: 3 km. Earth: 8.9 mm.
- The **event horizon** is a causal boundary, not a surface. Crossing a large one feels like nothing.
- Three classes: **stellar** (3–150 M⊙), **intermediate** (rare), and **supermassive** (millions to billions) at galaxy centres.
- **Black holes do not suck.** Replace the Sun with one of equal mass and Earth's orbit is unchanged.
- Tides scale as $1/M^2$, so **bigger holes are gentler**.
- Time dilation makes an infalling object appear to freeze and fade at the horizon — while it crosses uneventfully in its own frame.
- **Hawking radiation** makes black holes evaporate, absurdly slowly, and creates the still-unresolved **information paradox**.

CHAPTER 21 · STARS

Photographing a Shadow

> To image an object that emits no light, 55 million light-years away and smaller than the Solar System, astronomers built a telescope the size of the Earth — and then flew the data across the world on hard drives, because the internet was too slow.

On 10 April 2019, in six simultaneous press conferences, the Event Horizon Telescope collaboration released a photograph of a black hole. It was an orange ring with a dark centre, blurry by the standards of ordinary photography, and it was one of the great technical achievements of the century.

The resolution problem

A telescope's ability to resolve detail is limited by diffraction, and the relation is unforgiving:

```
                 λ
θ  ≈  1.22 × ───            θ in radians
                 D          D = aperture diameter
```

Better resolution needs shorter wavelength or a bigger dish. There is no third option.

The target, M87*, has an event horizon roughly 38 billion kilometres across — enormous, but 55 million light-years away. Its apparent size is about **20 microarcseconds**: the angle subtended by an orange on the surface of the Moon, or by a doughnut in New York seen from Delhi.

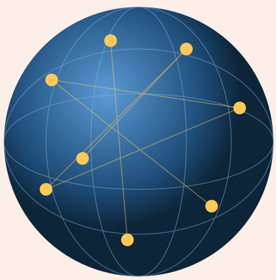
To resolve that at the 1.3 mm wavelength where the surrounding plasma is transparent, you need a dish roughly **10,000 kilometres** across. That is not an engineering challenge; it is an impossibility. The Earth is only 12,742 km wide.

Using the planet as the telescope

The way around it is **very long baseline interferometry**. Instead of one enormous dish, use many small dishes spread across the planet and combine their signals. The resolution you achieve is set not by the size of each dish but by the **distance between them** — the baseline.

The price is that you collect only a tiny fraction of the light a real 10,000 km dish would gather, so the image must be reconstructed from sparse, incomplete data. That is a mathematics problem, and it is where most of the difficulty lies.

HOW YOU BUILD AN EARTH-SIZED TELESCOPE



Eight observatories, from Hawaii to Spain to the South Pole

1 · Observe together
All eight sites watch the same source at once, each timestamping data with a hydrogen maser atomic clock.

2 · Record — enormously
5 petabytes in a few nights. Too much to send over any network, so half a tonne of hard drives is flown to MIT and Bonn. The South Pole drives had to wait six months for the Antarctic winter to end.

3 · Correlate
Supercomputers align the streams to picosecond precision, turning eight dishes into one aperture.

4 · Reconstruct — carefully
Four independent teams, deliberately kept apart.

Figure 21.1 — Very long baseline interferometry. Resolution comes from the separation between dishes, not their size. The EHT achieves an angular resolution about 2,000 times finer than the Hubble Space Telescope.

Not trusting yourselves

Sparse data means many possible images are consistent with the measurements. Choosing between them requires assumptions — and the obvious danger is that a team hoping to see a ring will, through a thousand small choices, produce a ring.

The EHT's response was the most impressive part of the project. They split into **four independent teams**, using different algorithms and different assumptions, and forbade them from communicating for seven weeks. Some teams used traditional radio reconstruction; others used regularised maximum likelihood methods. They also ran their pipelines on synthetic data — some containing rings, some containing other shapes such as a snowflake — without knowing which was which, to check that their methods did not manufacture rings from nothing.

When the teams finally compared results, all four had produced a ring of the same size, with the same brightness asymmetry. That agreement, not the picture itself, is why the result was believed.

The imaging work was led by Katie Bouman, then a 29-year-old computer scientist. She was widely and wrongly portrayed in the press as having single-handedly produced the image, and then subjected to a wave of online abuse when people objected to that framing. Her own repeated statement is the accurate one: the image came from a collaboration of over 200 scientists, and no single person made it.

CASE FILE · WHAT THE PICTURE ACTUALLY SHOWS

The bright ring is **not** the event horizon, and it is not an accretion disc seen edge-on. It is light that has been bent around the black hole — including photons that orbited it one or more times before escaping towards us. Because gravity deflects light from behind the hole into our line of sight, we see a ring even though the emitting material is a disc.

The dark centre is the **shadow**: the region from which no light can reach us. Its angular diameter is about **5.2 Schwarzschild radii**, noticeably larger than the horizon itself, because of that same light-bending. General relativity predicts this number precisely, and the measurement matched.

The ring is brighter on one side because material on that side is moving towards us at a substantial fraction of light speed, and relativistic beaming boosts its apparent brightness. From the asymmetry the team determined the rotation direction: clockwise as seen from Earth.

M87*'s mass came out at **6.5 billion solar masses** — matching one of the two competing prior estimates and ruling out the other. In May 2022 the collaboration released **Sagittarius A***, our own galaxy's black hole. That one was harder despite being a thousand times closer: it is a thousand times smaller, so material orbits it in minutes rather than days, and the source changes appreciably *during* the observation. It is the difference between photographing a landscape and photographing a running child.

DO THE MATH · 21.1

Check the EHT's specification yourself. Use $\theta \approx 1.22\ \lambda/D$, in radians. Remember 1 radian = 206,265 arcseconds.

- At λ = 1.3 mm with D = 10,000 km, what is θ in microarcseconds?
- M87* has a Schwarzschild radius of about 1.9×10^{13} m and is 5.2×10^{23} m away. What angle does its horizon subtend, in microarcseconds? (Use θ = size/distance.)
- Is the EHT's resolution sufficient? By how much?

Then the comparison that makes it vivid. The Hubble Space Telescope has D = 2.4 m and works at λ = 500 nm. What is its resolution in arcseconds? How many times better is the EHT — and why does using a wavelength 2,600 times longer not ruin everything?

GET THIS STRAIGHT

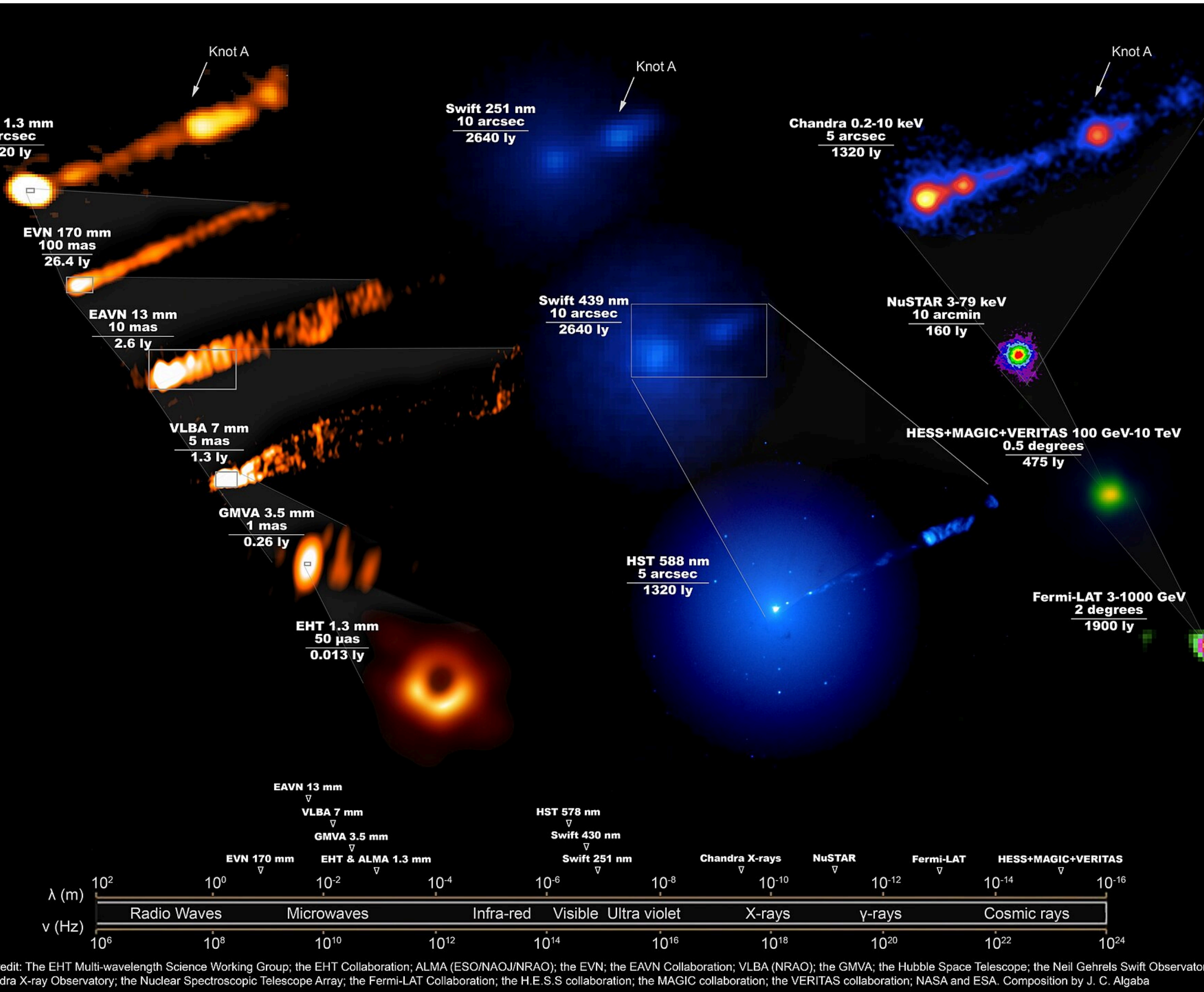
"That famous image is a photograph, like one from a camera." It is a **reconstruction**, and the distinction matters.

No detector recorded that picture. What the telescopes recorded were interference measurements — a sparse sampling of the mathematical transform of the sky brightness. Turning those into an image requires solving an underdetermined problem, which is why four teams worked separately and why so much effort went into testing the pipelines against known inputs.

This is not a weakness or a fudge. Medical CT scans, MRI images and radio maps all work the same way, and nobody doubts a CT scan. But "photograph" implies a passive recording, and this was an inference — a very carefully validated one.

CAREER NOTE

Notice who actually built this. The EHT's hardest problems were signal processing, algorithm design and statistics — Katie Bouman is a computer scientist by training, not an astronomer. Modern astrophysics is increasingly a computational discipline, and the people in demand are those who can handle both the physics and the code. If you enjoy programming, do not treat it as a distraction from physics. It is now one of the main routes in.



The photograph this chapter is about

M87*, the supermassive black hole at the centre of the galaxy Messier 87 — 6.5 billion solar masses, 55 million light-years away. The bright ring is light bent around the hole; the dark centre is the shadow, about 5.2 Schwarzschild radii across, exactly as general relativity predicts. The ring is brighter at the bottom because material there is moving towards us at a large fraction of the speed of light.

Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble.

IN A HURRY?

- Resolution needs **$\theta \approx 1.22\ \lambda/D$**. Imaging M87* at 20 microarcseconds required a 10,000 km aperture.
- **VLBI** links dishes across the planet; resolution comes from their **separation**.
- 5 petabytes of data were **flown on hard drives** — the internet was too slow.
- **Four independent teams** reconstructed the image in isolation and agreed. That is why it was believed.
- The bright ring is **gravitationally bent light**; the dark centre is the **shadow**, about 5.2 R_S across, exactly as general relativity predicts.
- M87* released 2019 at **6.5 billion solar masses**; Sagittarius A* in 2022, harder because it varies during the observation.

V

Galaxies and Structure

Zoom out far enough and stars stop mattering individually. What remains is a web — the largest pattern that exists.

CHAPTER 22 · GALAXIES AND STRUCTURE

The Milky Way: Our Address

> Mapping the galaxy you live inside is like mapping a forest without leaving one tree. It took two centuries, and the crucial breakthrough came from looking at the things nobody else was interested in.

Every star you can see without a telescope belongs to the Milky Way, and nearly all of them lie within a few thousand light-years. The faint band across a dark sky is the disc of our own galaxy seen edge-on from the inside — a view described in Sanskrit as *Ākāśagaṅgā*, the Ganga of the sky, long before anyone knew what it was.

The specification

The Milky Way is a **barred spiral galaxy**, classified SBbc. Its stellar disc is about 100,000 light-years across and remarkably thin — roughly 1,000 light-years thick, making it proportionally thinner than a sheet of paper. It holds somewhere between 100 and 400 billion stars; the uncertainty is large because most stars are faint red dwarfs and counting them is genuinely hard.

The Sun sits about **26,000 light-years** from the centre, roughly halfway out, in a minor structure called the Orion Spur between two major arms. We are travelling at about 230 km/s and take roughly **230 million years** to complete one orbit — a **galactic year**. The Sun has managed about twenty of them. The last time the Solar System was in this part of the galaxy, the first dinosaurs were appearing.

The total mass, including dark matter, is around 1.5×10^{12} solar masses. Only about 5 per cent of that is stars. Chapter 26 explains the rest.

TWO VIEWS OF HOME

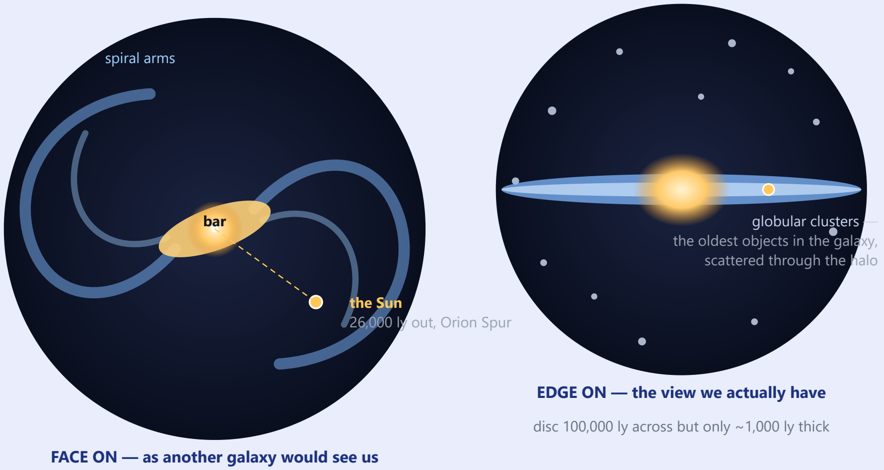


Figure 22.1 — Where we live. The face-on view is a reconstruction; no spacecraft has ever been in a position to take it. The edge-on view is what you see from a dark site, looking along the plane of the disc.

Why mapping it was so hard

Two problems defeated astronomers for a century and a half.

The first is **perspective**. We sit inside the disc, so we see stars piled up in every direction along the plane. William Herschel's careful star counts in 1785 produced a map that put the Sun near the middle of a small flattened system — a reasonable inference from the data, and wrong.

The second, and the reason Herschel was wrong, is **dust**. The galactic plane is full of it, and it absorbs visible light so effectively that in the direction of the galactic centre we can see only a few thousand light-years before the view closes off entirely. Herschel found himself apparently at the centre of a small universe because he could see the same short distance in every direction along the plane.

The resolution came from ignoring the plane. Harlow Shapley studied **globular clusters** — dense balls of hundreds of thousands of ancient stars, which sit in a halo well above and below the dust. In 1918 he used variable stars to measure their distances and found they were not centred on the Sun at all, but on a point tens of thousands of light-years away in Sagittarius. That point is the centre of the galaxy, and it is where the black hole in Chapter 24 lives. Shapley's number was too large by about a factor of two, but he had moved humanity out of the centre of the galaxy — a second Copernican demotion.

Modern maps use light dust cannot stop. Radio waves from neutral hydrogen at 21 cm pass straight through it, which is how the spiral structure was first traced in the 1950s. Infrared does the same, which is how the central bar was confirmed. And since 2013 the **Gaia** satellite has measured precise positions, distances and motions for nearly two billion stars, turning the galaxy from a picture into a dataset.

CASE FILE · THE GREAT DEBATE, 26 APRIL 1920

The Smithsonian Museum of Natural History hosted a formal debate between Harlow Shapley and Heber Curtis on "The Scale of the Universe". The question was whether the spiral nebulae — fuzzy pinwheels visible in telescopes — were gas clouds inside our galaxy, or entire separate galaxies far outside it.

Shapley argued for one galaxy. His Milky Way was enormous, some 300,000 light-years across, and the spirals were features within it. Curtis argued the Milky Way was small, perhaps 30,000 light-years, and the spirals were "island universes" — galaxies in their own right, comparable to ours.

The outcome is a good lesson in how science actually resolves: **each man was half right**. Shapley was correct that the Milky Way is large and that the Sun is not at its centre. Curtis was correct that the spirals are separate galaxies. Both had good arguments and both had bad data — Shapley leaned on a colleague's measurement of rotation in a spiral that later proved simply wrong.

The question was settled four years later by Edwin Hubble, using the new 100-inch telescope at Mount Wilson to find a Cepheid variable in Andromeda and measure its distance: far beyond any plausible boundary of our galaxy. Chapter 23 tells that story.

DO THE MATH · 22.1

Weigh the galaxy from the Sun's orbit. For a roughly circular orbit, the mass enclosed inside that orbit is

$$M = \frac{v^2 r}{G}$$

Take v = 230 km/s and r = 26,000 ly. You will need to convert: 1 ly = 9.46×10^{15} m.

- Find the mass enclosed within the Sun's orbit, in kg and in solar masses.
- Compute the orbital period and check it against the quoted 230 million years.
- The visible stars inside that radius total roughly 5×10^{10} solar masses. Compare with your answer. What is the discrepancy?

That discrepancy is not an error in your arithmetic. It is dark matter, and you have just performed, in outline, the measurement that revealed it.

TRY THIS · FIND THE CENTRE OF THE GALAXY

On a clear moonless night away from city lights, between about May and September in India, look south. The Milky Way rises as a hazy band, and if you follow it down towards the southern horizon you reach the constellation **Sagittarius** — often described as looking like a teapot.

Just above the spout of the teapot, the Milky Way is at its brightest and densest. You are looking directly towards the **centre of the galaxy**: 26,000 light-years away, hidden behind dust, containing a black hole of 4.3 million solar masses.

You will not see it — the dust dims it by a factor of about 10^{12} in visible light. But you are pointed at it, and the direction alone is worth knowing. The dark patches splitting the band are not gaps between stars; they are dust clouds in the foreground, blocking the light of everything behind.

GET THIS STRAIGHT

"The spiral arms are made of a fixed set of stars, like the arms of a pinwheel." If that were true the arms would wind themselves up tight within a few rotations, because inner material orbits faster than outer material. The galaxy has completed twenty rotations, and the arms are still open. This is called the winding problem.

The leading explanation is **density wave theory**: the arms are waves of enhanced density that move through the disc, not fixed structures. Stars drift into an arm, are slowed and compressed, and drift out again — much as cars bunch up behind a slow lorry on a highway. The traffic jam persists and moves; the individual cars pass through it.

Arms are bright not because they hold more stars but because the compression triggers star formation, and the resulting hot blue stars are enormously luminous and very short-lived — so they light up the arm and die before leaving it.

The objects that found the centre of the galaxy

A globular cluster: hundreds of thousands of stars bound into a sphere a few dozen light-years across, orbiting in the halo well above the dust of the disc. Because they sit outside the obscuring plane, Harlow Shapley could measure their distances in 1918 — and found them centred not on the Sun but on a point 26,000 light-years away in Sagittarius.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- The Milky Way is a **barred spiral**, ~100,000 ly across, ~1,000 ly thick, with 100–400 billion stars.
- The Sun is **26,000 ly** from the centre and orbits every **230 million years** at 230 km/s.
- Dust blocks the view along the plane, which misled Herschel into placing us at the centre.
- **Shapley** used globular clusters above the dust to find the true centre in Sagittarius in 1918.
- The **Great Debate** of 1920 was settled by Hubble in 1924: the spirals are other galaxies.
- Spiral arms are **density waves**, not fixed structures — otherwise they would have wound up long ago.
- Weighing the galaxy from the Sun's orbit gives far more mass than the visible stars account for.

CHAPTER 23 · GALAXIES AND STRUCTURE

Galaxy Types and Galactic Collisions

> There are around two trillion galaxies in the observable universe, they come in a handful of shapes, and a great many of them are the wreckage of earlier collisions — including, in four and a half billion years, ours.

Until 1924 the word "galaxy" had no plural. The Milky Way was understood to be the universe, and the spiral nebulae were assumed to be clouds within it. Then Edwin Hubble found a single variable star in Andromeda, and the universe acquired a population.

CASE FILE · THE NIGHT THE UNIVERSE GOT BIGGER

In October 1923, Hubble photographed the Andromeda Nebula with the 100-inch Hooker telescope at Mount Wilson, then the largest in the world. He identified what he took to be a nova and marked the plate "N". Comparing with earlier plates, he realised it brightened and faded on a regular cycle. It was not a nova but a **Cepheid variable**.

Cepheids obey a relation discovered by Henrietta Swan Leavitt in 1912: the period of pulsation determines the true luminosity. Measure the period, and you know how bright the star really is; compare with how bright it looks, and you have the distance. Hubble crossed out the "N", wrote "VAR!" on the plate, and calculated a distance of roughly 900,000 light-years — far outside any possible boundary of the Milky Way. (The modern figure is 2.5 million.)

He wrote to Shapley with the result. Shapley, who had argued for a single-galaxy universe in the Great Debate, read the letter and said to a colleague: "Here is the letter that destroyed my universe."

It is worth noticing whose work made this possible. Leavitt was employed at Harvard as a "computer", paid 30 cents an hour to examine photographic plates, and was not permitted to direct her own research. Her period–luminosity relation is the foundation of the entire cosmic distance ladder. She died of cancer in 1921, four years before Hubble's result, and was never given a professorship.

The tuning fork

Hubble sorted galaxies by appearance in 1926, and the scheme he drew — the **tuning fork diagram** — is still the standard vocabulary.

HUBBLE'S TUNING FORK

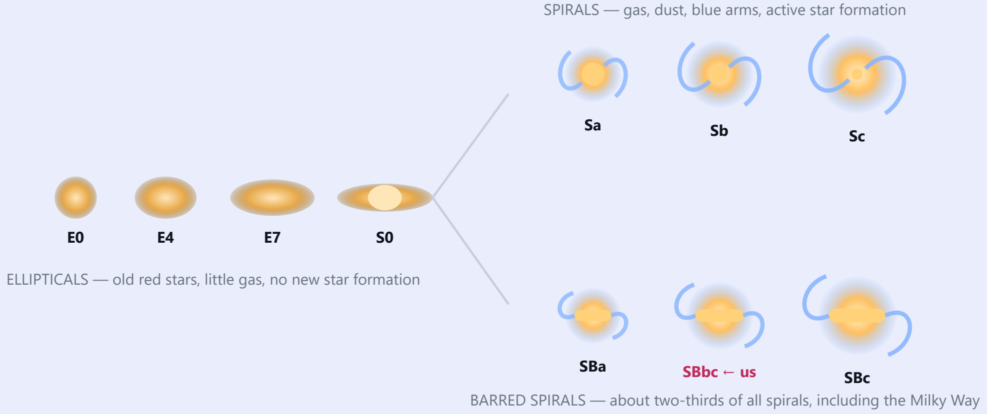


Figure 23.1 — The classification everyone still uses. Hubble called ellipticals "early type" and spirals "late type", believing galaxies evolved left to right. That is wrong — but the terminology survives and still confuses students a century later.

What the tuning fork leaves out is that most galaxies are none of these. **Dwarf galaxies** — irregular blobs with a few million to a few billion stars — outnumber everything else by a wide margin. The Milky Way alone has more than sixty known satellites. They are simply too faint to have been noticed when the classification was drawn up.

Galaxies collide, and it is not violent

Galaxy separations are typically only a few dozen galaxy-diameters — very close, by the standards of Chapter 1, where stars were separated by millions of stellar diameters. Galaxies therefore interact often, and the universe is full of wreckage.

Here is the counterintuitive part. When two galaxies collide, **essentially no stars hit each other**. Recall the cricket-ball model: stars are grains of sand separated by thousands of kilometres. Run two such swarms through one another and the probability of any individual collision is negligible.

What does collide is the **gas**. Gas clouds fill space rather than being points, so they slam into each other, compress violently, and trigger enormous bursts of star formation — a **starburst**. And gravity reshapes everything: tidal forces pull out long streamers of stars, orbits are scrambled, and the ordered rotation of two discs is converted into the random motions of a single elliptical.

This is the current best answer to where ellipticals come from. They are not an early stage of galaxy evolution; they are the **end product of mergers**, which explains why they are common in dense clusters and rare in empty regions.

CASE FILE · ANDROMEDA IS COMING

Almost every galaxy is receding from us. Andromeda is not. It is approaching at about **110 km/s**, because at 2.5 million light-years it is close enough that the Local Group's mutual gravity beats cosmic expansion.

The collision will begin in roughly **4.5 billion years**. Gaia's measurements of Andromeda's sideways motion suggest a closer, more head-on encounter than once thought. The two galaxies will pass through each other, be pulled back, pass again, and after perhaps a billion years of thrashing settle into a single large elliptical galaxy — informally called Milkomeda.

From the surface of the Earth, if anything were there to watch, it would be spectacular and entirely harmless. Andromeda would swell across the whole night sky over hundreds of millions of years. Star formation would flare. The Sun — if it still existed, which is doubtful, since this coincides with its red giant phase — would most likely be flung into a wider orbit, or ejected from the merged galaxy altogether.

The chance of the Solar System being struck by another star during all of this is close to zero.

DO THE MATH · 23.1

Why stars miss each other. Estimate the chance of a stellar collision when two galaxies pass through one another.

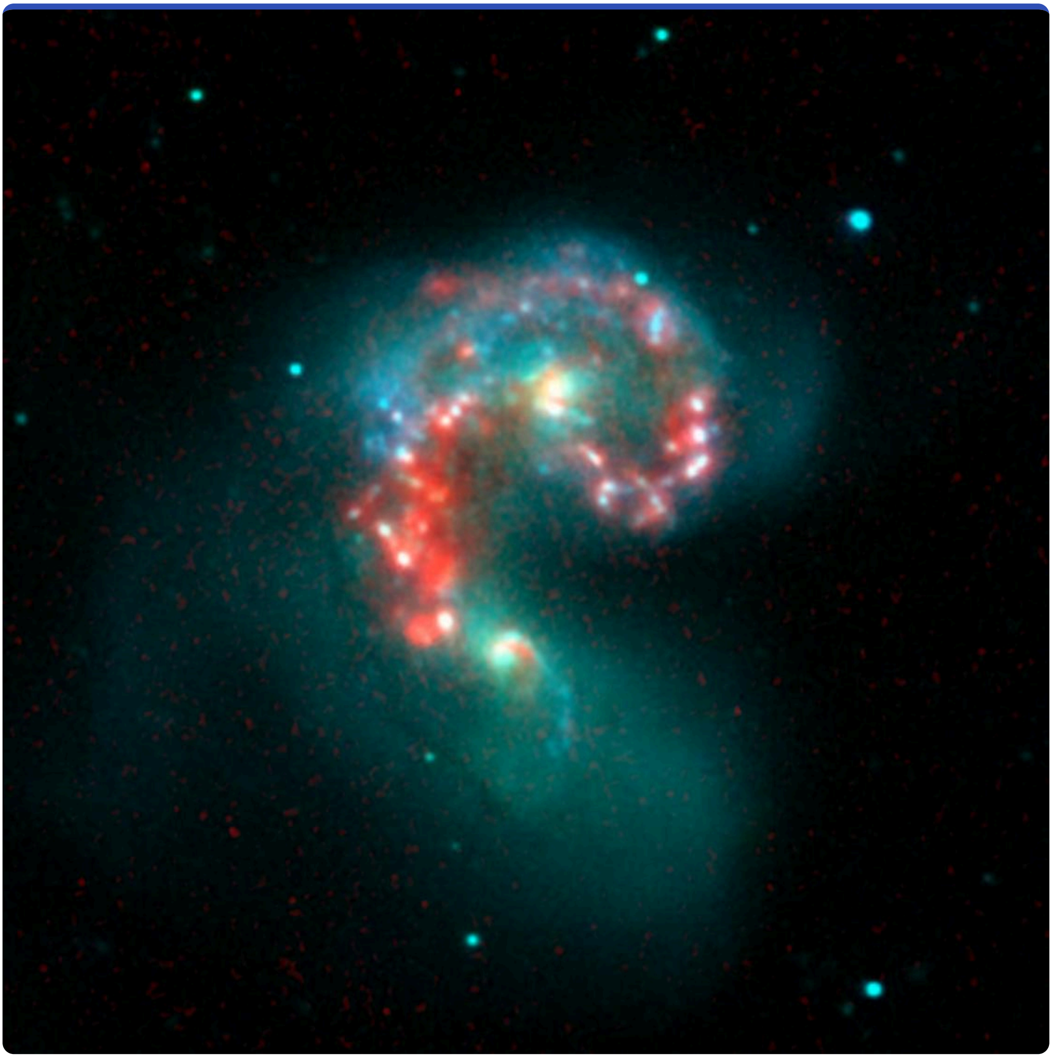
- The Sun's radius is 7×10^8 m. Its cross-sectional area for a direct hit (allowing a factor of 2 for gravitational focusing) is about $4\pi R^2 \approx 6 \times 10^{18}$ m^2.
- Typical stellar density in a galactic disc is about 0.1 stars per cubic parsec. Convert to stars per m^3 (1 pc = 3.086×10^{16} m).
- Crossing a galaxy means travelling about 30 kpc. The expected number of collisions is roughly (area) × (number density) × (path length). Compute it.

Your answer should be an extremely small number. Then contrast: gas clouds are around 10 pc across rather than 10^9 m. Redo the estimate with that radius and see how the conclusion flips completely.

GET THIS STRAIGHT

"Galaxies evolve along the tuning fork, from elliptical to spiral." Hubble thought so, and his terms "early-type" and "late-type" have misled students ever since. The sequence is a **classification of shape, not a timeline**.

If anything, the arrow points the other way. Spirals merge to become ellipticals, not the reverse. An elliptical galaxy has typically exhausted or lost its gas and stopped forming stars — which is why it is red, made of old cool stars, and often described as "red and dead".



The Antennae Galaxies. Two spirals roughly 45 million light-years away, part-way through a collision that began a few hundred million years ago. The bright knots are starbursts — regions where colliding gas clouds have been compressed hard enough to trigger star formation on an enormous scale. Almost no individual stars have hit each other.

Credit: NASA/JPL-Caltech/Harvard-Smithsonian CfA/NOAO/AURA. NASA — free to use with credit.

A spiral, and the small galaxy tearing at it

M51, the Whirlpool Galaxy, about 27 million light-years away. The companion at the top is not a coincidence of perspective — it is interacting with the larger galaxy, and the gravitational disturbance is a large part of why the spiral arms are so sharply defined. The blue in the arms is hot young stars; the arms are bright because of star formation, not because more stars live there.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- **Hubble, 1924**: a Cepheid in Andromeda proved other galaxies exist. The method was **Henrietta Leavitt's**.
- Roughly **two trillion galaxies** in the observable universe.
- The **tuning fork** sorts them into ellipticals, spirals and barred spirals. It is **not** an evolutionary sequence.
- **Dwarf galaxies are the most numerous** type and are missing from the diagram entirely.
- In galaxy collisions, **stars essentially never hit** — but gas clouds do, triggering starbursts.
- Mergers of spirals produce **ellipticals**.
- **Andromeda arrives in 4.5 billion years.** Nothing will hit the Earth.

Quasars and the Monsters at the Centre

> An object smaller than the Solar System, outshining a galaxy of a hundred billion stars, powered by matter falling into a hole. For thirty years nobody could work out what they were.

In the late 1950s radio surveys began finding strong sources that, when matched to optical images, looked like ordinary faint stars. Their spectra made no sense — broad emission lines at wavelengths matching no known element. They were labelled quasi-stellar radio sources, shortened to **quasars**, and filed under unexplained.

CASE FILE · MAARTEN SCHMIDT, FEBRUARY 1963

Schmidt was at Caltech, staring at the spectrum of the radio source **3C 273**. He had been at it for weeks. The lines were strong, clean and unidentifiable.

Then he tried something almost too simple. What if they were the perfectly ordinary hydrogen Balmer lines — but shifted a very long way to the red? The pattern fitted immediately, at a redshift of $z = 0.158$. The object was receding at 16 per cent of the speed of light, which by Hubble's law put it about 2.4 billion light-years away.

That created a far worse problem than the one it solved. To appear as bright as it does from that distance, 3C 273 must be emitting roughly **four trillion times the Sun's luminosity** — around 100 times the entire Milky Way. And its brightness varied noticeably over weeks, which caps its size: nothing can vary coherently faster than light can cross it, so the emitting region had to be smaller than a few light-weeks. About the size of the Solar System.

A hundred galaxies' worth of light, from a volume smaller than the orbit of Neptune. No known process could do it. Nuclear fusion converts 0.7 per cent of mass to energy (Chapter 15), and even at 100 per cent efficiency the numbers did not work.

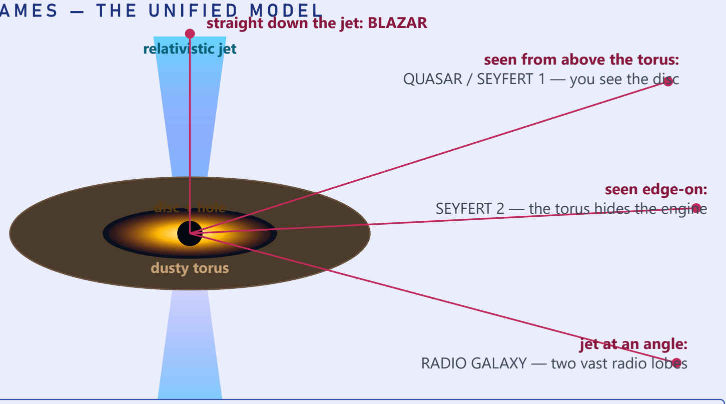
The answer: gravity as a power source

The mechanism, proposed by Salpeter and Zeldovich in 1964 and now beyond doubt, is **accretion onto a supermassive black hole**.

Gas spiralling towards a black hole forms a disc. Friction and magnetic turbulence heat it to millions of kelvin, and it radiates furiously before crossing the horizon. The efficiency is extraordinary: infalling matter converts **6 to 42 per cent** of its rest mass into radiation, depending on how fast the hole spins — against fusion's 0.7 per cent. **Accretion onto a black hole is the most efficient energy source in the universe**, roughly fifty times better than the process that powers stars.

A quasar needs to swallow only a few solar masses of gas per year to outshine a galaxy.

ONE OBJECT, FIVE NAMES — THE UNIFIED MODEL



The unified model: these are not different objects. They are the same object seen from different directions.

Figure 24.1 — Why the zoo turned out to be one animal. Quasars, Seyferts, radio galaxies and blazars are active galactic nuclei viewed at different angles relative to the obscuring torus and the jets.

The one in our own galaxy

Sagittarius A* is a compact radio source at the centre of the Milky Way. Proving it is a black hole required watching stars orbit it — for decades.

Two teams did this independently: Reinhard Genzel's group in Germany using the Very Large Telescope, and Andrea Ghez's group at UCLA using Keck. Both tracked individual stars in the central cluster through the dust, in the infrared, using adaptive optics to defeat atmospheric blurring.

The prize object is a star called **S2**, which orbits the centre every 16 years on a highly elliptical path, reaching 7,650 km/s at closest approach — about 2.5 per cent of the speed of light. Both teams followed it through a complete orbit. Applying Kepler's third law gives the enclosed mass: **4.3 million solar masses**, inside a region smaller than the orbit of Mercury.

Nothing else can be that dense. Genzel and Ghez shared the 2020 Nobel Prize with Roger Penrose. In 2018 the same observations detected the gravitational redshift of S2's light at closest approach, exactly as general relativity predicts — a further test passed.

Black holes and galaxies grew up together

In the 1990s astronomers noticed something that should not have been true. The mass of a galaxy's central black hole is tightly correlated with the velocity dispersion of stars in its bulge — the **M–σ relation**. Black hole mass is typically about 0.1 per cent of bulge mass, and the scatter is remarkably small.

This is strange, because the black hole's gravity is utterly negligible at the scale of the bulge. Sagittarius A* is a millionth of the galaxy's mass, and its influence extends only a few light-years out of 50,000. It has no business knowing how big the galaxy is.

The explanation is **feedback**. When the black hole feeds, it radiates so violently that it heats and expels the surrounding gas — shutting down both its own food supply and the galaxy's star formation. The black hole regulates the galaxy, and the galaxy regulates the black hole. Getting this feedback right is now one of the central problems in galaxy formation, and it is the main reason simulations and observations still disagree.

DO THE MATH · 24.1

Weigh Sagittarius A* the way Ghez and Genzel did. For an orbiting body,

$$M = \frac{4\pi^2 a^3}{G T^2}$$

S2 has a semi-major axis a = 970 AU and a period T = 16.05 years. Convert to metres and seconds (1 AU = 1.496×10^{11} m; 1 yr = 3.156×10^{7} s).

- Compute M in kg, then in solar masses. You should land near 4×10^{6}.
- Using $R_s = 2GM/c^2$ from Chapter 20, find its Schwarzschild radius in km, and in AU.
- S2's closest approach is 120 AU. How many Schwarzschild radii is that?

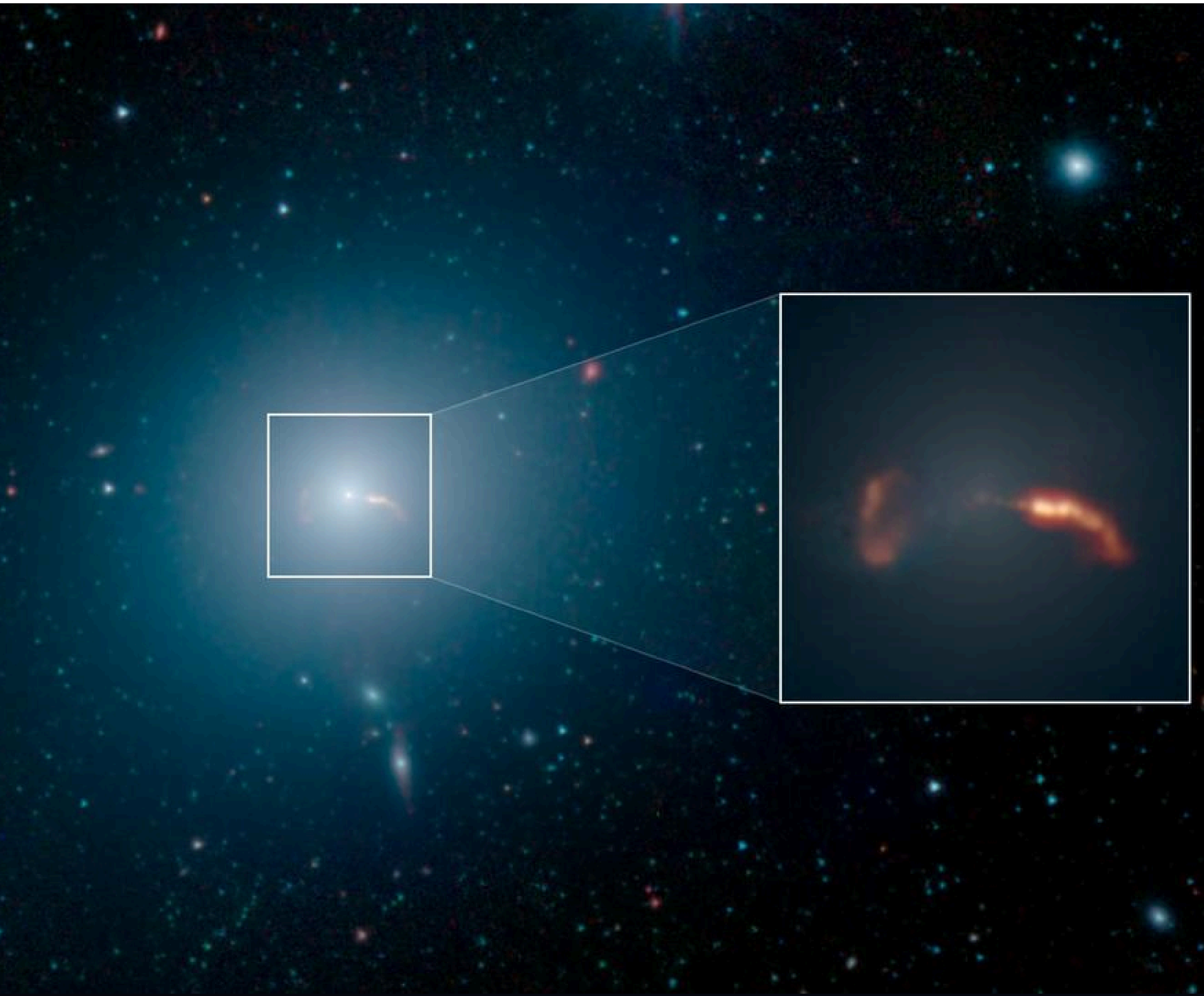
Then the argument that clinches it. Compute the average density if 4.3 million solar masses were spread evenly through a sphere of radius 120 AU. Compare with a star cluster, which cannot exceed about 10^{8} solar masses per cubic parsec before it collapses. What does that rule out?

GET THIS STRAIGHT

"Quasars are exploding galaxies" — or "quasars no longer exist." Both are common, and both are wrong in an interesting way.

Quasars are not explosions; they are steady accretion, running for tens of millions of years. And they have not vanished — but they are overwhelmingly found at high redshift, meaning they were common when the universe was two to three billion years old and are rare now.

The reason is fuel. Early galaxies were gas-rich and merging constantly, which funnelled material into their centres. Today's galaxies are settled and comparatively dry, so most supermassive black holes are dormant — including ours, which accretes so little that its luminosity is around a hundred-millionth of what it could manage. The quasars are not gone. They have run out of food.



A jet five thousand light-years long

Messier 87, the same galaxy whose black hole appears in Chapter 21. The straight beam is a relativistic jet launched from the accretion disc and travelling at close to the speed of light — visible here across roughly 5,000 light-years. It has been observed since 1918, long before anybody could explain what could possibly produce it.

Credit: NASA/JPL-Caltech/IPAC/Event Horizon Telescope Collaboration. NASA — free to use with credit.

IN A HURRY?

- **Quasars** outshine entire galaxies from a region smaller than the Solar System. **Schmidt cracked 3C 273 in 1963** by recognising redshifted hydrogen lines.
- The engine is **accretion onto a supermassive black hole** — 6–42% efficient, against fusion's 0.7%.
- Quasars, Seyferts, radio galaxies and blazars are **one object seen from different angles**.
- **Sagittarius A*** is 4.3 million solar masses, proven by tracking the star **S2** through a full 16-year orbit. Nobel Prize 2020.
- The **M–σ relation** ties black hole mass to the host galaxy, implying **feedback** between the two.
- Quasars were common in the young universe and are rare now — the fuel ran out.

CHAPTER 25 · GALAXIES AND STRUCTURE

The Cosmic Web

> Zoom out past galaxies and clusters and a pattern appears that nobody predicted and everybody now takes for granted: matter is arranged in filaments and sheets around enormous empty bubbles.

Galaxies are not scattered at random. They are grouped, and the groups are grouped, in a hierarchy that runs all the way up until it stops — and where exactly it stops is one of the more interesting questions in cosmology.

Your full address

WHERE YOU LIVE, FROM THE BOTTOM UP

Structure	Size	Members	Note
The Solar System	~100 AU	1 star	Chapter 29
The Orion Spur	3,500 ly	millions	a minor branch, not a real arm
The Milky Way	100,000 ly	10^{11}–4×10^{11} stars	Chapter 22
The Local Group	10 million ly	~80 galaxies	dominated by us and Andromeda
The Virgo Cluster	50 million ly	~1,300 galaxies	we are falling towards it
The Virgo Supercluster	110 million ly	~100 groups	once thought to be the top level
Laniakea	520 million ly	~100,000 galaxies	defined in 2014 by galaxy flows
Filaments and voids	billions of ly	everything	the largest pattern that exists

The last two rows deserve explanation. In 2014 a team led by Brent Tully proposed a new way of defining superclusters: instead of counting galaxies in a region, map their **velocities** and find the watershed — the boundary within which everything is flowing towards a common point. By that definition our home supercluster is far larger than previously thought, and they named it **Laniakea**, Hawaiian for "immeasurable heaven". We are on its outskirts, drifting towards a gravitational focus called the Great Attractor.

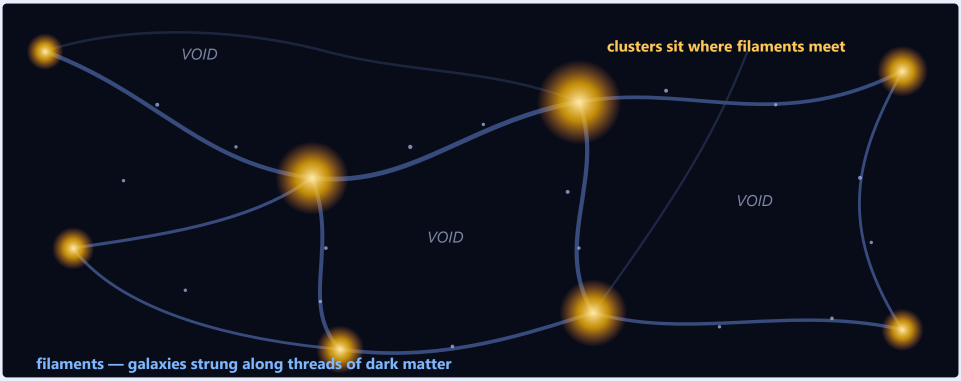
Bubbles and walls

In 1989 Margaret Geller and John Huchra published the first substantial three-dimensional map of galaxies. They had measured redshifts for a thin slice of sky, converted them to distances, and plotted the result. What appeared was not a scatter of dots but a structure that Geller described as looking like **soap bubbles** — galaxies concentrated on thin sheets and filaments surrounding vast empty regions.

One feature in their map stretched across 500 million light-years and became known as the CfA Great Wall. Later surveys found bigger ones. The Sloan Great Wall runs about 1.4 billion light-years.

The empty regions are as remarkable as the walls. The **Boötes Void** is roughly 330 million light-years across and contains around 60 galaxies where a typical volume that size would hold about 2,000. If the Milky Way were at its centre, we would not have known other galaxies existed until the 1960s.

THE COSMIC WEB



Roughly 80% of the volume of the universe is void. Almost all the matter is in the threads.
This pattern grew, over 13.8 billion years, from the one-part-in-100,000 lumps of Figure 12.1.

Figure 25.1 — The largest structure there is. Matter collects along filaments; clusters form where filaments intersect; the space between is close to empty. Simulations reproduce this pattern in detail — but only if dark matter is included.

Why simulations matter here

You cannot experiment on the universe. What you can do is simulate one: start with the measured fluctuations from the microwave background, apply gravity, and let it run for 13.8 billion years of model time.

Projects like the Millennium Simulation and IllustrisTNG do exactly this, following billions of particles on supercomputers for months. The output is compared statistically with real galaxy surveys — filament lengths, void sizes, cluster counts, correlation functions.

The agreement is excellent, and it is one of the strongest arguments for the standard cosmological model. But it comes with a condition: **the simulations only work if about 85 per cent of the matter is dark**. Run them with ordinary matter alone and structure grows far too slowly, because ordinary matter could not begin clumping until 380,000 years after the Big Bang, whereas dark matter — being blind to radiation — had a head start. Without dark matter, the universe would still be a smooth soup. Part VI is next for a reason.

CASE FILE · A RULER FROZEN INTO THE SKY

The sound waves in the early universe from Chapter 12 did not only leave marks on the microwave background. They left a mark on the distribution of galaxies too.

Before recombination, a pressure wave from each initial density peak travelled outward at over half the speed of light. When the universe became neutral at 380,000 years, the pressure vanished and the wave stopped, leaving a spherical shell of slightly enhanced density at a fixed radius around each original peak. Galaxies formed preferentially both at the centre and on that shell.

The result is a faint but real excess of galaxy pairs separated by about **490 million light-years** — a preferred distance stamped into the universe. This is the **baryon acoustic oscillation** scale, and because its physical size is calculable from first principles, it works as a **standard ruler**: measure how large it appears at various redshifts and you map the expansion history directly.

It was detected in 2005 by the Sloan Digital Sky Survey and the 2dF survey, working independently. It is now one of the primary tools for studying dark energy, and it is the main purpose of the DESI instrument, whose 2024 and 2025 results have hinted — not yet conclusively — that dark energy may not be constant after all. Chapter 27.

DO THE MATH · 25.1

How empty is empty? The Boötes Void is about 330 million light-years across and contains roughly 60 galaxies.

- Treating it as a sphere, find its volume in cubic megaparsecs. (1 Mpc = 3.26 million ly.)
- Bright galaxies average roughly **0.004** per cubic megaparsec. How many *should* a volume that size contain?
- What fraction of the expected number is actually there?

Then a perspective question worth answering in a sentence: if the Milky Way sat at the centre of the Boötes Void, the nearest galaxy would be over 100 million light-years away. What would that have meant for the Great Debate of 1920, and for the discovery of cosmic expansion?

GET THIS STRAIGHT

"The universe has a centre, and the cosmic web is arranged around it." No. The web looks statistically the same everywhere on scales above about a billion light-years — a property called **homogeneity** — and the same in every direction, called **isotropy**. Together these make up the cosmological principle, and they are tested rather than assumed.

This is why claims about "the largest structure in the universe" should be treated carefully. Several announced record-holders, such as the Hercules–Corona Borealis Great Wall, are large enough to be in tension with homogeneity, and there is an active argument about whether they are genuine structures or statistical artefacts of how clumps get linked together. It is not settled.

IN A HURRY?

- Structure is hierarchical: **galaxies → groups → clusters → superclusters → filaments and voids**.
- We are in the Local Group, inside **Laniakea** — 520 million light-years across, defined in 2014 by galaxy flows.
- Matter forms **filaments and sheets around vast voids**. About 80% of the volume is nearly empty.
- Simulations reproduce the web accurately — **but only with dark matter included**.
- **Baryon acoustic oscillations** leave a preferred galaxy separation of ~490 million ly, used as a standard ruler for measuring expansion.
- Above about a billion light-years the universe is **homogeneous and isotropic**. There is no centre.

VI

The Dark Sector

Everything in the previous five parts — every star, planet, atom and person — is under five per cent of the universe. This part is about the other ninety-five.

CHAPTER 26 · THE DARK SECTOR

Dark Matter: The Missing Mass

> Five times more matter exists than we can see. We know where it is, how much there is, and how it moves. We have no idea what it is made of, and every attempt to catch a piece has failed.

This is an uncomfortable chapter to write, because the honest summary is that the evidence is overwhelming and the explanation is absent. Dark matter is not a fudge factor invented to patch one anomaly. It is the single hypothesis that simultaneously resolves six independent observations, made with different instruments at wildly different scales — and it has resisted eighty years of attempts to find out what it is.

The observation that made it undeniable

Fritz Zwicky noticed the problem first, in 1933, studying the Coma cluster. The galaxies in it were moving far too fast for the visible mass to hold them together — the cluster should have dispersed long ago. He coined the term *dunkle Materie*. Zwicky was abrasive, frequently wrong about other things, and largely ignored for forty years.

The result that could not be ignored came from **Vera Rubin** and Kent Ford in the 1970s. They measured how fast stars orbit at different distances from the centres of spiral galaxies — the **rotation curve** — using Doppler shifts of the kind in Chapter 8.

The prediction was simple. Most of a galaxy's visible light is concentrated in the middle, so beyond the bright region orbital speeds should fall off as $1/\sqrt{r}$, exactly as the planets do in the Solar System. Neptune orbits far more slowly than Mercury, and stars in the outskirts of a galaxy should do the same.

They do not. The curves go **flat**. Stars at the visible edge of a galaxy orbit as fast as stars well inside it, and this holds for essentially every spiral galaxy ever measured.

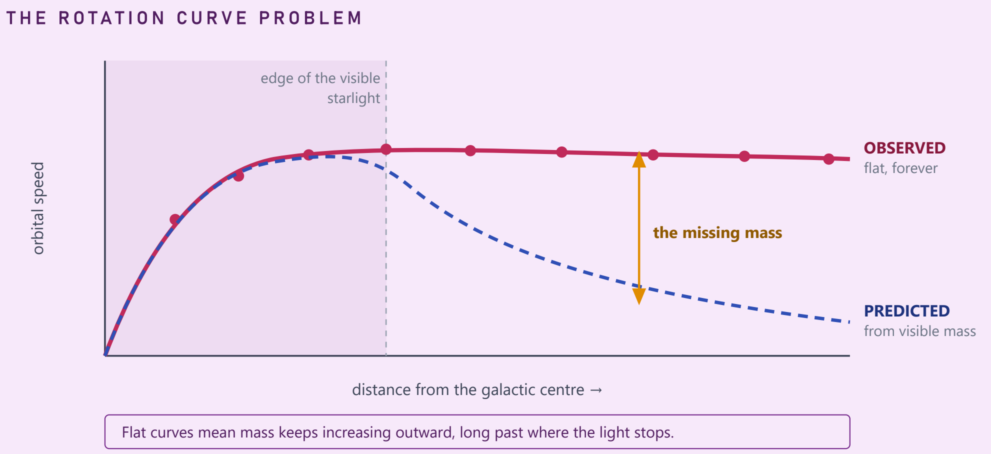


Figure 26.1 — What Vera Rubin found. If the visible stars were all the mass there is, orbital speeds would fall off beyond the bright region. Instead they stay constant far out into the dark — which requires a halo of unseen mass extending well beyond the galaxy.

Flat rotation curves imply that the mass enclosed keeps growing in proportion to radius, far beyond where the starlight fades. Galaxies are embedded in enormous roughly spherical **haloes** of invisible material, typically five to six times the mass of everything visible.

Six independent lines of evidence

Rotation curves alone could conceivably be explained by modifying gravity. What makes dark matter compelling is that five other measurements, using entirely different physics, demand the same amount of extra mass.

1 · **Rotation curves** — galaxies spin too fast at their edges.

2 · **Cluster dynamics** — Zwicky's original observation, now measured for hundreds of clusters.

3 · **Gravitational lensing** — the light-bending of Chapter 5 measures total mass directly, without any assumption about motion or equilibrium. It gives the same answer.

4 · **The microwave background** — the third acoustic peak of Figure 12.1 is sensitive to matter that does *not* interact with radiation. Its height gives 26.8 per cent dark matter, entirely independently of any galaxy observation.

5 · Structure formation — as Chapter 25 explained, the cosmic web cannot grow fast enough without matter that started clumping before recombination.

6 · Big Bang nucleosynthesis — the observed abundances of deuterium and helium fix the total amount of *ordinary* matter at about 5 per cent of the critical density. The dark matter therefore cannot be ordinary matter hiding somewhere. It is not cold gas, dead stars or rogue planets.

CASE FILE · THE BULLET CLUSTER

The most direct evidence comes from a cosmic accident 3.8 billion light-years away. 1E 0657-558 is two galaxy clusters that collided at about 4,500 km/s and passed through each other roughly 150 million years ago.

Recall Chapter 23: in such a collision the galaxies pass through untouched, but the hot gas — which is where most of the *ordinary* mass lives — slams together, heats up, and is left stranded in the middle.

The Chandra X-ray Observatory mapped the hot gas: as expected, it sits in the centre, shocked and glowing. Then astronomers mapped the **total mass** using gravitational lensing of background galaxies. If the ordinary gas were all the mass, the two maps should coincide.

They do not. The lensing mass is in **two clumps, well ahead of the gas**, travelling with the galaxies — exactly as expected if most of the mass is collisionless material that passed straight through the collision, like the galaxies and unlike the gas.

This is a serious problem for modified-gravity alternatives such as MOND, which propose changing the law of gravity instead of adding mass. In the Bullet Cluster the gravity is demonstrably **not where the visible matter is**. Modifying how mass attracts cannot move the attraction somewhere else. Some hybrid theories survive, but the simple versions do not.

What it might be, and eighty years of not finding it

The constraints are tight. Dark matter must have mass, must not interact electromagnetically (or it would shine), must barely interact with itself or with ordinary matter, must be stable over 13.8 billion years, and must have been moving slowly in the early universe — "cold" — or structure would not have formed correctly.

WIMPs — weakly interacting massive particles — were the favoured candidate for three decades, partly because supersymmetry predicted suitable particles and partly because a particle at the weak-interaction scale naturally produces the right abundance, a coincidence called the WIMP miracle. Enormous detectors were built deep underground to catch one: XENONnT, LUX-ZEPLIN, PandaX. Each generation has improved sensitivity by orders of magnitude. **None has detected anything.** The available parameter space is now largely excluded, and the field's confidence in WIMPs has fallen sharply.

Axions are now the leading alternative — very light particles originally proposed to solve an unrelated problem in the strong nuclear force. Experiments such as ADMX try to convert them into microwave photons in a strong magnetic field. **Sterile neutrinos** and **primordial black holes** remain possible; the latter are increasingly constrained by lensing and by LIGO.

It is worth stating plainly: **this is one of the great unsolved problems in physics**, it has resisted enormous effort and expenditure, and it may well be solved by somebody currently in school.

DO THE MATH · 26.1

Measure the dark matter in your own galaxy. In Chapter 22 you found the mass inside the Sun's orbit. Extend it.

- The Milky Way's rotation curve stays near 220 km/s out to at least 60,000 ly. Using $M = v^2r/G$, find the mass enclosed at that radius.
- Compare with the mass at 26,000 ly. By what factor did the mass grow while the starlight was fading to nothing?
- If the orbital speed is constant, show that $M \propto r$ — mass increases in direct proportion to radius.
- For a spherical halo, that implies density falls as $1/r^2$. Verify this using $M = (4/3)\pi r^3\rho$.

You have just derived the density profile of a dark matter halo from a single observational fact.

GET THIS STRAIGHT

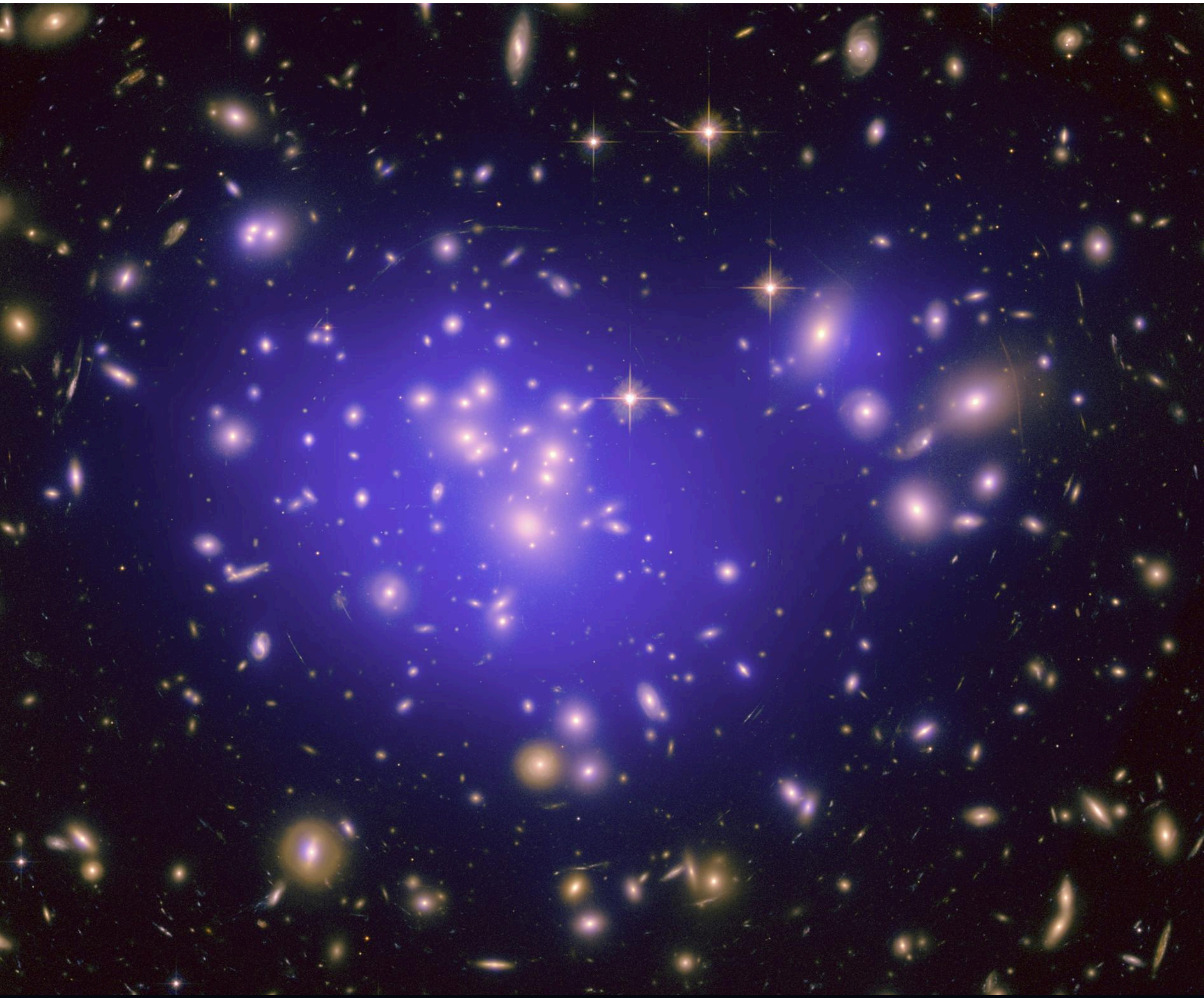
"Dark matter is just a name for our ignorance — scientists made it up to fix their equations." The complaint has a fair core and a wrong conclusion.

The fair core: yes, dark matter is currently defined by what it does rather than what it is, and that is unsatisfying. The wrong conclusion: it is not unfalsifiable hand-waving. Dark matter makes **specific quantitative predictions** — the height of the third CMB peak, the growth rate of structure, the lensing map of the Bullet Cluster — which were made in advance and confirmed.

Compare with Le Verrier in Chapter 4. He inferred an unseen mass from anomalous motion and found Neptune. He also inferred the planet Vulcan from Mercury's anomaly, and that turned out to require new physics instead. Either outcome is possible here. What is not reasonable is pretending the anomaly is not there.

The Sombrero Galaxy, M104. The bulge is swarming with old stars on randomly-oriented orbits and is surrounded by an unusually rich system of globular clusters. Galaxies like this were among the first where the orbital speeds of the outer material refused to match the visible mass.

Credit: NASA/JPL-Caltech. NASA — free to use with credit.



Mass you cannot see, bending light you can

The galaxy cluster Abell 1689. The thin arcs scattered around the centre are not features of the cluster — they are **distorted images of galaxies far behind it**, smeared by the cluster's gravity acting as a lens. Measuring the distortion weighs the cluster, including everything invisible. The answer comes out roughly five times the mass of everything that shines.

Credit: GSFC. NASA — free to use with credit.

IN A HURRY?

- Galaxy **rotation curves are flat** instead of falling — first mapped by **Vera Rubin** in the 1970s.
- **Six independent lines of evidence** agree: rotation curves, clusters, lensing, the CMB, structure formation and nucleosynthesis.
- Nucleosynthesis proves it is **not ordinary matter** hiding.
- The **Bullet Cluster** shows mass separated from visible matter — very hard for modified-gravity theories.
- Dark matter is **26.8%** of the universe; ordinary matter is 4.9%.
- WIMP searches have found **nothing** after decades. Axions are now the leading candidate.
- Nobody knows what it is. This is a genuinely open problem.

CHAPTER 27 · THE DARK SECTOR

Dark Energy and the Runaway Universe

> Two rival teams set out in the 1990s to measure how fast cosmic expansion was slowing down. Both found it was speeding up. Neither believed their own result for months.

In 1929 Edwin Hubble published the observation that gives the subject its shape: distant galaxies are receding, and the further away a galaxy is, the faster it recedes. The relationship is linear —

HUBBLE'S LAW

$$v = H_0 \cdot d$$

v = recession velocity · d = distance

$H_0 \approx 67$ to 73 km/s per megaparsec

Every galaxy sees the same thing, which is the signature not of galaxies flying apart through space but of **space itself expanding**. The standard analogy is raisins in rising bread dough: every raisin sees every other raisin receding, and the distant ones recede fastest, because there is more dough in between. No raisin is at the centre.

One consequence deserves attention. Beyond about 14.5 billion light-years, the recession velocity implied by Hubble's law exceeds the speed of light. This breaks no rule, for the reason given in Chapter 11: nothing is *moving* through space faster than light. The space between is growing.

1998: the year everyone was wrong in the same direction

Gravity is attractive, so the expansion should be slowing. The only question was by how much — and the answer would decide whether the universe expands forever or eventually recollapses. Measuring that deceleration was the goal of two competing teams: the Supernova Cosmology Project under Saul Perlmutter, and the High-Z Supernova Search Team under Brian Schmidt and Adam Riess.

Both used Type Ia supernovae as standard candles (Chapter 18). The method compares how bright a supernova appears with how bright it must actually be, which gives distance; the redshift gives how much the universe has expanded since. Together they trace the expansion history.

Both teams found the distant supernovae were **fainter than expected** — around 25 per cent fainter. That means further away than expected. Which means the universe expanded *less* in the past than a decelerating model predicts, and has been speeding up since.

Both groups spent months hunting for an error. Was there dust dimming the supernovae? Are distant supernovae intrinsically different? Was the photometry wrong? Riess has described the period as trying to make the result go away and failing. In late 1998 and early 1999, the two teams published independently, with different data, different software and a strong competitive interest in contradicting each other. They agreed. Perlmutter, Schmidt and Riess shared the 2011 Nobel Prize.

THE EXPANSION HISTORY OF THE UNIVERSE

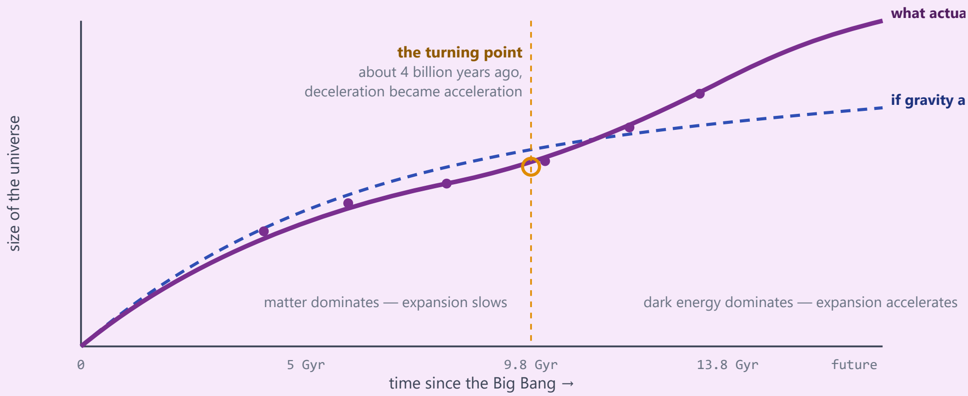


Figure 27.1 — The kink that won a Nobel Prize. For the first ten billion years, gravity slowed the expansion. As matter thinned out and dark energy did not, the balance tipped, and the curve bent upward.

What could possibly do that

Something is pushing space apart, its effect grows as the universe expands, and it makes up **68.3 per cent** of the total energy content. It was named **dark energy**, which — like dark matter — is a label rather than an explanation.

The simplest candidate is the **cosmological constant**, Λ. Einstein added exactly such a term to his field equations in 1917, to allow a static universe, and abandoned it after Hubble's discovery — reportedly calling it his greatest blunder. It was reinstated in 1998, eighty-one years later, for the opposite reason.

Physically, Λ behaves like an energy inherent in empty space itself. Quantum field theory says empty space should indeed have an energy, from vacuum fluctuations, and it can be estimated. The estimate exceeds the observed value by a factor of about **10^{120}**.

This is, by an enormous margin, the worst quantitative prediction in the history of physics. Some cancellation must be at work that nobody understands, and it must be precise to 120 decimal places without being exact. That is not a small gap to be tidied up later. It is a signal that something fundamental is missing.

CASE FILE · THE HUBBLE TENSION

There are two good ways to measure how fast the universe is expanding today, and they disagree.

The local route builds the distance ladder from the bottom: parallax to nearby stars, then Cepheid variables, then Type Ia supernovae. The SH0ES team, led by Adam Riess, gets $\mathbf{H_0 = 73.0 \pm 1.0}$ km/s/Mpc.

The early-universe route takes the CMB power spectrum from Chapter 12, fits the standard cosmological model, and extrapolates forward 13.8 billion years. Planck gets $\mathbf{H_0 = 67.4 \pm 0.5}$ km/s/Mpc.

These differ by about five standard deviations. In particle physics, five sigma is the threshold for claiming a discovery. Both measurements have been repeated, cross-checked and rebuilt with independent methods — the tip of the red giant branch, gravitational-wave sirens, JWST re-observations of Cepheids — and the gap has stubbornly refused to close.

Either one measurement has a systematic error nobody has found, or the standard cosmological model is incomplete between recombination and now. Proposals include early dark energy, extra relativistic species, and modifications to how dark energy evolves. **This is the most important unresolved discrepancy in cosmology**, it is very much live, and it is exactly the sort of problem a research career gets built on.

DO THE MATH · 27.1

Age the universe from Hubble's constant. If the expansion rate had always been what it is now, the age would simply be $1/H_0$.

```
1 Mpc = 3.086 × 10¹⁹ km

H₀ = 70 km/s/Mpc  =  70 / 3.086×10¹⁹  s⁻¹

age  ≈  1 / H₀
```

- Convert H_0 to units of s^{-1}.
- Compute $1/H_0$ in seconds, then in billions of years.
- Compare with the measured 13.8 billion years. Why are they so close, given that the expansion rate has certainly *not* been constant?

The answer to the last question is a genuine coincidence worth understanding: the early deceleration and the recent acceleration very nearly cancel out. Now redo the calculation with H_0 = 67.4 and again with 73.0, and see how much the Hubble tension shifts the inferred age.

GET THIS STRAIGHT

"Everything is expanding, so atoms, the Earth and the Solar System are all getting bigger." They are not, and the reason is instructive.

Cosmic expansion is a property of space on the largest scales, where matter is diffuse and gravity is weak. Anything bound together by a stronger local force simply does not participate. Atoms are held by electromagnetism, the Earth by chemical bonds and its own gravity, the Solar System and the Milky Way by gravity, and the Local Group by its own mutual attraction.

Expansion only wins where nothing is holding things together — between galaxy clusters. Andromeda is approaching us, not receding, precisely because the Local Group is gravitationally bound and has decoupled from the expansion entirely.

CAREER NOTE

Dark energy is being attacked with very large surveys: **DESI** in Arizona, mapping tens of millions of galaxy redshifts; the **Vera Rubin Observatory**, which began full operations in 2025 and will photograph the entire southern sky every few nights for a decade; and ESA's **Euclid**, launched in 2023. DESI's 2024 and 2025 data releases have produced hints that dark energy may be weakening over time rather than being a true constant — which, if it holds up, would be the biggest result in cosmology since 1998.

The work is overwhelmingly computational: pipelines, statistics, and terabyte-scale data handling. India is a full member of the LSST/Rubin collaboration through IUCAA and the IITs.

IN A HURRY?

- **Hubble's law**: $v = H_0 d$. Space expands; galaxies are not flying through it.
- In **1998** two rival teams found distant supernovae too faint — the expansion is **accelerating**. Nobel Prize 2011.
- The cause is called **dark energy**: 68.3% of the universe. The name is a label, not an explanation.
- The simplest model is Einstein's **cosmological constant** Λ — but quantum theory overpredicts it by $\mathbf{10^{120}}$.
- Acceleration began about **4 billion years ago**, when matter thinned enough for dark energy to dominate.
- The **Hubble tension** — 67.4 versus 73.0 km/s/Mpc — is unresolved and may signal new physics.
- **Bound systems do not expand.** Atoms, planets and galaxies are unaffected.

CHAPTER 28 · THE DARK SECTOR

How It All Ends

> The universe has a future, and physics can describe most of it. The numbers involved make 13.8 billion years look like a rounding error.

Cosmic fate hangs on a single number: the **equation of state** of dark energy, written w, which describes how its pressure relates to its energy density. If $w = -1$ exactly, dark energy is a true cosmological constant and the universe expands forever at an accelerating rate. If $w < -1$, dark energy strengthens with time and the expansion becomes infinitely fast in finite time. If $w > -1$ and dark energy weakens or reverses, other endings become possible.

The best current measurements give $w = -1.03 \pm 0.03$. That is consistent with exactly -1, and consistent with a slow drift in either direction. DESI's recent results hint at evolution. We do not yet know.

The default ending: a very slow fade

Assume $w = -1$. The universe then has an extremely long and extremely boring future, conventionally divided into four eras.

THE REST OF TIME

10^9 years — the Earth becomes uninhabitable
The Sun brightens ~10% per billion years. Oceans evaporate. This is the deadline that matters.

5×10^9 years — the Sun becomes a red giant
Then a white dwarf. Around the same time, Andromeda arrives.

10^{11} years — the sky empties
Expansion carries all other galaxies beyond the horizon. Observers then could not discover cosmology.

10^{14} years — the last star goes out
Gas for star formation is exhausted; the longest-lived red dwarfs finally cool. End of the stelliferous era.

10^{15} years — the degenerate era
Only white dwarfs, neutron stars and black holes remain. Planets are stripped from their orbits by stellar encounters. The first black dwarfs finally appear.

10^{34} to 10^{40} years — matter may dissolve
If protons decay — which is predicted by some theories and has never been observed — all ordinary matter evaporates into positrons and radiation. Experiments say the half-life exceeds 10^{34} years.

10^{40} to 10^{100} years — the black hole era
Black holes are the only structures left. They slowly evaporate by Hawking radiation: a stellar-mass hole takes 10^{67} years, a supermassive one about 10^{100}.

beyond 10^{100} years — the dark era
A thin, cold, expanding fog of photons, neutrinos, electrons and positrons. No structure. No events. Nothing that could be called a change, ever again. This is the *heat death*.

Note the scale: each label below the fourth is a jump of many orders of magnitude, not a step.

Figure 28.1 — A logarithmic future. The entire history of the universe so far — 1.38×10^{10} years — occupies less than the first tick. The stelliferous era in which stars exist is a brief opening episode.

The alternatives

The Big Rip. If $w < -1$ — so-called phantom energy — dark energy's density grows without limit. The expansion then tears apart progressively smaller bound structures: first galaxy clusters, then galaxies, then solar systems, then planets, and finally atoms and nuclei, all within a finite time. Current data allows this but does not favour it; if it happens, estimates put it at least 100 billion years away.

The Big Crunch. If dark energy weakens and reverses, gravity eventually wins, expansion halts and reverses, and everything falls back together into a hot dense state. This was the fashionable ending before 1998 and is now considered unlikely — but DESI's hint that w may be evolving has put it marginally back on the table.

Vacuum decay. The most unsettling possibility, and the one with the best physics behind it. Measurements of the Higgs boson and top quark masses suggest the vacuum we live in may be **metastable** — not the lowest-energy state available, merely a local minimum. If so, a quantum fluctuation somewhere could tunnel to the true vacuum, and a bubble of it would expand at the speed of light, rewriting physics inside. You would not see it coming, because it arrives at exactly the speed of the light that would have warned you.

Before this alarms anyone: the expected timescale is of order 10^{100} years or more, and the calculation depends on physics at energies far beyond anything tested. It is a curiosity, not a forecast.

CASE FILE · THE COSMOLOGISTS OF THE FAR FUTURE

In 2007 Lawrence Krauss and Robert Scherrer published a paper with a genuinely disquieting point. Accelerating expansion is steadily carrying galaxies beyond our cosmic event horizon. In roughly 100 billion years, every galaxy outside the merged Milky Way–Andromeda system will have receded past the point where its light can ever reach us.

At that point the observable universe consists of one galaxy in an apparently infinite void. The microwave background will have been redshifted to wavelengths longer than the observable universe and become undetectable. The primordial deuterium that dates the Big Bang will have been processed by generations of stars.

Astronomers then — assuming any exist — would observe a static, eternal, single-galaxy universe. They would have no evidence of expansion, no microwave background, no nucleosynthesis signature, and no reason whatsoever to suspect a Big Bang. Doing excellent science with the evidence available, they would reach a confident and completely wrong conclusion.

Krauss and Scherrer's point is not really about the future. It is about us. We happen to live in a narrow window in which the evidence for cosmic origins is still visible. That raises an uncomfortable question worth sitting with: **what evidence has already disappeared before we arrived?**

DO THE MATH · 28.1

Feel the size of these numbers. The point of this exercise is not the arithmetic but the shock at the end.

- The universe is 1.38×10^{10} years old. The degenerate era begins at 10^{15} years. What fraction of the way there are we?
- A stellar-mass black hole evaporates in 10^{67} years. Express the current age of the universe as a fraction of that.
- Suppose the universe's whole history so far were compressed into one second. On that scale, how long is 10^{100} years?

For the last one, note that there are only about 10^{80} atoms in the observable universe. Your answer will exceed that by twenty orders of magnitude. There is no physical quantity to compare it to — which is itself the lesson.

GET THIS STRAIGHT

"The universe will die of entropy, so everything is pointless." The physics is roughly right and the inference does not follow — and it is worth separating them, because students meet this argument early and it can be corrosive.

Heat death means the universe reaches maximum entropy, with no usable energy gradients and therefore no possible process. That is a real prediction under $w = -1$. But the timescale is 10^{100} years, and a claim about the state of the universe after 10^{100} years has no bearing on whether anything matters now. A structure is not made meaningless by being temporary; if it were, nothing anyone has ever done or valued would qualify, since every one of it is temporary.

Physics describes what will happen. It does not adjudicate what is worth doing, and it is not equipped to. Be suspicious of any argument that smuggles a conclusion about value out of a statement about thermodynamics.

IN A HURRY?

- The fate depends on dark energy's **equation of state *w***. Measured at -1.03 ± 0.03 — consistent with a constant.
- Default ending: **eternal accelerating expansion** to heat death.
- Earth becomes uninhabitable in **~1 billion years**, long before the Sun's red giant phase at 5 billion.
- Last stars burn out at **10^{14} years**; black holes evaporate between 10^{67} and 10^{100}.
- Alternatives: **Big Rip** ($w < -1$), **Big Crunch** (dark energy reverses), **vacuum decay** (the Higgs vacuum is metastable).
- In ~100 billion years, all other galaxies will be invisible — and cosmology will become **undiscoverable**.

VII

Neighbourhood and Life

Astrophysics eventually has to answer a personal question: is this arrangement — rock, water, chemistry, curiosity — common or freakish?

CHAPTER 29 · NEIGHBOURHOOD AND LIFE

The Solar System, Reconsidered

> You learnt the planets in school. What school probably left out is why they are arranged the way they are, and why the most interesting places are not planets at all.

The Solar System is not a collection of unrelated objects that happen to share a star. It is the leftover material from the disc in Chapter 14, sorted by a single organising principle — **temperature** — and then reshuffled by four and a half billion years of gravitational bullying.

The frost line explains almost everything

In the young disc, temperature fell with distance from the proto-Sun. Somewhere around 3 AU — out past Mars, in the region of the asteroid belt — it dropped below about 150 K, the point where water can freeze into solid ice. That boundary is the **frost line**, and it divided the Solar System in two.

Inside it, only substances with high melting points could condense: metals and silicate rock. These are cosmically scarce, so the planets built there stayed small. Mercury, Venus, Earth and Mars are what you get from a limited supply of rock.

Outside it, water ice could condense too — and water is far more abundant than rock. Cores grew several times faster and several times larger, and once a core passed roughly ten Earth masses it could capture hydrogen and helium directly from the disc. That runaway produced Jupiter and Saturn. Uranus and Neptune formed later and further out, where the disc was thinner, and never got their full share of gas — which is why they are "ice giants" rather than gas giants.

One line in the disc, and the entire architecture follows: small rocky worlds close in, giants further out, and a belt of unfinished material at the boundary.

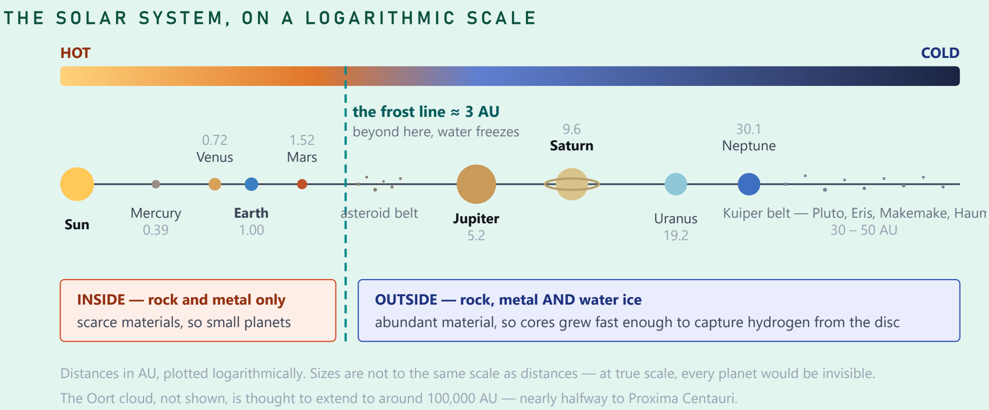


Figure 29.1 — One temperature boundary, two kinds of world. The frost line is the single most important structural feature of any planetary system, and Chapter 30 shows what happens when it ends up somewhere else.

The moons are where the action is

If you were allocating a research budget to look for life, you would not spend much of it on planets. The most promising real estate in the Solar System is in orbit around the giants, and the reason is **tidal heating** — the $1/r^3$ effect from Chapter 4. A moon on a slightly elliptical orbit is flexed continuously by its planet's gravity, and the internal friction produces heat with no need for sunlight at all.

Europa, at Jupiter, has a smooth cracked ice shell over a global salt-water ocean estimated to hold **twice as much liquid water as all of Earth's oceans combined**. **Enceladus**, a Saturnian moon only 500 km across, vents plumes of water, salts, silica and organic molecules into space through fractures at its south pole — Cassini flew through them and sampled a subsurface ocean without landing. **Titan** has a thick nitrogen atmosphere, rain, rivers and seas — of liquid methane, at −179 °C. And **Io** is the most volcanically active body known, resurfacing itself constantly from tidal heating alone.

Four worlds with oceans, weather or active geology, all powered by orbital mechanics rather than starlight. That is a serious expansion of where life might be possible, and Chapter 31 takes it up.

CASE FILE · WHAT ACTUALLY HAPPENED TO PLUTO

The 2006 decision is usually reported as an insult to a beloved planet. It was really a filing problem that had been building for a decade.

In 1992 the first Kuiper belt object beyond Pluto was found. By 2005 there were over a thousand, and Mike Brown's team discovered **Eris** — which appeared to be *more massive than Pluto*. The International Astronomical Union faced a straightforward choice: admit Eris and a growing queue of similar bodies as planets, or define the term.

The definition adopted requires a planet to (1) orbit the Sun, (2) be massive enough for gravity to have pulled it into a round shape, and (3) have **cleared its orbital neighbourhood** of other bodies. Pluto passes the first two and fails the third: it shares its region with countless Kuiper belt objects and is not even gravitationally dominant there. It was reclassified as a **dwarf planet**.

The third criterion is genuinely contested — planetary scientists point out it depends on orbital distance rather than the object itself, so the same body could be a planet at 1 AU and not at 40 AU. That argument has never been settled.

What is not in dispute is that Pluto turned out to be far more interesting than anybody expected. When New Horizons flew past in July 2015, it revealed nitrogen-ice plains with *no impact craters at all* — meaning a surface being actively renewed, on a world so cold and small it should have been geologically dead for billions of years. Nobody has fully explained where the energy is coming from.

DO THE MATH · 29.1

Kepler's third law, the easy version. For anything orbiting the Sun, if you measure the period T in **years** and the semi-major axis a in **AU**, all the constants vanish:

$$T^2 = a^3$$

- Jupiter is at 5.20 AU. How long is its year?
- Neptune is at 30.1 AU. How long is its year? Neptune was discovered in 1846 — has it completed even one orbit since?
- Halley's Comet returns every 75.3 years. What is its semi-major axis?
- A hypothetical planet orbits in exactly 8 years. How far out is it?

Then use it as a tool. In Chapter 24 you applied the same law — in its full form, with G and M — to weigh a black hole from the orbit of a star. It is the same physics either way: **an orbit is a scale that weighs whatever it goes around.**

GET THIS STRAIGHT

"When the planets align, their combined gravity affects the Earth." Two things are wrong here, and the arithmetic is worth doing because it settles the matter permanently.

First, the planets never really align. Their orbits are tilted relative to one another, and "alignments" reported in the press mean they appear roughly in the same part of the sky — typically spread over 30 degrees or more.

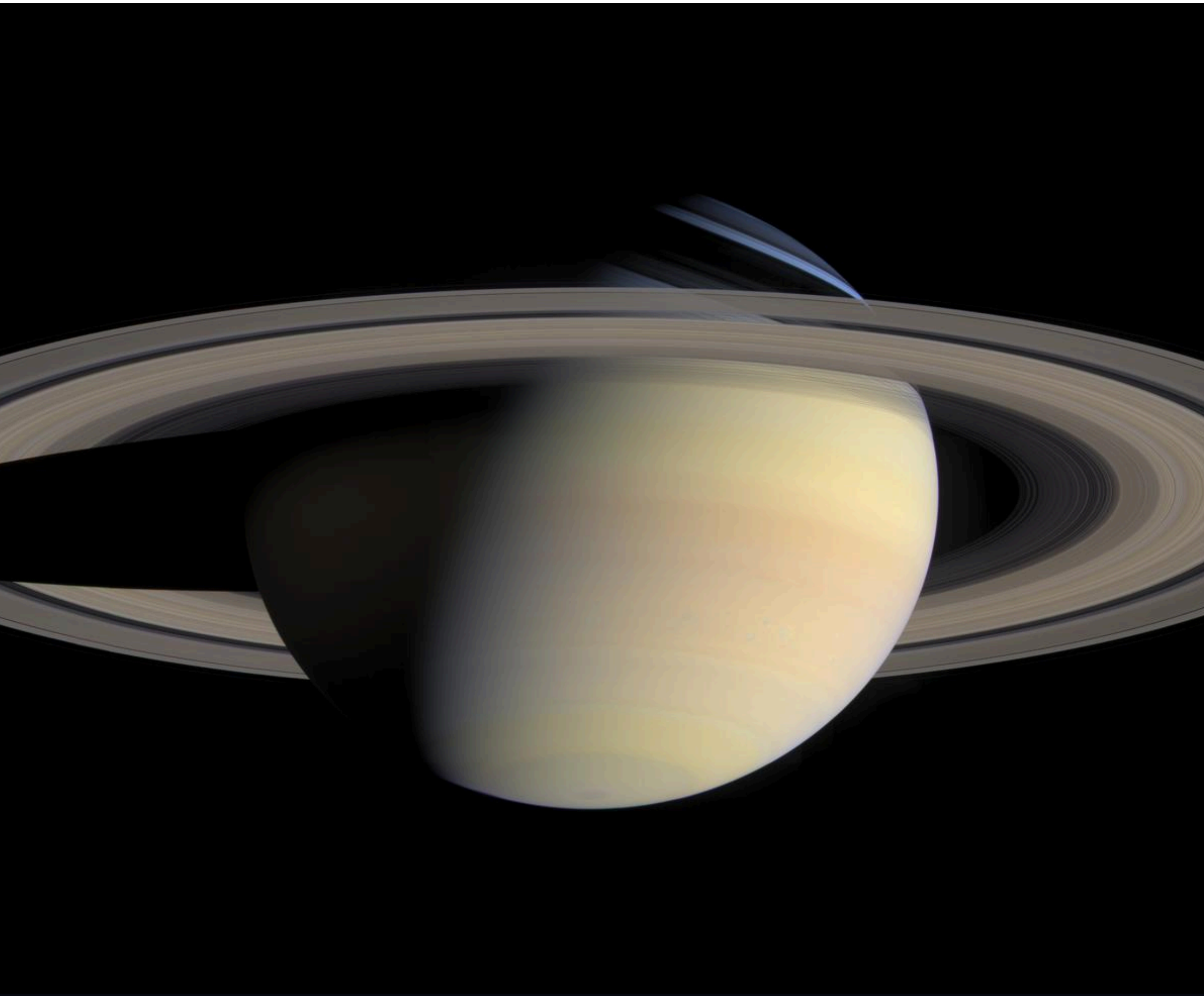
Second, even a perfect alignment would do nothing. Using $F = GMm/r^2$, Jupiter at closest approach pulls on you about **1/17,000** as hard as the Moon does. All the planets combined, perfectly aligned, would exert less tidal force on you than a lorry parked across the street — an effect you can and should verify yourself with the numbers in Appendix A.

TRY THIS · WATCH A PLANET MOVE

Planets were originally named from the Greek for "wanderer", and the reason is something you can confirm in a fortnight.

Find a bright planet — Jupiter, Venus, Mars and Saturn are all easily visible and much steadier than stars, which twinkle because they are point sources and planets are not. Sketch its position relative to two or three nearby stars. Repeat every three or four nights for a month, from the same spot at the same time.

The stars will not move relative to one another. The planet will drift measurably against them. If you catch Mars near opposition you may even see it **reverse direction** for a few weeks — retrograde motion, produced simply by the Earth overtaking it on the inside track. It was the single hardest thing for Earth-centred astronomy to explain, and it falls out of the Sun-centred picture immediately.



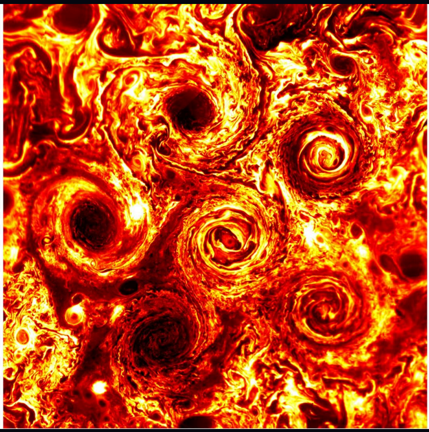
The Solar System's best argument for going and looking

Saturn photographed by Cassini, which orbited the planet from 2004 to 2017 and ended by deliberately burning up in its atmosphere to avoid contaminating the moons. The rings are almost pure water ice, tens of metres thick and 280,000 km wide — proportionally far thinner than a sheet of paper the size of a cricket ground.

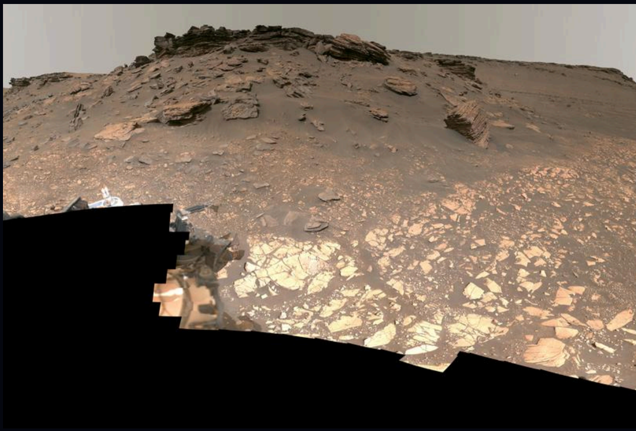
Credit: NASA/JPL/Space Science Institute. NASA — free to use with credit.

The neighbourhood, as actually photographed

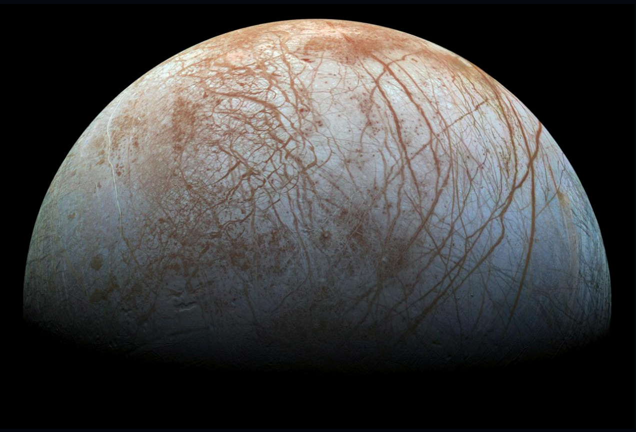
Six worlds, all visited by spacecraft within one human lifetime.



Jupiter's south pole
— cyclones the size of continents, imaged by Juno in the infrared.



Jezero Crater, Mars
— a river delta photographed by Perseverance, where water once stood.



Europa
— a cracked ice shell over a salt-water ocean holding twice Earth's water.

Pluto
— nitrogen-ice plains and no craters, meaning a surface being actively renewed.

IN A HURRY?

- The **frost line** at ~3 AU divides the Solar System: rock-only inside, rock plus abundant water ice outside.
- That is why the inner planets are **small and rocky** and the outer ones are **giant**.
- **Tidal heating** makes moons the most promising places for life — **Europa, Enceladus, Titan, Io**.
- **Pluto** was reclassified in 2006 for failing to clear its orbit, after Eris forced the IAU to define "planet". The criterion is still argued about.
- Kepler's third law in convenient units: $T^2 = a^3$, years and AU.
- Planetary "alignments" have **no physical effect** — Jupiter's pull on you is 1/17,000 of the Moon's.

CHAPTER 30 · NEIGHBOURHOOD AND LIFE

Exoplanets: Six Thousand Other Worlds

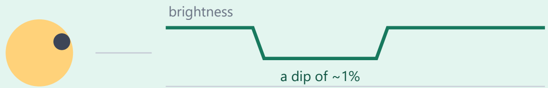
> When your parents were at school, the Solar System was the only planetary system known to exist. The count is now past six thousand, and almost none of them look like ours.

The problem was never that planets around other stars seemed unlikely. It was that detecting them is absurdly hard. A planet is perhaps a billionth as bright as its star and separated from it, as seen from Earth, by a fraction of an arcsecond. It is the optical equivalent of photographing a firefly next to a searchlight in Mumbai — from Chennai.

So astronomers stopped trying to see planets and started looking for their **effects**.

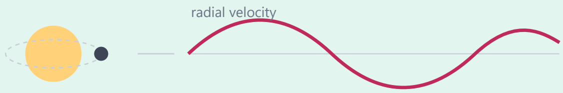
FOUR WAYS TO FIND A PLANET YOU CANNOT SEE

1 · TRANSIT — the planet crosses in front



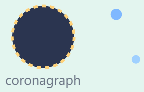
Gives the planet's **size** and orbital period. Only works if the orbit is edge-on to us — so it misses most systems. Kepler's method.

2 · RADIAL VELOCITY — the star wobbles



The star orbits the shared centre of mass, Doppler-shifting its lines. Gives a **minimum mass**. Jupiter moves the Sun by 12 m/s; Earth by 0.09.

3 · DIRECT IMAGING — block the star, photograph the planet



Works only for big, hot, young planets far from their star — a tiny minority. But it is the only method that yields a spectrum directly.

4 · MICROLENSING — the planet's gravity magnifies a background star

Chapter 5's lensing, in miniature. Finds distant, cold planets — but each event happens once and never repeats.

Figure 30.1 — Every method is biased. Transits favour large planets in tight orbits; radial velocity favours massive planets close in; imaging favours young giants far out. The catalogue is not a fair sample of what exists, and correcting for that is a large part of the science.

CASE FILE · 51 PEGASI B, AND A RESULT NOBODY WANTED TO BELIEVE

In October 1995, Michel Mayor and Didier Queloz of the University of Geneva announced a planet orbiting 51 Pegasi, a Sun-like star 50 light-years away. It was the first confirmed planet around an ordinary star.

It was also, by every theory of the time, impossible. It had roughly half Jupiter's mass — and an orbital period of **4.2 days**. It was circling its star at one-eighth the distance of Mercury, with a surface temperature above 1,000 °C. Giant planets were supposed to form beyond the frost line and stay there. Nothing that large should exist that close.

The initial reaction was scepticism, and a rival group suggested the signal came from pulsations of the star itself. Geoffrey Marcy and Paul Butler in California pointed their own instrument at 51 Pegasi expecting to disprove it — and confirmed it within a week. Then they went back through years of their own archived data and found several more.

The lesson was uncomfortable: **the planets had been in the data for years, and nobody had looked for signals with periods that short**, because theory said they could not exist. Mayor and Queloz shared the 2019 Nobel Prize.

These "hot Jupiters" are now understood to have formed far out and **migrated** inward through interaction with the disc. Planetary migration is now standard theory — and it began with one object that refused to be where it belonged.

What six thousand planets look like

The Kepler space telescope, which stared at a single patch of sky from 2009 to 2018, and its successor TESS, which surveys the whole sky, transformed the field from a collection of curiosities into a statistical science. The confirmed count is now above **6,000**, with thousands more candidates awaiting follow-up.

Three findings stand out.

Planets are ordinary. Statistically, essentially every star has at least one planet. There are more planets than stars in the Milky Way. The default state of a star is to have a planetary system.

The most common planet is a type we do not have. Between Earth (1 Earth radius) and Neptune (3.9) sit the **super-Earths** and **mini-Neptunes**, and they are by a wide margin the commonest planets in the galaxy. The Solar System contains none. Whatever is typical, we are not it.

There is a gap where there should not be. Planets between about 1.5 and 2.0 Earth radii are conspicuously rare — the **radius valley**, found in 2017. The favoured explanation is photoevaporation: planets in that range are large enough to have captured a hydrogen envelope but not massive enough to hold it against their star's radiation, so they lose it and shrink into the super-Earth category. It is a rare case of a sharp, unexpected feature in the data with a clean physical explanation.

SOME WORLDS WORTH KNOWING BY NAME

System	Distance	Why it matters
Proxima Centauri b	4.25 ly	the nearest exoplanet; roughly Earth-mass, in the habitable zone — but its star flares violently
TRAPPIST-1	40 ly	seven Earth-sized planets round one red dwarf; three or four in the habitable zone
K2-18 b	124 ly	a mini-Neptune where JWST detected methane and carbon dioxide, and made a contested claim of dimethyl sulphide
WASP-121 b	880 ly	a hot Jupiter with vaporised metal in its atmosphere; it may rain liquid iron
PSR B1257+12	2,300 ly	the true first exoplanets, found in 1992 orbiting a *pulsar* — the least hospitable place imaginable

DO THE MATH · 30.1

Size a planet from a light curve. During a transit, the fractional dip in brightness is simply the ratio of the areas:

$$\frac{\Delta F}{F} = \left(\frac{R\_planet}{R\_star} \right)^2$$

- A Sun-like star (R = 696,000 km) dims by 1.0%. How large is the planet, in km and in Jupiter radii (71,500 km)?
- The same star dims by 0.0084% — the value the Earth would produce. What planet radius is that? Compare with Earth's 6,371 km.
- A red dwarf of radius 0.15 $R_{\odot}$ dims by 0.7%. How big is the planet? Why are small stars so much easier to survey for Earth-sized planets?

That last answer explains the entire strategy of TESS and of the TRAPPIST-1 discovery, and it also explains a serious problem: red dwarfs flare, and their habitable zones are so close in that planets there are probably tidally locked and repeatedly irradiated.

GET THIS STRAIGHT

"Astronomers have found dozens of Earth-like planets." They have found dozens of planets that are **Earth-sized** and receive **roughly Earth-like amounts of starlight**. That is a very different claim.

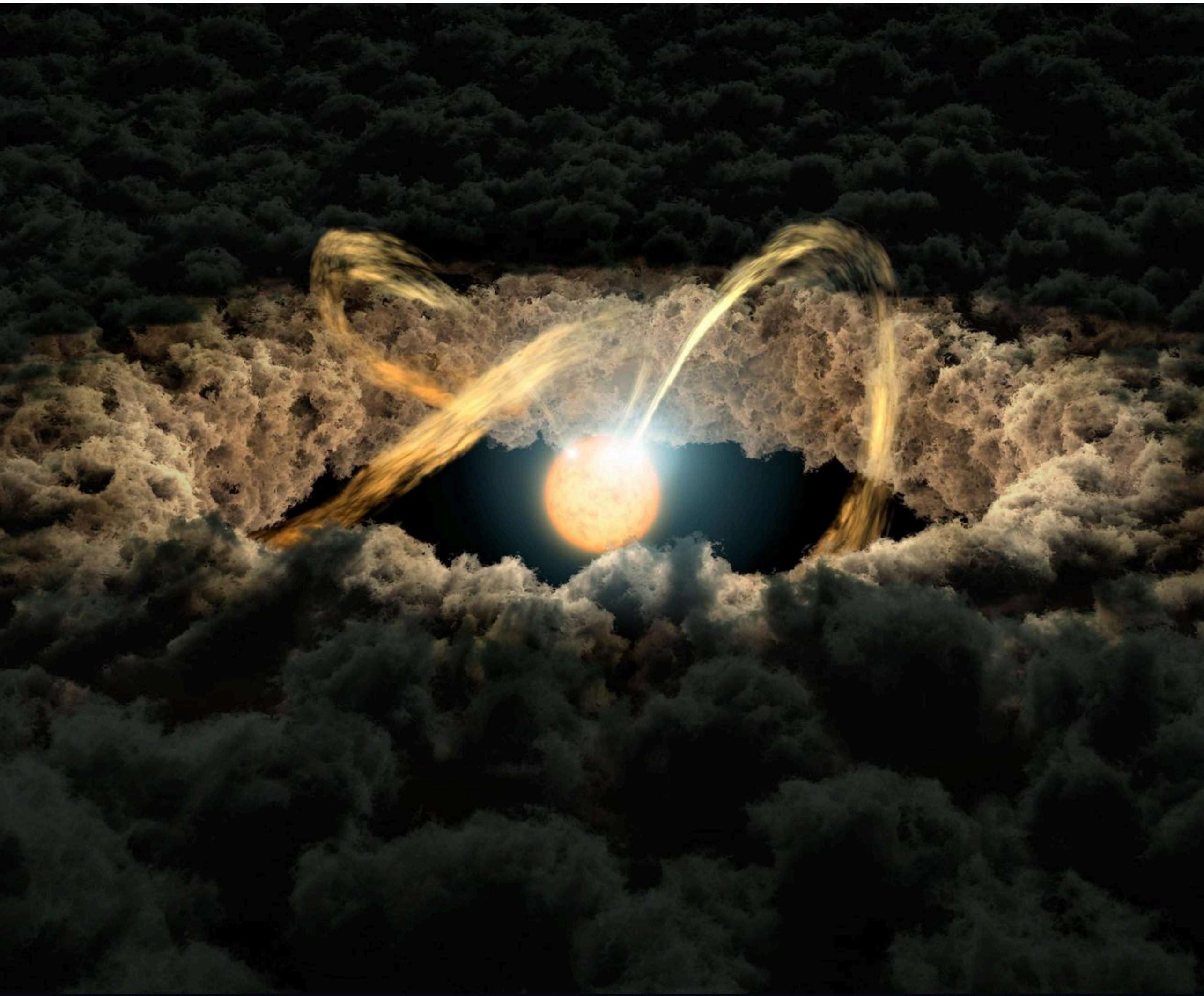
For almost all of them we know the radius, sometimes the mass, and the orbital period. We usually do not know whether there is an atmosphere, what it is made of, whether there is liquid water, whether there is a magnetic field, or whether the planet rotates. Venus is Earth-sized and sits at the inner edge of the habitable zone, and its surface is at 464 °C under a crushing carbon dioxide atmosphere. By the criteria used in most headlines, Venus is an Earth-like planet.

"Potentially habitable" in a press release means "we have not yet ruled it out", which is a much weaker statement than it sounds.

CAREER NOTE

Exoplanet science is one of the most accessible fields for a student, because the data is public. NASA's Exoplanet Archive, the Kepler and TESS light curves, and the JWST archive are all downloadable by anyone. Amateurs have genuinely co-discovered planets through the **Planet Hunters** citizen-science project by spotting transits algorithms missed.

In India, PRL Ahmedabad operates **PARAS**, a high-precision radial-velocity spectrograph on the 1.2-m telescope at Mount Abu, which has discovered several exoplanets — the first Indian-discovered planets. It is a small group and it takes students.



Where planets come from

An artist's rendering of a protoplanetary disc — the flattened cloud of gas and dust left over from a star's formation, and the raw material of every planet that exists. Real discs imaged by ALMA show sharp concentric gaps, carved by planets already forming inside them. **This is an illustration, not a photograph**; it is included because the real images are harder to read at this size.

Credit: NASA/JPL-Caltech. NASA — free to use with credit.

IN A HURRY?

- Planets are found by their **effects**: transits (size), radial velocity (mass), direct imaging (spectra), microlensing (distant cold planets).
- **51 Pegasi b**, 1995 — a "hot Jupiter" that theory said was impossible, and which forced the idea of **planetary migration**.
- Over **6,000 confirmed**. Essentially every star has planets; there are more planets than stars.
- The commonest type — **super-Earths and mini-Neptunes** — does not exist in our Solar System.
- The **radius valley** at 1.5–2.0 Earth radii is explained by atmospheric loss.
- "Earth-like" in the press means **Earth-sized and similarly lit**. It does not mean habitable.

CHAPTER 31 · NEIGHBOURHOOD AND LIFE

Are We Alone?

> The only honest answer is that nobody knows. What is worth learning is how to think about the question properly — and why the silence is itself a piece of evidence.

This is the one chapter where you should be most suspicious of confident people. The question of life elsewhere attracts certainty from all directions: it is obviously everywhere, given the number of stars; it is obviously unique, given how improbable we are. Both arguments are made with the same total absence of data. We have exactly one example of life, and you cannot compute a rate from a sample of one.

Drake's equation is not a calculation

In 1961 Frank Drake wrote down a way of organising the question for a small meeting at Green Bank. It has been misunderstood ever since as a formula that produces an answer.

THE DRAKE EQUATION

```
N  =  R★ · f_p · n_e · f_l · f_i · f_c · L

R★   rate of star formation in the galaxy        ~1.5–3 per year
KNOWN
f_p  fraction of stars with planets              ~1                KNOWN
since 2015
n_e  habitable planets per such system           ~0.1–1
roughly known
f_l  fraction where life actually begins         ?
UNKNOWN
f_i  fraction of those developing intelligence   ?
UNKNOWN
f_c  fraction that broadcast detectably          ?
UNKNOWN
L    how long such civilisations last            ?
UNKNOWN
```

The first three terms have been measured, and Chapter 30 is why. The last four are not merely unmeasured; for three of them we have **no way even in principle** of estimating the value from one example. Multiply four unknowns spanning many orders of magnitude each and you can obtain any answer you please, which is exactly what people do.

Drake's equation is valuable as a **way of decomposing ignorance** — it tells you precisely which questions matter and which have been answered. It is worthless as a prediction, and anyone quoting a specific value of N is telling you about their assumptions rather than about the galaxy.

The Fermi paradox

Over lunch at Los Alamos in 1950, Enrico Fermi asked the question that has organised the field since: "**Where is everybody?**"

The argument is a scale argument, of the kind Chapter 1 was training you for. The galaxy is 13.6 billion years old. Even at speeds achievable without new physics — a per cent of light speed — a civilisation could cross it in a few million years, which is nothing. If intelligent life were at all common, the galaxy should show signs of it. It does not.

The proposed resolutions fall into three families, and it is worth being clear that **none is established**.

They are rare. Something in the chain is a severe bottleneck — Robin Hanson's "Great Filter". Perhaps abiogenesis is fantastically improbable. Perhaps the jump from simple to complex cells is: on Earth it happened once, took two billion years, and has never been repeated. Whether the filter is behind us or ahead of us is a genuinely uncomfortable question.

They are there and we cannot tell. Our search has been extraordinarily narrow. We have examined a small number of stars, in a small number of radio bands, for a few decades, for signals resembling what *we* would send. Radio may be a brief technological phase; Earth's own accidental radio leakage has been falling for thirty years as broadcasting moved to cable, fibre and tightly-beamed satellites.

They do not last. If L is short — because civilisations reliably destroy themselves or their environments — then even a galaxy that has produced many would be almost empty at any given moment. This is the possibility Carl Sagan considered most likely, and its implication is uncomfortably local.

CASE FILE · THE WOW! SIGNAL, 15 AUGUST 1977

Jerry Ehman was reviewing printouts from the Big Ear radio telescope at Ohio State a few days after the observation. One sequence read **6EQUJ5** — a narrowband burst 30 times above background, at 1420 MHz, close to the neutral hydrogen line that has long been argued to be the obvious frequency for interstellar signalling. He circled it in red pen and wrote "Wow!" in the margin.

It lasted 72 seconds, which is exactly how long the fixed telescope's beam took to sweep across a point in the sky — so the source behaved precisely as something outside the Earth should. It came from the direction of Sagittarius. It was narrowband, which nature rarely produces. It has never been seen again, despite more than a hundred attempts over five decades.

Proposed explanations include a passing comet's hydrogen cloud (largely ruled out), an unshielded terrestrial transmitter reflecting off space debris, and a 2024 proposal involving a stimulated hydrogen maser from a cold cloud. None is confirmed.

The Wow! signal is worth studying not because it was aliens — the honest position is that **a single unrepeatable event is not evidence of anything** — but as a lesson in scientific discipline. Nobody serious claimed a detection. Everyone tried to reproduce it. Fifty years on it is still filed as unexplained, which is where genuinely ambiguous observations belong.

What we can actually look for

Two categories of evidence are now within reach, and they are quite different.

Biosignatures are chemical traces of life in a planet's atmosphere, and the strongest argument is not any single molecule but **chemical disequilibrium**. Earth's atmosphere contains 21 per cent oxygen and a persistent trace of methane. These two react readily; left alone, the methane would be gone within a decade. Their coexistence means something is replenishing both continuously. That combination is very hard to produce without biology, and it is detectable in transmission spectra of the kind JWST now takes routinely.

The caution is real. In 2020 phosphine was reported in Venus's clouds and widely interpreted as a possible biosignature; the detection has since been strongly disputed on data-analysis grounds. In 2023 and 2025 the JWST team studying **K2-18 b** reported possible dimethyl sulphide, which on Earth is produced almost entirely by marine plankton. That claim is also contested — the statistical significance is marginal and abiotic routes have been proposed. Both episodes show how the field should work: extraordinary claims, independent reanalysis, and no rush.

Technosignatures are evidence of technology rather than biology: narrowband radio, optical laser pulses, industrial pollutants such as CFCs in a spectrum, or waste heat in the infrared. The modern effort is **Breakthrough Listen** — a ten-year, $100 million programme funded privately by Yuri Milner since 2015, surveying a million nearby stars using Green Bank, Parkes and MeerKAT. It is the most comprehensive search ever attempted. It has found nothing.

That "nothing" is not a failure. Every non-detection tightens the constraints on how common loud civilisations can be, and a well-characterised null result is a real scientific product. Astronomy is one of the few fields honest enough to publish them prominently.

DO THE MATH · 31.1

Run the Drake equation twice, and see what you have learnt. Take $R_\star$ = 2 per year, f_p = 1, n_e = 0.2.

- **Optimistic:** f_l = 0.5, f_i = 0.5, f_c = 0.5, L = 1,000,000 years. Compute N.
- **Pessimistic:** f_l = 0.01, f_i = 0.001, f_c = 0.1, L = 500 years. Compute N.
- What is the ratio between your two answers?

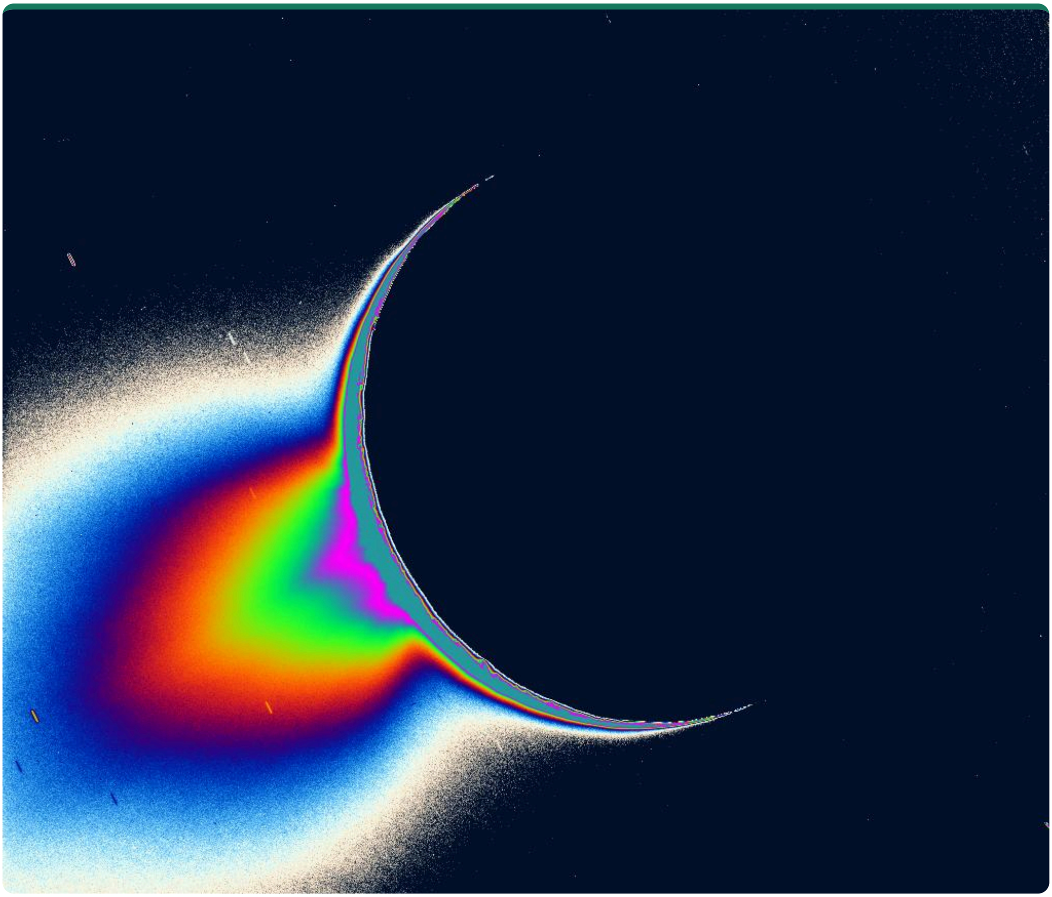
Then the real question, which is not arithmetic: **which of the two sets of numbers is better justified by evidence?** Write down, in one sentence each, what observation would be needed to pin down f_l and f_i. Notice that finding *independent* life anywhere in our own Solar System — Europa, Enceladus, Mars — would move f_l from "unknown" to "common" in a single stroke. That is why those missions matter far beyond their own targets.

GET THIS STRAIGHT

"The universe is so vast that there must be life out there." This is an intuition, not an argument, and it is worth seeing why it fails.

The observable universe holds perhaps 10^{22} stars — an enormous number. But the probability of life arising on a given suitable planet is genuinely unknown, and could be anywhere from near 1 to smaller than 10^{-40}. If it is 10^{-40}, then 10^{22} stars produce, on average, no life at all anywhere — and we would be a fluke that had to happen somewhere for anyone to be asking.

A very large number multiplied by an unknown number is an unknown number. The vastness argument feels compelling because we can picture 10^{22} and cannot picture 10^{-40}. That is a limitation of imagination, not a fact about the universe. The same trap catches people arguing the other way, who treat the improbability of any specific outcome as though it were the improbability of *some* outcome.



Enceladus, venting into space. Cassini caught these jets erupting from fractures near the south pole of a moon only 500 km across, and then flew straight through them. The plumes contain water, salts, silica and organic molecules — evidence of a liquid ocean in contact with a rocky floor. It is one of the two best places in the Solar System to look for life.

Credit: NASA/JPL/Space Science Institute. NASA — free to use with credit.

IN A HURRY?

- The **Drake equation** organises the question. Its first three terms are now measured; the last four are unknown and largely unmeasurable.
- The **Fermi paradox**: the galaxy is old enough to have been crossed many times over. Where is everybody?
- Three families of answer: **they are rare**, **we cannot detect them**, or **they do not last**. None is established.
- **Biosignatures** rely on chemical disequilibrium — oxygen and methane together. Recent claims (Venus phosphine, K2-18 b) are contested.
- **Technosignature** searches — Breakthrough Listen, privately funded since 2015 — have found nothing. Null results are real results.
- "The universe is vast, so there must be life" is **not an argument**: a huge number times an unknown number is unknown.
- Finding independent life anywhere in our own Solar System would settle more than any other single discovery.

VIII

Doing Astrophysics

Nobody in this field looks through an eyepiece. Modern astrophysics is instruments, statistics and software — and a growing number of ways to sense the sky that have nothing to do with light.

CHAPTER 32 · DOING ASTROPHYSICS

Tools of the Trade

> Nobody in this profession looks through an eyepiece. Modern astronomy is detectors, statistics and software — and, increasingly, a commercial rocket industry that has made getting to orbit routine.

A telescope does two things, and only one of them is what most people imagine. Magnification is almost irrelevant. What matters is **collecting area** — how many photons you can gather — and **resolution**, how finely you can distinguish detail. Both scale with aperture, which is why the history of astronomy is a history of building bigger mirrors.

Why every big telescope is a reflector

Refracting telescopes use a lens, and they hit hard limits. A lens can only be supported at its rim, so beyond about a metre it sags under its own weight. Glass absorbs ultraviolet and infrared. And different colours refract by different amounts, producing chromatic aberration. The largest refractor ever built, at Yerkes in 1897, has a 1.02-metre lens, and nobody has exceeded it in 128 years.

Mirrors have none of these problems. They can be supported from behind, they reflect all wavelengths identically, and they can be segmented. The **Extremely Large Telescope**, under construction in Chile, has a 39-metre primary made of 798 hexagonal segments, each actively adjusted hundreds of times a second.

That last detail is the real modern breakthrough. **Adaptive optics** measures how the atmosphere is distorting incoming light — often by firing a laser into the sky to create an artificial reference star — and deforms a small mirror to cancel the distortion in real time. It is why ground-based telescopes can now rival Hubble at some wavelengths, and it is what let Genzel and Ghez track the star S2 in Chapter 24.

THE INSTRUMENTS THAT MATTER, AND WHAT EACH IS FOR

Instrument	Band	Where	What it does that others cannot
James Webb (JWST)	infrared	L2, 1.5 M km out	6.5 m, cooled to 40 K; sees the first galaxies and exoplanet atmospheres
Hubble	optical / UV	low Earth orbit	35 years of consistent imaging; still the UV workhorse
Chandra	X-ray	high Earth orbit	accretion, cluster gas, supernova remnants
ALMA	millimetre	Atacama, 5,000 m	66 dishes; cold gas, protoplanetary discs
GMRT	metre radio	near Pune, India	30 dishes over 25 km; world-leading at low frequencies
Gaia	astrometry	L2	positions and motions of two billion stars
Vera Rubin	optical survey	Chile	images the whole southern sky every few nights, for ten years
Event Horizon Telescope	1.3 mm VLBI	whole planet	the finest angular resolution ever achieved

The part nobody warns students about

An astronomer's working day is mostly not spent observing. A typical professional gets perhaps a few nights of telescope time a year, awarded competitively, and increasingly does not travel to the telescope at all — observations are queued and executed by staff when conditions suit.

The rest of the time is **data reduction** and **analysis**. Raw astronomical data is unusable: it carries detector bias, dark current, uneven sensitivity across the field, cosmic ray hits, sky background and instrument signatures, all of which must be measured and removed before the science begins. Then comes statistics — because almost every result in this book is a small signal extracted from a noisy background, and knowing whether you have found something is a statistical question, not a visual one.

In practice this means **Python**. Astropy, numpy, scipy, matplotlib, and increasingly machine learning for classification and anomaly detection in surveys too large for humans to inspect. Vera Rubin will generate about 20 terabytes every night and issue roughly ten million alerts per night about things that changed. No human will look at most of it.

The commercial turn

Something changed in the 2010s that has affected astronomy more than any single instrument: **launch became cheap**.

For fifty years, putting a kilogram into low Earth orbit cost roughly $18,000 and the rocket was thrown away. SpaceX's Falcon 9, which lands and reflies its first stage — the most expensive part — brought that to around $2,700 per kilogram, and Starship is designed to go much lower. Rocket Lab's Electron did the same for very small payloads, launching frequently enough that a university-scale satellite is now a realistic student project rather than a national undertaking.

The consequences for science are direct. Missions that were unaffordable are now merely expensive. Small dedicated space telescopes, of a size no agency would previously have flown, become viable. Commercial lunar landers — Intuitive Machines, Firefly — now carry NASA instruments to the Moon under fixed-price contracts rather than agency-built spacecraft.

But the same industry has created astronomy's most serious new problem, and it is worth understanding properly rather than as a slogan.

CASE FILE · THE SATELLITE CONSTELLATION PROBLEM

Before 2019 there were roughly 2,000 active satellites in orbit. There are now over 10,000, the large majority of them Starlink, with tens of thousands more planned by SpaceX, Amazon's Kuiper, China's Guowang and others.

They are bright. A freshly deployed Starlink train is easily visible to the naked eye, and even at operational altitude the satellites are around magnitude 5 to 7 — comfortably detectable by any survey telescope. Each one crossing a long exposure leaves a saturated streak.

The worst-affected instrument is the one designed to survey the entire sky: the Vera Rubin Observatory. Estimates suggest that with 100,000 satellites in orbit, a substantial fraction of Rubin's twilight exposures would contain at least one trail. Software can mask trails, but masking loses real data, and satellites can also produce spurious transient alerts — precisely what the observatory exists to detect.

Radio astronomy faces a harder version. Satellite downlinks are enormously brighter than any astronomical radio source, and unintended electromagnetic radiation leaks well outside allocated bands. SKA and MeerKAT have both reported interference. Unlike optical trails, you cannot simply mask a signal that saturates your receiver.

There has been real cooperation — SpaceX has trialled darkening coatings and sunshades and works with the IAU's Centre for the Protection of the Dark and Quiet Sky. But there is **no international law** requiring any operator to limit brightness, and the number of satellites is set by commercial and strategic considerations, not scientific ones. This is a live policy problem, it will be argued about for the whole of your working life, and it is a genuine case where science and commerce have collided with no obvious referee.

DO THE MATH · 32.1

Why aperture is everything. Collecting area goes as D^2; resolution goes as $1/D$.

- How much more light does JWST's 6.5 m primary gather than Hubble's 2.4 m?
- How much more than a 200 mm amateur telescope?
- Compare the ELT's 39 m with JWST's 6.5 m, by area.
- Using $\theta \approx 1.22\,\lambda/D$ from Chapter 21, find the theoretical resolution of the ELT at 500 nm, in arcseconds. Ordinary atmospheric seeing is about 1 arcsecond — by what factor must adaptive optics improve on the atmosphere for the mirror to be worth building?

Finally, an economics question that working astronomers face constantly: a telescope's cost scales roughly as $D^{2.5}$. If a 10 m telescope costs ₹800 crore, what would a 40 m cost? Compare with the ELT's actual budget of about €1.5 billion.

CAREER NOTE

The private space sector has created a category of job that did not exist when your teachers were students: physics and engineering graduates working on spacecraft at companies rather than agencies. In India that now includes **Skyroot Aerospace**, **Agnikul Cosmos**, **Pixxel**, **Dhruva Space** and **Bellatrix Aerospace**, all founded since 2015 and all hiring. Chapter 35 covers them properly.

It is worth being clear-eyed: these are engineering jobs, not astrophysics research jobs. They pay considerably better and they are not the same work. Both are legitimate; knowing which one you actually want is worth thinking about before you choose a degree.

What the case file opposite looks like from the ground. A Starlink train crossing the evening sky. Each satellite is a moving point of reflected sunlight; in a long astronomical exposure each one becomes a saturated streak across the frame. There are now more than ten thousand active satellites in orbit, and no international rule limits how bright any of them may be.

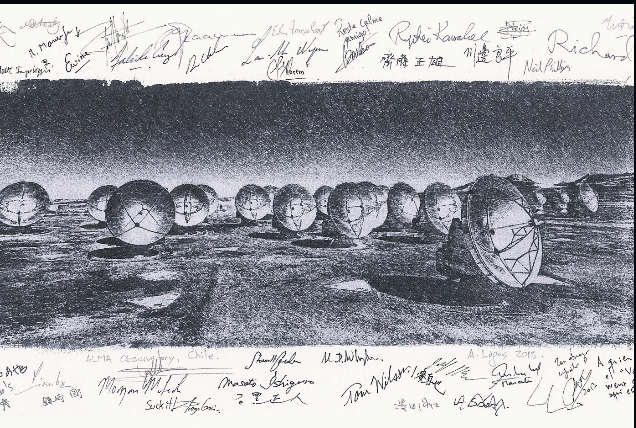
Credit: Dktue. CC0.

Why observatories go where nobody lives

ESO's Very Large Telescope on Cerro Paranal in the Atacama Desert, 2,635 m up in one of the driest places on Earth. Four 8.2-metre telescopes that can be combined interferometrically. The site was chosen for thin, dry, steady air — the same reasoning that put India's Himalayan Chandra Telescope at Hanle, 4,500 m up in Ladakh.

Instruments and missions, worldwide

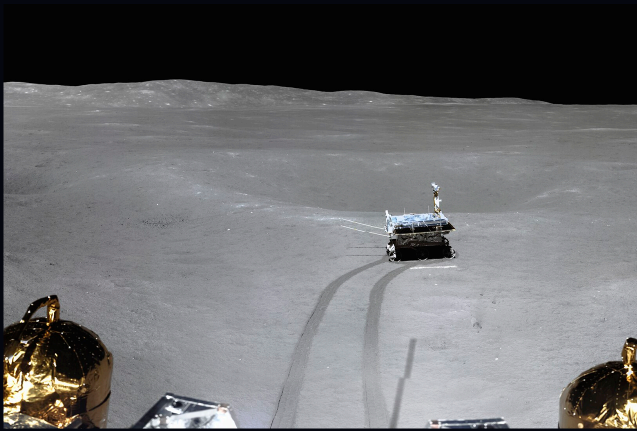
Astronomy has been an international enterprise for a long time.



ALMA, Chile
— 66 dishes at 5,000 m, run by Europe, North America and East Asia.

Comet 67P
— imaged by ESA's Rosetta, which orbited a comet and landed on it.

Asteroid Ryugu
— JAXA's Hayabusa2 collected samples and returned them to Earth.



Yutu-2 on the Moon
— the CNSA rover on the lunar far side, a first for any nation.

IN A HURRY?

- Telescopes are about **collecting area and resolution**, not magnification. Both scale with aperture.
- All large telescopes are **reflectors**; the biggest refractor ever built dates from 1897.
- **Adaptive optics** cancels atmospheric blurring in real time and is why ground telescopes can rival space ones.
- The job is mostly **data reduction, statistics and Python**, not observing.
- Reusable rockets cut launch costs roughly **sevenfold**, making small space missions viable.
- Satellite constellations now **actively damage** optical surveys and radio astronomy, and no law limits them.

CHAPTER 33 · DOING ASTROPHYSICS

Gravitational Waves

> Einstein predicted them in 1916, then spent years doubting they were real. It took ninety-nine years, four kilometres of vacuum and a measurement of one part in ten thousand billion billion to prove him right.

If mass curves spacetime (Chapter 5), then *moving* mass should make the curvature change — and a changing curvature should propagate outward as a wave, at the speed of light. Einstein derived this in 1916. In 1936 he wrote a paper with Nathan Rosen concluding that gravitational waves did not exist, submitted it to *Physical Review*, received a critical referee report, withdrew it in irritation, and never published in that journal again. The referee was right; the paper had an error in its choice of coordinates.

A gravitational wave is a ripple in the geometry of space itself. As one passes, it **stretches space in one direction while squeezing it in the perpendicular direction**, then reverses, oscillating as it goes. Everything within it is stretched and squeezed — including any ruler you might use to measure the effect, which is why detecting them is far harder than it sounds.

The scale of the problem

The strain — the fractional change in length — from a violent astrophysical event reaching Earth is around $\mathbf{10^{-21}}$.

Over LIGO's 4-kilometre arm, that is a displacement of about 4×10^{-18} metres: roughly **one thousandth of the diameter of a proton**. It is the equivalent of measuring the distance to Proxima Centauri to within the width of a human hair.

Everything interferes. Seismic noise, traffic, ocean waves hundreds of kilometres away, thermal vibration of the mirror atoms, and the quantum shot noise of the laser light itself. The mirrors hang from multi-stage pendulums inside one of the largest vacuum systems on Earth, and even so the detectors spend a great deal of time being defeated by trucks.

HOW LIGO WORKS

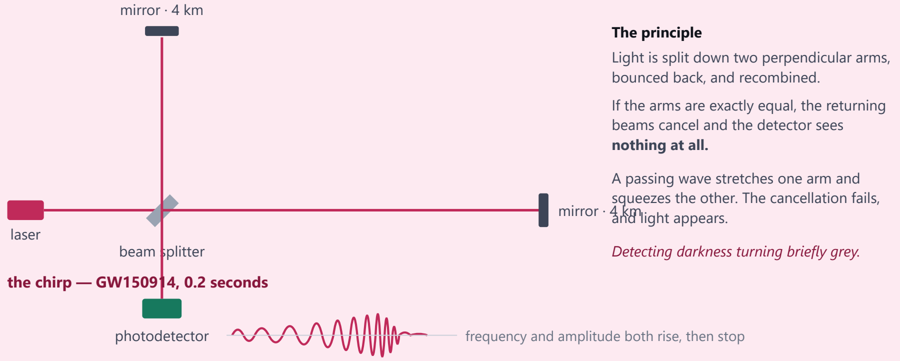


Figure 33.1 — An interferometer measures a difference, not a length. That is the trick: absolute distances cannot be measured to this precision, but the *difference* between two arms can, because the comparison is made with the light itself.

CASE FILE · GW150914 — 14 SEPTEMBER 2015

At 09:50:45 UTC, the Livingston detector in Louisiana registered a signal. Seven milliseconds later — consistent with a wave travelling at light speed across the 3,000 km between them — Hanford in Washington recorded the same thing.

It lasted 0.2 seconds. The frequency swept upward from 35 to 250 Hz, and the amplitude grew and then cut off: the characteristic **chirp** of two objects spiralling together, faster and faster, until they merged.

The waveform matched general relativity's prediction for two black holes of **36 and 29 solar masses**, 1.3 billion light-years away, merging into a single hole of 62 solar masses. Three solar masses had been converted directly into gravitational-wave energy in a fraction of a second — briefly radiating more power than all the light from every star in the observable universe combined.

The detectors had only just finished a major upgrade and were still in engineering runs. The signal was so clean and so exactly matched to theory that the collaboration's first serious hypothesis was that somebody had secretly injected a fake — a procedure they use to test themselves. It took months to confirm that nobody had.

Announced on 11 February 2016. Nobel Prize 2017 to Weiss, Barish and Thorne. It confirmed in one event that gravitational waves exist, that black holes exist and merge, that stellar black holes can be far heavier than expected, and that general relativity holds in the strongest fields ever tested.

A new sense, not a better telescope

The important point is that gravitational waves are not electromagnetic radiation, and the difference is not one of degree. Light is emitted by *matter* and is absorbed, scattered and reddened on its way to us. Gravitational waves are emitted by **the motion of mass itself** and pass through everything essentially unimpeded — through dust clouds, through stars, through the entire Earth.

This lets us observe things that emit no light at all. Two black holes merging in empty space produce no photons whatsoever. Before 2015, such an event was completely undetectable by any means. It is not that we could not see it well; there was nothing to see.

Over a hundred mergers have now been catalogued. They have already produced results nobody expected: black holes in mass ranges stellar evolution said should not exist, a 142-solar-mass remnant filling the "intermediate" gap, and the neutron-star merger of Chapter 13 that settled the origin of gold.

What is coming, including in India

The current network is LIGO Hanford, LIGO Livingston, Virgo in Italy and KAGRA in Japan. More detectors mean better sky localisation, because the direction to a source is worked out from arrival-time differences — with two detectors you get a broad arc, with four you get a patch.

LIGO-India, approved by the Union Cabinet in April 2023 with a budget of about ₹2,600 crore, is being built at Aundha in the Hingoli district of Maharashtra, with completion targeted around 2030. Its location matters enormously: adding a detector far from the existing ones dramatically improves localisation, which is what allows optical telescopes to find the counterpart of a merger in time to observe it. Indian groups at IUCAA, ICTS-TIFR, RRCAT and several IITs have been part of the LIGO Scientific Collaboration since well before the first detection.

Further out, **LISA** — an ESA-led constellation of three spacecraft 2.5 million km apart, due for launch in the mid-2030s — will observe much lower frequencies, where supermassive black hole mergers live. And **pulsar timing arrays**, including the Indian Pulsar Timing Array using the GMRT, reported evidence in 2023 for a nanohertz gravitational-wave background, most likely from a population of supermassive black hole binaries across the whole universe.

DO THE MATH · 33.1

How small is 10^{-21}? Strain $h = \Delta L/L$.

- For LIGO, L = 4,000 m and $h = 1 \times 10^{-21}$. Find ΔL. Compare with a proton's diameter, 1.7×10^{-15} m.
- Apply the same strain to the Earth's diameter, 1.27×10^{7} m.
- Apply it to the distance to Proxima Centauri, 4.0×10^{16} m. Compare with a human hair, 7×10^{-5} m.

Then check the energy claim. Three solar masses (5.97×10^{30} kg) converted to energy via $E = mc^2$, released over 0.2 s — what is the peak power in watts? The observable universe's stars emit roughly 10^{49} W in total. Which is larger?

GET THIS STRAIGHT

"Gravitational waves are ripples travelling through space." Nearly right, and the correction matters. They are ripples **of** space — oscillations in the geometry itself, not a disturbance moving through some medium sitting inside space.

There is no aether. Nothing is waving except distance. When a gravitational wave passes through your body, the actual separation between your atoms changes — by about 10^{-21} of your height, which is why you have never noticed. Several passed through you while you read this page.

Four kilometres, measured to a thousandth of a proton

LIGO Hanford in Washington State. Each arm of the L is 4 km long, held under vacuum, with laser light bouncing between mirrors suspended to be as close to motionless as engineering permits. A passing gravitational wave changes the arm lengths by about one part in 10^{21}. A second, identical detector 3,000 km away in Louisiana is what makes a detection believable.

Credit: Caltech/MIT/LIGO Laboratory. Public domain.

IN A HURRY?

- Gravitational waves are **ripples in spacetime geometry**, predicted 1916, detected **2015**.
- They stretch one direction while squeezing the perpendicular one, with strain around **10^{-21}** — a thousandth of a proton over LIGO's 4 km.
- An interferometer measures the **difference** between two arms, not an absolute length.
- **GW150914**: two black holes of 36 and 29 $M_\odot$ merging 1.3 billion ly away, converting **3 solar masses to pure radiation**.
- This is a **new sense**, not a better telescope — it detects events that emit no light at all.
- **LIGO-India** is being built at Aundha, Maharashtra, targeted for around 2030, and will greatly improve sky localisation.

CHAPTER 34 · DOING ASTROPHYSICS

Multi-Messenger Astronomy

> For four centuries astronomy had one sense. It now has four, and the interesting results come from using them together — which turns out to be as much an organisational problem as a scientific one.

Four fundamentally different kinds of signal now reach us from space, and each is produced by different physics, escapes from different places, and carries different information. Using them together is called **multi-messenger astronomy**, and it is where the field is going.

THE FOUR MESSENGERS

Messenger	Travels	Blocked by	Tells you about
Photons radio → gamma	at *c*, in straight lines	dust, gas, atmosphere	surfaces, atmospheres, temperature, composition, motion
Cosmic rays protons, nuclei	near *c*, but *deflected*	nothing much	extreme particle acceleration — but direction is scrambled by magnetic fields
Neutrinos	at very nearly *c*, straight	essentially nothing	the insides of stars, collapsing cores, dense environments photons cannot leave
Gravitational waves	at *c*, straight	nothing at all	the motion of mass itself — mergers, and objects that emit no light

The complementarity is the point. Photons show you the surface of things; neutrinos show you the core; gravitational waves show you mass moving, whether or not it shines. Cosmic rays prove that extreme acceleration is happening somewhere, though their bent paths mean they rarely tell you where.

CASE FILE · GW170817, HOUR BY HOUR

Chapter 13 described what this event settled about gold. What is worth studying here is how it actually unfolded, because it is the template for how the field now works.

12:41:04 UTC. LIGO Hanford, LIGO Livingston and Virgo record a 100-second chirp — far longer than any black hole merger, because lighter objects spiral for longer. Two neutron stars.

12:41:06. Two seconds later, the Fermi Gamma-ray Burst Monitor triggers on a short gamma-ray burst. An automated alert goes out.

13:21. A joint LIGO–Virgo–Fermi alert reaches the astronomical community. Virgo's *non*-detection is crucial: because the source fell in a blind spot of Virgo's antenna pattern, the sky region is narrowed to about 30 square degrees. With two detectors it would have been hundreds.

23:33. Just under eleven hours after the merger, the Swope telescope in Chile images galaxy NGC 4993 and finds a new point of light that was not there before. Five other teams find it independently within the hour.

The following weeks. Roughly **70 observatories** and thousands of astronomers follow it across radio, infrared, optical, ultraviolet, X-ray and gamma. The optical counterpart fades from blue to red over days — the kilonova signature of freshly synthesised heavy elements decaying. X-ray and radio emission rises over months as the jet, pointed slightly away from us, spreads.

The scientific yield from one event: the origin of r-process elements confirmed; short gamma-ray bursts shown to come from neutron-star mergers; an independent measurement of the Hubble constant using the merger as a "standard siren"; and — because the gravitational waves and the gamma rays arrived within 1.7 seconds after 130 million years of travel — proof that **gravity propagates at the speed of light to within one part in 10^{15}**, which immediately killed a whole class of alternative gravity theories.

The unglamorous part: telling everyone in time

Multi-messenger astronomy has an awkward property. The events are transient — a kilonova fades in days, a gamma-ray burst afterglow in hours — and the instruments that detect the first signal are usually not the ones that can identify the source. So the whole enterprise depends on **alert infrastructure**: automated systems that push a position and a timestamp to every telescope on Earth within minutes.

These are real, working systems with unglamorous names — GCN for gamma-ray bursts, SNEWS for supernova neutrinos, the LIGO-Virgo-KAGRA public alerts, and the brokers being built for Vera Rubin's ten million nightly alerts. A large amount of the actual scientific productivity of this field now depends on software written by people whose names do not appear on the discovery papers.

There is a related and genuinely difficult judgement to make: **how confident should you be before alerting the world?** Alert too readily and you waste enormous amounts of telescope time on false positives. Alert too cautiously and the event has faded before anyone can look. Both LIGO and the neutrino observatories publish their false-alarm rates openly and let each observatory decide its own threshold, which is a sensible answer to a problem with no clean solution.

CASE FILE · THE BLAZAR AND THE NEUTRINO, 2017

On 22 September 2017, IceCube — a cubic kilometre of Antarctic ice instrumented with 5,160 light detectors — recorded a single neutrino of about 290 TeV. Its direction was reconstructed to within about half a degree, and an automated alert went out within 43 seconds.

Telescopes pointed at that patch of sky found a known blazar, **TXS 0506+056**, four billion light-years away — and it was in an unusually active state, flaring in gamma rays. Chapter 24 explains what a blazar is: an active galactic nucleus with its jet aimed almost directly at us.

A single neutrino coinciding with a single flare is not proof. So the team went back through nine and a half years of archived IceCube data and found an excess of neutrinos from that same direction during 2014–15. The combined significance reached about 3.5 sigma — suggestive, not conclusive by particle-physics standards.

It remains the best evidence for an identified source of high-energy cosmic neutrinos, and by implication for where the highest-energy cosmic rays are accelerated — a question open since Victor Hess discovered cosmic rays in 1912. Note that the result depended on **a 43-second automated alert** and on **a decade of carefully archived data**. Neither is glamorous; without either, there is no result.

DO THE MATH · 34.1

Test relativity with two arrival times. GW170817's gravitational waves and gamma rays travelled 130 million light-years and arrived **1.7 seconds** apart.

- Convert 130 million years into seconds.
- The fractional difference in speed is at most (1.7 s) ÷ (travel time). Compute it.
- Express the constraint as: $|v_{gw} - c| / c < ?$

You should get a bound of roughly 10^{-15}. Then think about the assumption hiding in it: the 1.7 s could be an intrinsic delay in the astrophysics — the gamma rays may genuinely have been emitted slightly after the merger. Does that make the bound weaker or stronger? (It makes it *conservative*: the true speed difference is even smaller than your number, since some of the 1.7 s is not travel time at all.)

CAREER NOTE

Multi-messenger astronomy is unusually welcoming to people with computing skills, because so much of it is real-time infrastructure, alert brokering, and cross-matching enormous catalogues under time pressure. India is well placed: it is a partner in LIGO with **LIGO-India** under construction, has GMRT for rapid radio follow-up, AstroSat for X-ray, and a growing network of optical telescopes at Hanle, Devasthal and Mount Abu that can respond to alerts. The **GROWTH-India** telescope at Hanle exists specifically to chase transient alerts, and it is run by a small team at IIT Bombay and IIA.

IN A HURRY?

- Four messengers: **photons, cosmic rays, neutrinos, gravitational waves**. Each reaches us from places the others cannot.
- **GW170817** (2017) was seen in gravitational waves and then across every electromagnetic band by ~70 observatories.
- It confirmed the origin of gold, explained short gamma-ray bursts, and showed gravity travels at *c* to **one part in 10^{15}**.
- **IceCube's 2017 neutrino** was traced to a flaring blazar — the best evidence yet for where cosmic rays are accelerated.
- The field depends on **automated alert systems** and on archived data, both written by people who rarely get the credit.
- India contributes through **LIGO-India, GMRT, AstroSat** and the transient-chasing GROWTH-India telescope at Hanle.

CHAPTER 35 · DOING ASTROPHYSICS

India Looks Up

> Fifteen hundred years of astronomy, a space programme built on a shoestring, and — since about 2020 — a private industry that did not exist when you started school.

India's relationship with the sky is unusually long, and it is worth knowing properly rather than as a list of patriotic bullet points. Some of what follows is genuinely world-leading. Some of it was superseded and deserves to be described as history rather than as a claim. Distinguishing the two is itself a scientific skill.

Before telescopes

The **Vedanga Jyotisha**, compiled somewhere around 1400–1200 BCE, is among the oldest surviving astronomical texts anywhere, concerned mainly with fixing the calendar for ritual purposes.

The decisive figure is **Aryabhata**, who completed the *Aryabhatiya* in 499 CE at the age of 23. In it he stated that the apparent daily motion of the stars is caused by the **Earth's rotation on its own axis**, using the image of a man in a moving boat seeing the riverbank slide past. He explained eclipses correctly as shadows — the Moon entering Earth's shadow, the Moon's shadow falling on Earth — explicitly rejecting the mythological account of Rahu and Ketu. He gave π as 3.1416 and described it as "approximate", which is a remarkably modern thing to do. And he tabulated sine values, effectively founding trigonometry as a computational tool; the word "sine" reaches English through a chain of mistranslation from his Sanskrit *jya*.

Brahmagupta (628 CE) worked on gravity as an attractive property of the Earth and formalised zero as a number. **Bhaskara II** (1150) computed the length of the sidereal year as 365.2588 days — about three and a half minutes from the modern value.

Least known and most striking is the **Kerala school**, founded by Madhava of Sangamagrama around 1380. They derived infinite series expansions for sine, cosine and arctangent — including the series usually called the Gregory–Leibniz series for π — roughly **250 years before** Newton and Leibniz reached the same results in Europe. Whether this constitutes calculus is a genuine scholarly argument; that the series are correct and were derived first is not.

Then, in the 1720s and 1730s, Sawai Jai Singh II built the **Jantar Mantar** observatories at Jaipur, Delhi, Ujjain, Varanasi and Mathura — enormous masonry instruments designed to beat the precision limits of small brass devices. The Samrat Yantra at Jaipur is a sundial 27 metres tall that reads local time to about two seconds.

It is also, quietly, the end of an era. Jai Singh was building the finest naked-eye instruments in the world at a moment when Europe had already had telescopes for a century. Magnificent engineering, aimed at a problem that had already been solved a different way — a useful and slightly uncomfortable lesson about the cost of working in isolation.

CASE FILE · MEGHNAD SAHA, AND AN EQUATION EVERY ASTRONOMER USES

In 1920, working in Calcutta with very little equipment, Meghnad Saha derived what is now called the **Saha ionisation equation**. It relates the degree of ionisation of a gas to its temperature, pressure and the ionisation energies of its atoms.

This is the missing piece that makes Chapter 16 work. Before Saha, nobody could explain why spectral classes looked so different — hydrogen lines strong in A stars, weak in both hotter and cooler ones. Saha showed the differences are almost entirely a matter of **temperature** determining which ionisation states exist, not of composition. It is what turned stellar spectroscopy from cataloguing into physics, and it is the tool Cecilia Payne used five years later to show that stars are made of hydrogen.

Saha was nominated for the Nobel Prize repeatedly and never received it. He later became a member of the Lok Sabha, drove the reform of the Indian calendar, and campaigned for science funding — arguing, in a phrase worth remembering, that a country cannot import its scientific base.

The space programme

India's space effort was founded by **Vikram Sarabhai**, who came to it through cosmic ray research at the Physical Research Laboratory in Ahmedabad. The first sounding rocket flew from Thumba, near Thiruvananthapuram, in 1963; components were famously transported to the pad by bicycle and bullock cart, which is an anecdote worth keeping in proportion — it reflects a deliberate strategy of doing what could be afforded rather than waiting.

Sarabhai's stated justification is unusual among space programmes and has shaped everything since: India would not compete in Moon races, but would apply space technology to **communications, weather forecasting, agriculture and education** — problems of development. Remote sensing for crop monitoring and satellite television for rural schools came before any planetary science.

THE MISSIONS WORTH KNOWING

Mission	Year	Why it matters
Aryabhata	1975	first Indian satellite, launched by the Soviet Union
SLV-3	1980	first indigenous orbital launch; India becomes the sixth nation able to reach orbit
Chandrayaan-1	2008	found **water molecules on the Moon** — a genuinely major result, from NASA's M^3 instrument on an Indian orbiter
Mangalyaan	2013–14	first nation to reach Mars orbit on its **first attempt**
AstroSat	2015	India's first space observatory; simultaneous UV, optical and X-ray
Chandrayaan-3	2023	first soft landing near the **lunar south pole**, after Chandrayaan-2's lander failed in 2019
Aditya-L1	2023–24	solar observatory in halo orbit at the L1 point, 1.5 million km out
XPoSat	2024	only the second X-ray polarimetry mission ever flown
LIGO-India	~2030	gravitational-wave detector at Aundha, Maharashtra (Chapter 33)

CASE FILE · WHY MANGALYAAN COST SO LITTLE

The Mars Orbiter Mission cost about **₹450 crore** — roughly $74 million at the time. NASA's MAVEN, launched to Mars the same year, cost about $672 million. The comparison was repeated everywhere, usually with the observation that the Indian mission cost less than the film *Gravity*.

The comparison is real but needs honest unpacking, because the interesting part is not "Indians are cheap".

Lower salaries account for a large share — a significant structural advantage, not an engineering achievement. **Modular reuse** of proven components from earlier missions avoided new development. **A deliberately modest payload**: 15 kg of instruments against MAVEN's 65 kg, so it did less. **Rapid development**, about 15 months, kept standing costs down. And a clever **orbit-raising strategy**: PSLV could not send it directly to Mars, so the spacecraft made six progressively larger orbits of Earth before a slingshot, trading time for launch capability.

MOM was primarily a **technology demonstrator** — proving India could navigate to another planet and insert into orbit — and it succeeded completely at that. It returned useful data on the Martian atmosphere and dust storms, and operated for over eight years against a design life of six months. It was not, and was not meant to be, a mission of MAVEN's scientific depth. Both statements are true, and the achievement stands without needing the exaggeration.

The part that is new: private Indian space

Until 2020 there was effectively one customer, one supplier and one regulator in Indian space, and all three were the government. Three changes broke that open: the creation of **IN-SPACe** in 2020 as an independent authorisation body, the **Indian Space Policy 2023** which formally allowed private end-to-end activity, and the 2024 rules permitting **up to 100 per cent foreign direct investment** in parts of the sector.

There are now well over 200 space startups in India. Four are worth knowing by name.

Skyroot Aerospace (Hyderabad, founded 2018 by two former ISRO engineers) launched **Vikram-S** on 18 November 2022 — the first privately built Indian rocket to reach space, a suborbital flight to 89.5 km. Its orbital vehicle, Vikram-1, uses carbon-composite structures and 3D-printed thrusters.

Agnikul Cosmos (Chennai, incubated at IIT Madras) flew **Agnibaan SOrTeD** on 30 May 2024, from India's first private launchpad at Sriharikota. Its engine, Agnilet, is claimed to be the **world's first single-piece 3D-printed semi-cryogenic engine** — printed as one part rather than assembled from many, which removes most of the joints where rocket engines fail.

Pixxel (Bengaluru) builds **hyperspectral** imaging satellites — instruments that record hundreds of narrow spectral bands per pixel rather than three. That is Chapter 8's spectroscopy, pointed downward: the same technique that identifies elements in a star identifies crop disease, methane leaks and mineral deposits from orbit.

Dhruva Space (Hyderabad) builds satellite platforms and deployers, and **Digantara** works on space situational awareness — tracking debris and satellites, a problem that grows directly out of Chapter 32's constellation boom.

A necessary caution, since this is a chapter a student might read as career advice: these are young companies in a capital-intensive industry with long timelines and a high failure rate worldwide. Several will not survive. That is normal, and it is not a reason to avoid the sector — but it is a reason to build transferable skills rather than betting on one employer.

TRY THIS · WATCH A LAUNCH, PROPERLY

ISRO streams its launches live, and they are worth watching with the commentary rather than as spectacle. Things to listen for, each of which is physics from earlier chapters:

- **"Max Q"** — maximum dynamic pressure, where aerodynamic stress on the vehicle peaks and the engines are usually throttled back.
- **Stage separation** — dropping empty mass, because the rocket equation punishes carrying dead weight.
- **Fairing jettison** — once above the atmosphere, the nose cone is dead mass.
- **"Velocity 7.8 km/s"** — compare with your answer to Do the Math 4.1. Orbit is about *sideways speed*, not height.

Sriharikota launches are visible from parts of coastal Andhra Pradesh and Tamil Nadu. ISRO occasionally opens a public viewing gallery, and it is bookable.

CAREER NOTE · THE TWO DIFFERENT DOORS

People conflate "working in space" with "doing astrophysics". They are different careers with different entry routes, and choosing wrongly wastes years.

ISRO and the space industry want engineers. The main route is a BTech in mechanical, electronics, aerospace, computer science or electrical engineering, then ISRO's ICRB recruitment exam, or IIST Thiruvananthapuram, which is ISRO's own institute and places graduates directly. Private companies hire on the same profiles and pay more.

Astrophysics research wants physicists. The route is BSc physics or a BS–MS at an IISER, then a PhD at IUCAA, TIFR, IIA, ARIES, RRI, PRL, NCRA or an IIT, entered through JEST or GATE. This is a longer path to a lower salary, and it is the one where you get to work on the questions in this book.

You do not have to decide now. You do have to know that the decision exists — most students discover it far too late.

The Samrat Yantra at Jantar Mantar, Jaipur. Built in the 1730s by Sawai Jai Singh II — a sundial 27 metres tall, reading local time to about two seconds. Superb naked-eye engineering, constructed a century after the telescope had already made the approach obsolete.

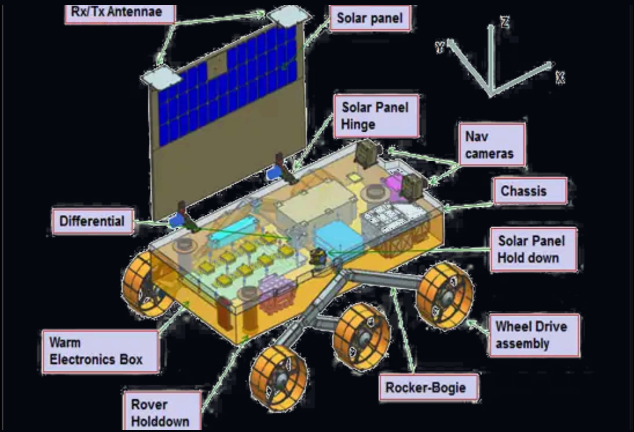
Chandrayaan-3 leaves the pad

LVM3-M4 lifting off from the Second Launch Pad at Sriharikota on 14 July 2023. Forty-one days later its lander touched down near the lunar south pole, making India the fourth country to land on the Moon and the first anywhere near that terrain. The vehicle is the heaviest India operates — 640 tonnes at lift-off, with two solid boosters, a liquid core and a cryogenic upper stage.

Credit: Indian Space Research Organisation / derivative work: UnpetitproleX. GODL-India.

India looks up

Four facilities, from a launch pad on the Bay of Bengal to a telescope at 4,500 metres in Ladakh.



Pragyan, laid out
— ISRO's own diagram of the Chandrayaan-3 rover: 26 kg, solar powered, six wheels.

PSLV at Sriharikota
— ISRO's workhorse, with over 55 successful launches.

The GMRT, near Pune
— thirty 45-metre dishes over 25 km; world-class at metre wavelengths.

Hanle, Ladakh
— the Indian Astronomical Observatory at 4,500 m, one of the highest on Earth.

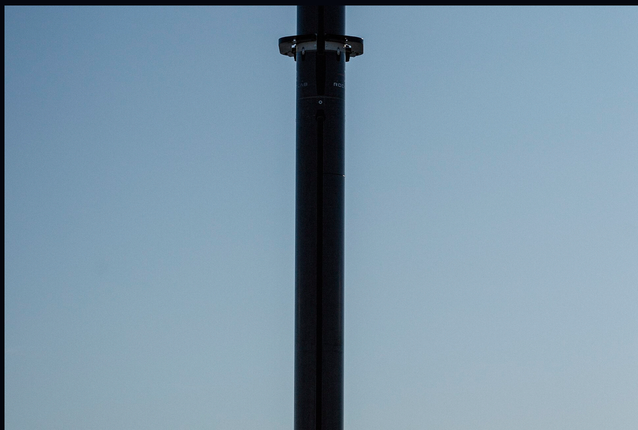
The new space industry

Private companies now build and fly launch vehicles that only governments once could.

Vikram-S, November 2022
— Skyroot's vehicle, the first privately built Indian rocket to reach space.

Falcon 9 lands
— reusing the first stage cut launch costs roughly sevenfold.

Starbase, Texas
— SpaceX's Starship tower, designed for far heavier payloads still.



Rocket Lab Electron
— small dedicated launches, frequent enough to make student satellites realistic.

IN A HURRY?

- **Aryabhata** (499 CE) explained the Earth's rotation and eclipses correctly, and founded trigonometric computation.
- The **Kerala school** derived infinite series for sine, cosine and π roughly 250 years before Europe.
- **Jantar Mantar** (1720s) is superb naked-eye engineering built a century after the telescope made it obsolete.
- **Meghnad Saha's ionisation equation** (1920) made stellar spectroscopy into physics.
- ISRO was built around **development applications first**. Chandrayaan-1 found **water on the Moon**; Mangalyaan reached Mars first try; Chandrayaan-3 landed near the **lunar south pole**.
- Since 2020, **IN-SPACe** and the 2023 space policy opened the sector: **Skyroot** flew India's first private rocket in 2022, **Agnikul** flew a 3D-printed engine in 2024.
- **Engineering and astrophysics are different careers.** Know which door you are walking through.

IX

Your Turn

The last part is not about the universe. It is about you, and the fairly specific set of things you should do between Class 9 and a research career.

CHAPTER 36 · YOUR TURN

The Maths You Will Actually Need

> Astrophysics uses less exotic mathematics than people expect, and uses a small amount of ordinary mathematics extremely heavily. Here is what actually earns its keep.

Students who want to do this often assume the barrier is some fearsome advanced topic. It usually is not. The people who struggle in a physics degree almost never struggle with the exotic material; they struggle because algebraic rearrangement is slow, or because they never really internalised logarithms, and everything downstream costs them extra effort.

The list below is short on purpose. Get genuinely fluent in these — fluent meaning you can do them without thinking, not that you have seen them — and the rest is learnable when you need it.

WHAT TO LEARN, AND ROUGHLY WHEN

CLASS 9–10 · NOW

Scientific notation
10^n arithmetic without a calculator

Algebra — rearranging
any formula, for any variable

Logarithms
log rules, and why they turn multiplication into addition

Ratios and proportionality
"if $L \propto M^{3.5}$, then doubling M …"

Basic trigonometry
sin, cos, tan and the unit circle

Units and dimensions
carrying units through every step

Python — start now

CLASS 11–12

Calculus
derivatives as rates of change, integrals as accumulated totals

Vectors
components, dot and cross products

Small-angle approximation
$\theta \approx \sin\theta \approx \tan\theta$ for small θ

Complex numbers
and why waves are written as e^(iθ)

Probability and statistics
mean, standard deviation, error bars

Mechanics and waves
done properly, not memorised

numpy · matplotlib

UNDERGRADUATE

Differential equations
ordinary, then partial

Linear algebra
matrices, eigenvalues, bases

Fourier analysis
the backbone of all signal work

Statistical mechanics
and thermodynamics

Quantum mechanics

Tensor calculus
only if you want relativity theory

Bayesian inference
how modern results are actually claimed

astropy · scipy · MCMC

Figure 36.1 — A realistic sequence. Nothing in the first column is beyond Class 9, and everything in it is used constantly for the rest of a career. The third column is where most people expect the difficulty to be; it is not.

The four that do the most work

1 · Scientific notation and orders of magnitude. Every number in this book is in it. You should be able to multiply 3×10^8 by 3.16×10^7 in your head to one significant figure, and to spot instantly that an answer of 10^{52} when you expected 10^{26} means you squared something by mistake. This is not arithmetic drill; it is error detection.

2 · Logarithms. Astronomy is a logarithmic subject because its quantities span forty orders of magnitude. Magnitudes are logarithmic (Chapter 6). The H–R diagram is logarithmic (Chapter 16). Decibels, pH, the Richter scale and stellar luminosities are all the same idea. If $\log(ab) = \log a + \log b$ is not automatic for you, fix that this month.

3 · The small-angle approximation. For a small angle θ measured in radians, $\theta \approx \sin\theta \approx \tan\theta$. Astronomically this becomes $\theta = s/d$: angular size equals physical size over distance. It is how parallax works, how the transit method sizes a planet and how the EHT's resolution was checked in Chapter 21. One approximation, used everywhere.

4 · Error bars. This is the one that separates people who have understood science from people who have memorised it. Every measurement has an uncertainty; every calculation must propagate it; and whether a result is interesting depends entirely on the ratio of the signal to the uncertainty. Chapter 2's Methuselah star and Chapter 27's Hubble tension are both stories about error bars, not about central values.

DO THE MATH · 36.1

Propagate an uncertainty. The two rules cover most cases. For a sum or difference, add the *absolute* uncertainties in quadrature; for a product or quotient, add the *relative* uncertainties in quadrature:

```
Q = A × B      ⟹    (σ_Q/Q)² = (σ_A/A)² + (σ_B/B)²

Q = A + B      ⟹    σ_Q² = σ_A² + σ_B²
```

- A star's luminosity is $L = 4\pi d^2F$. If the distance is known to 10% and the flux to 3%, how well is the luminosity known? (Careful: the d^2 doubles the relative uncertainty on d.)
- Two teams measure H_0 as 67.4 ± 0.5 and 73.0 ± 1.0. How many combined standard deviations apart are they? (Difference divided by the quadrature sum of the uncertainties.)
- Is that a disagreement worth losing sleep over? What threshold do particle physicists use?

TRY THIS · YOUR FIRST FOUR PYTHON PROGRAMS

Install Python and write these, in order. Between them they use every idea in this book's calculations, and together they take a weekend.

1. **A unit converter.** Light-years to metres to AU to parsecs, both ways. Boring, and you will use it constantly.
2. **A blackbody calculator.** Input a temperature, output Wien's peak wavelength (Chapter 7) and the Stefan–Boltzmann flux (Chapter 16). Then plot the curve with matplotlib.
3. **An H–R diagram.** Download a chunk of the Gaia catalogue with astroquery, plot colour against absolute magnitude, and watch the main sequence appear out of two million dots you fetched yourself.
4. **A transit finder.** Pull a real TESS light curve with the lightkurve package, plot it, and find the dip. You will have detected a planet.

Nobody will teach you this in school, every one of these is a normal afternoon's work for a professional, and being able to do them at sixteen puts you ahead of most people applying to PhD programmes.

GET THIS STRAIGHT

"You have to be a maths genius to do astrophysics." You have to be persistent and comfortable with being stuck, which is a different quality and a trainable one.

The mathematics in a physics degree is standard and taught in sequence. What actually filters people out is the experience of not understanding something for weeks and continuing anyway. Almost every student hits a wall — for many it is quantum mechanics, for others electromagnetism — and concludes they are not clever enough. Almost everyone who continued hit the same wall and simply kept going.

Einstein's own remark on this is worth taking seriously rather than as a poster: "Do not worry about your difficulties in mathematics. I can assure you mine are still greater."

IN A HURRY?

- Get fluent **now** in scientific notation, algebraic rearrangement, logarithms, ratios, trigonometry and unit-carrying.
- **Logarithms** matter more than students expect — the whole subject spans forty orders of magnitude.
- The **small-angle approximation**, $\theta = s/d$, appears everywhere from parallax to the EHT.
- **Error bars are not decoration.** A measurement without an uncertainty is not a measurement.
- Learn **Python** years before anyone asks you to. It is the working language of the field.
- The filter is **persistence**, not talent. Everybody hits a wall.

CHAPTER 37 · YOUR TURN

How to Become an Astrophysicist

> A specific, honest plan from Class 9 onwards — including the parts nobody mentions, such as how few permanent jobs there are and what else the training is good for.

This chapter is deliberately practical. It also tries to be honest, which means it contains some discouraging numbers. Read them as information rather than as advice to stop: people who go in knowing the shape of the path do considerably better than people who find out at 26.

Right now — Class 9 and 10

Nothing you do at this stage is an entrance exam. What matters is building three things: fluency, evidence of genuine interest, and the habit of finishing.

Do the mathematics from Chapter 36 until it is automatic. This is the single highest- return activity available to you, and it is almost entirely within your school syllabus.

Enter the olympiad pipeline. In India the astronomy route runs through HBCSE: **NSEA** (National Standard Examination in Astronomy, usually taken in Class 11 or 12) → **INAO** → an orientation camp → the national team for the **International Olympiad on Astronomy and Astrophysics**. Class 9 is the right time to start preparing, not the right time to sit it. There is also NSEP for physics and the RMO/INMO mathematics pipeline, and doing well in any of these is taken seriously by every institute in the country. Check current dates and eligibility on the HBCSE site, because the schemes change.

Learn Python properly. Chapter 36 lists four projects. Do them.

Actually look at the sky. Learn ten constellations. Find Andromeda. Watch Jupiter's moons through binoculars over four nights and see them move. A student who has done this talks about astronomy differently from one who has only read about it, and interviewers notice.

Read beyond textbooks. Appendix D lists specific books. Beyond that: read one research paper a month on arXiv even though you will not understand most of it. Read the abstract, the introduction and the conclusions, and skip the rest. After two years you will find you understand a surprising amount, and you will have learnt how the literature is written — which is a skill in itself.

Class 11 and 12

Take physics, chemistry and mathematics. Chemistry matters more than students think — spectroscopy, planetary atmospheres and astrochemistry all rest on it.

Then a point that surprises many families: **you do not need JEE for astrophysics.** The IITs are excellent and several have strong astronomy groups, but the more natural routes are research-focused institutions:

- **IISERs** (Pune, Kolkata, Mohali, Bhopal, Thiruvananthapuram, Tirupati, Berhampur) — five-year integrated BS–MS, admission through the **IAT** (IISER Aptitude Test). Research from the first year. For a future astrophysicist this is arguably the best undergraduate option in the country.
- **IISc Bengaluru** — four-year BS in research.
- **NISER Bhubaneswar** and **CEBS Mumbai** — integrated MSc.
- **IIST Thiruvananthapuram** — ISRO's own institute, for the engineering route.
- **Strong BSc physics programmes** — St Stephen's, Hindu, Miranda House, Fergusson, Presidency, Loyola, and many others. A good BSc followed by a good MSc is a perfectly normal path, and cheaper.

Admission schemes in India change frequently — KVPY was folded into INSPIRE, NISER's route moved to JEE Advanced, CUET's role keeps shifting. **Verify everything against the current official notification** rather than trusting any book, including this one.

Apply for the **INSPIRE-SHE scholarship** if you take a BSc in basic sciences; it is ₹80,000 a year and specifically exists to keep good students out of engineering.

Undergraduate years — where the real filtering happens

Grades matter, but what actually determines whether you get into a PhD programme is **research experience**, and it is available earlier than most students realise.

India runs an unusually good summer research system, and it is free. The **IASc–INSA–NASI Summer Research Fellowship** places students in labs across the country. **IUCAA**, **IIA**, **NCRA**, **ARIES**, **PRL**, **RRI** and **TIFR** (through its VSRP) all run their own programmes. Apply in your first year even though you will probably be rejected; apply again in your second. Also write directly to individual researchers whose papers you have read — a specific, informed email from an undergraduate is rarer than you would think, and it works often enough to be worth the discomfort.

Then: **finish something**. A small completed analysis you can describe end to end is worth more than three impressive-sounding projects you abandoned.

PhD, and the part that is hard to hear

A PhD is the entry qualification for research, takes four to six years in India, and is paid — around ₹37,000 to ₹42,000 a month as a JRF. Entry is through **JEST**, **GATE**, **CSIR-UGC NET**, or individual institute examinations. Abroad, PhD positions in physics are normally funded through teaching or research assistantships, so you should never pay tuition for a physics PhD.

Now the honest part. The academic pipeline is a funnel with a very narrow end. Roughly speaking, of those who start a physics PhD, a minority continue to postdoctoral work, and of those, a small fraction — commonly estimated at well under one in five worldwide — obtain a permanent academic position. Postdocs typically last two to three years each, often two or three of them, usually in different countries, through your late twenties and thirties. That is genuinely hard on families, and it is the main reason people leave.

This is not a reason to avoid the field. It *is* a reason to be deliberate: build skills that transfer, keep programming seriously, and understand that leaving research is a normal outcome rather than a failure.

CASE FILE · WHAT THE TRAINING IS ACTUALLY WORTH

An astrophysics PhD teaches you to extract a faint signal from a noisy background, handle terabyte datasets, model systems with incomplete information, quantify your own uncertainty honestly, write software that other people rely on, and explain a difficult result to people who do not share your assumptions.

That combination is valuable well outside astronomy, and the people who leave research overwhelmingly do fine. Astronomers routinely move into data science and machine learning, quantitative finance, medical imaging, remote sensing and climate modelling, instrumentation and optics, semiconductor and defence R&D, science policy, and teaching and communication.

The image-reconstruction algorithms behind the black hole photograph in Chapter 21 are close relatives of those used in MRI. The statistical machinery for detecting exoplanet transits is the same as for detecting anomalies in financial or industrial data. This is not a consolation prize; it is a genuine reason the training is worth doing even if you end up somewhere else.

TRY THIS · A TWELVE-MONTH PLAN, STARTING THIS WEEK

- **This week** — install Python; learn to find Polaris, Orion and the Saptarishi (Ursa Major).
- **Month 1** — write the unit converter. Read one arXiv abstract a week.
- **Month 2** — logarithms until they are automatic. Do every Do the Math box in this book.
- **Month 3** — binoculars. Log Jupiter's moons for a fortnight and plot their orbits.
- **Months 4–6** — work through NSEA past papers, whether or not you sit the exam yet.
- **Months 7–9** — download Gaia data and make your own H–R diagram.
- **Months 10–12** — find a TESS light curve and detect a transit. Write up what you did, properly, in two pages.

That last document is the single most useful thing a 15-year-old can have. It shows you can start something, finish it, and describe it — which is, in the end, the whole job.

GET THIS STRAIGHT

"I should do engineering first and switch to astrophysics later — it's safer." This is the most common piece of advice given to Indian students who want physics, and it is usually wrong in a specific way worth understanding.

Switching *is* possible: BTech graduates do get into physics PhDs, particularly in instrumentation and computational areas. But you will arrive without the core physics coursework — classical mechanics at Lagrangian level, electrodynamics, quantum mechanics, statistical mechanics — that your competition took over three years, and you will spend your first two PhD years catching up while they are producing papers.

If you are confident you want research physics, take the physics route. If you are genuinely unsure, an IISER BS–MS is the better hedge than engineering: it keeps research open, and its graduates are hired readily into data and technology roles anyway.

IN A HURRY?

- **Now:** master Class-9 mathematics, learn Python, start the **NSEA/INAO** pipeline, and observe the sky yourself.
- **Class 11–12:** physics, chemistry, mathematics. **You do not need JEE.** Aim at **IISER (IAT)**, IISc, NISER — or a strong BSc plus INSPIRE-SHE.
- **Undergrad:** get **research experience early** through IUCAA, IIA, NCRA, TIFR VSRP or the IASc fellowship. Write to researchers directly.
- **PhD:** via **JEST** or GATE; funded, 4–6 years. Never pay for a physics PhD.
- **Be realistic:** permanent academic posts are scarce and postdoc years are itinerant. Leaving research is normal, not failure.
- The training transfers extremely well — data science, imaging, finance, instrumentation, policy.
- Verify every exam and scheme against current official notifications. They change.

CHAPTER 38 · YOUR TURN

Ten Questions Waiting For You

> Everything in this book is settled enough to teach. These ten are not. Each is open, each is being worked on now, and several will be answered within your career.

A textbook can give the impression that a subject is finished — that the work was done by people with statues and the rest is revision. Astrophysics is not remotely finished. What follows is a list of things nobody knows, ordered roughly by how likely they are to fall in the next few decades.

1 · WHAT IS DARK MATTER MADE OF?

Five-sixths of the matter in the universe, detected six independent ways, and completely unidentified. WIMP searches have excluded most of the once-favoured parameter space; axions are now the leading candidate, with primordial black holes and sterile neutrinos still alive. **It is also possible that all of it is wrong and gravity needs modifying** — although the Bullet Cluster makes that very hard. Chapter 26.

2 · WHAT IS DARK ENERGY, AND WHY IS IT SO ABSURDLY SMALL?

Sixty-eight per cent of the universe. The simplest model — a cosmological constant — is consistent with all data but disagrees with quantum field theory's estimate by a factor of 10^{120}, the worst prediction in physics. DESI's 2024–25 results hint that dark energy may be *weakening* with time, which would rule out a constant entirely and reopen the question of how the universe ends. Chapters 27 and 28.

3 · WHY IS THERE ANYTHING AT ALL?

Matter beat antimatter by one part in a billion, and the Standard Model's known mechanisms fall about ten orders of magnitude short of explaining it. Something in the early universe violated the symmetry between matter and antimatter far more strongly than any known physics permits. Experiments at neutrino facilities are hunting for CP violation in the lepton sector as the most promising lead. Chapter 10.

4 · HOW DO GRAVITY AND QUANTUM MECHANICS FIT TOGETHER?

General relativity describes spacetime as smooth and continuous. Quantum mechanics describes everything else as discrete and probabilistic. Both are extraordinarily well tested, and they are mathematically incompatible. The incompatibility only matters where gravity is strong *and* distances are tiny — black hole singularities, and the first 10^{-43} seconds. String theory and loop quantum gravity are the main candidate frameworks; neither has made a confirmed prediction. This is the biggest question on the list and the least likely to be settled soon.

5 · WHAT HAPPENS TO INFORMATION THAT FALLS INTO A BLACK HOLE?

Quantum mechanics says information cannot be destroyed. Hawking radiation appears to be purely thermal, carrying none. Something has to give. Most theorists now believe information escapes somehow — via subtle correlations in the radiation, holography, or entanglement islands — but the mechanism is unresolved, and it is currently the sharpest place where our two best theories openly contradict each other. Chapter 20.

6 · DID INFLATION HAPPEN, AND WHAT DROVE IT?

Inflation explains the horizon, flatness and monopole problems, and correctly predicted the fluctuation spectrum. But the field that drove it has never been identified, there are hundreds of viable models, and the decisive test — primordial B-mode polarisation in the microwave background — has not been detected. Simons Observatory and LiteBIRD are hunting it now. Chapter 11.

7 · HOW DID SUPERMASSIVE BLACK HOLES GET SO BIG SO FAST?

Quasars of a billion solar masses exist at redshift 7, when the universe was under 800 million years old. Growing that from a stellar-mass seed by ordinary accretion takes longer than the time available, because radiation pressure limits how fast a black hole can feed. Either the seeds were much larger to begin with — direct collapse of enormous gas clouds — or accretion can exceed the classical limit. JWST keeps finding early black holes that make the problem worse. Chapter 24.

8 · IS THE HUBBLE TENSION NEW PHYSICS?

The local distance ladder gives 73.0 km/s/Mpc; the microwave background gives 67.4. Five sigma apart, after a decade of independent cross-checks. Either there is a systematic error nobody has found in one of the two, or the standard cosmological model is missing something between recombination and today. This is the most likely item on this list to be resolved soon, and the most likely to produce something genuinely new. Chapter 27.

9 · HOW DOES LIFE BEGIN, AND HAS IT BEGUN ANYWHERE ELSE?

We have one example and no theory of abiogenesis that can predict a rate. Finding *independent* life anywhere — Europa, Enceladus, Mars, or an exoplanet atmosphere — would convert the Drake equation's most uncertain term from unknown to measured in a single result. Missions are on their way. Chapters 29 and 31.

10 · WHAT ACCELERATES THE HIGHEST-ENERGY COSMIC RAYS?

Some cosmic ray particles arrive carrying the kinetic energy of a well-struck cricket ball concentrated into a single atomic nucleus — tens of millions of times beyond anything the LHC can produce. No known accelerator in the universe should manage it, and because magnetic fields bend their paths, we usually cannot tell where they came from. The 2017 IceCube blazar association is the best lead so far. Chapter 34.

A closing thought, addressed to one reader in particular

Every question above is being worked on right now by people who were, not very long ago, fifteen years old and reading something like this.

None of them is going to be solved by a lone genius having an idea in a bath. They will be solved the way the results in this book were solved: by somebody spending three years building an instrument, or six months finding a bug in a pipeline, or a decade patiently tracking one star around the centre of the galaxy. Ghez and Genzel watched S2 for sixteen years to complete a single orbit. Davis counted argon atoms in a tank of dry-cleaning fluid for twenty years and was told he was probably wrong the entire time. Jocelyn Bell read thirty metres of chart paper a day by eye.

The romantic picture of science is inspiration. The real thing is mostly persistence, applied by people who found one question they could not stop thinking about.

You have the enormous advantage of arriving at a moment when the tools are extraordinary and the data is free. The Gaia catalogue, the JWST archive, the LIGO strain data and every observation this book describes are downloadable by anyone with an internet connection, including you, tonight. That was not true for any previous generation.

The last thing worth saying is the thing Chapter 13 established. The carbon in your hands was made inside a star that died before the Sun existed. The iron in your blood came from an exploding white dwarf. The gold in a ring on someone's finger was forged in the collision of two neutron stars, somewhere in this galaxy, billions of years ago.

You are made of the debris of dead stars, arranged by four billion years of chemistry into something that can look up and work out where it came from. That is not a sentimental statement. It is a measurement, and this book has shown you how it was made.

Now go and find out something nobody knows.

IN A HURRY?

- Astrophysics is **not a finished subject**. Ten major questions are wide open.
- Most likely to fall soon: the **Hubble tension**, the **nature of dark energy**, and **early supermassive black holes**.
- Least likely: **quantum gravity**.
- Discoveries come from **persistence and instruments**, not sudden inspiration.
- The data is **public and free**. You can start tonight.

APPENDIX A

Numbers Worth Knowing

> Everything needed for every calculation in this book. The starred ones are worth committing to memory — professionals know them without looking.

Physical constants

Quantity	Symbol	Value
Speed of light in vacuum ★	c	2.998×10^{8} m/s (use 3.00×10^{8})
Gravitational constant ★	G	6.674×10^{-11} N·m²/kg²
Planck constant	h	6.626×10^{-34} J·s
Boltzmann constant	k_B	1.381×10^{-23} J/K
Stefan–Boltzmann constant	σ	5.670×10^{-8} W·m^{-2}·K^{-4}
Wien displacement constant	b	2.898×10^{-3} m·K
Proton mass	m_p	1.673×10^{-27} kg
Electron mass	m_e	9.109×10^{-31} kg
Hydrogen atom mass	m_H	1.674×10^{-27} kg

Astronomical distances and times

Quantity	Value	Useful form
Astronomical unit ★	1.496×10^{11} m	≈ 150 million km
Light-year ★	9.461×10^{15} m	≈ 9.46 trillion km
Parsec ★	3.086×10^{16} m	= 3.262 ly = 206,265 AU
Megaparsec	3.086×10^{22} m	= 3.26 million ly
Seconds in a year	3.156×10^{7} s	$\pi \times 10^{7}$ is accurate to 0.5%
Radian in arcseconds	206,265″	for small-angle work
Age of the universe ★	13.797 ± 0.023 Gyr	Planck 2018
Hubble constant	67.4 or 73.0 km/s/Mpc	the two disagree — Chapter 27

The Sun and Earth

Quantity	Value
Solar mass ★	$M_\odot = 1.989 \times 10^{30}$ kg
Solar radius	$R_\odot = 6.96 \times 10^{8}$ m = 696,000 km
Solar luminosity	$L_\odot = 3.828 \times 10^{26}$ W
Solar surface temperature	5,772 K
Solar core temperature	1.57×10^{7} K
Age of the Sun	4.6 billion years
Earth mass ★	$M_\oplus = 5.972 \times 10^{24}$ kg
Earth radius (mean)	6,371 km
Surface gravity	$g = 9.81$ m/s^2
Escape velocity from Earth	11.2 km/s
Earth–Moon distance	3.844×10^{8} m

The composition of the universe

Component	Share	Status
Dark energy	68.3%	unexplained
Dark matter	26.8%	unidentified
Ordinary matter (atoms)	4.9%	everything in this book's periodic table
— of which hydrogen	~74% by mass	Payne, 1925
— of which helium	~24% by mass	Alpher & Gamow, 1948
— everything else	~2% by mass	made by stars — Chapter 13

The equations used in this book

Name	Form	Chapter
Universal gravitation	$F = Gm_1m_2/r^2$	4
Circular orbital speed	$v = \sqrt{(GM/r)}$	4
Escape velocity	$v = \sqrt{(2GM/r)}$	4
Kepler's third law (years, AU)	$T^2 = a^3$	29
Kepler's third law (full)	$M = 4\pi^2a^3/(GT^2)$	24
Mass–energy	$E = mc^2$	15
Photon energy	$E = hf$	6
Wave relation	$c = \lambda f$	6
Inverse-square flux	$F = L/(4\pi d^2)$	6
Magnitude ratio	$F_1/F_2 = 2.512^{(m_2-m_1)}$	6
Wien's displacement law	$\lambda_{max} = 2.898 \times 10^{-3}/T$	7
Stefan–Boltzmann law	$L = 4\pi R^2\sigma T^4$	16
Doppler shift (v ≪ c)	$\Delta\lambda/\lambda_0 = v/c$	8
Hubble's law	$v = H_0d$	27
Mass–luminosity relation	$L/L_\odot \approx (M/M_\odot)^{3.5}$	15
Schwarzschild radius	$R_s = 2GM/c^2$	20
Diffraction limit	$\theta \approx 1.22\ \lambda/D$	21
Small-angle relation	$\theta = s/d$ (θ in radians)	36
Free-fall time	$t_{ff} = \sqrt{(3\pi/32G\rho)}$	14
Transit depth	$\Delta F/F = (R_p/R_\star)^2$	30

Name	Form	Chapter
Angular momentum (collapse)	$T_2 = T_1(R_2/R_1)^2$	19
Cosmological cooling	$T_{then} = T_{now}(1 + z)$	12

A note on precision. Every calculation in this book works to two or three significant figures, which is standard practice for order-of-magnitude astrophysics. Do not report more digits than your least precise input justifies. If you multiply a number known to 10 per cent by one known to 0.001 per cent, your answer is known to 10 per cent — and writing it to six digits is not precision, it is a mistake.

APPENDIX B

Answers to the Do the Math Boxes

Worked to two or three significant figures. If your answer differs in the last digit, you are almost certainly fine. If it differs by a factor of ten, check your units first — it is nearly always the units.

1.1 · Building the light-year

1 ly = $(3.00 \times 10^8)(3.156 \times 10^7)$ = **9.47×10^{15} m**. Proxima at 4.25 ly = **4.02×10^{16} m** = 2.69×10^5 AU. The Parker Solar Probe at 690,000 km/h = 1.92×10^5 m/s would take 4.02×10^{16} / 1.92×10^5 = 2.1×10^{11} s ≈ **6,600 years** — with the fastest object humanity has ever built.

2.1 · The cosmic calendar

1 calendar second = 437 years. Cave paintings (45,000 yr) = 103 s before midnight, **31 Dec 23:58:17**. Indus cities (4,600 yr) = 10.5 s, **23:59:49.5**. IISc (1909, 117 yr) = **0.27 s** before midnight. An 80-year life = **0.18 seconds**.

3.1 · Lookback times

Mars: $5.5 \times 10^{10}/3 \times 10^8$ = 183 s = **3.1 minutes**. Jupiter: 2,100 s = **35 minutes** each way, so 70 minutes round trip — which is why a Jupiter rover must be autonomous; by the time you saw a hazard and reacted, over an hour would have passed. Proxima: 1.33×10^8 s = **4.25 years**. Voyager 1 at 167 AU = 2.50×10^{13} m: 8.3×10^4 s = 23.1 hours one way, **46 hours round trip**.

4.1 · The speed of the space station

$r = 6.791 \times 10^6$ m; $GM = 3.986 \times 10^{14}$. $v = \sqrt{(3.986 \times 10^{14}/6.791 \times 10^6)}$ = **7,660 m/s = 7.66 km/s**. $T = 2\pi r/v$ = 5,570 s = **92.8 minutes**, giving 15.5 orbits per day — which matches the sixteen daily sunrises. For the Moon at 3.84×10^8 m: v = 1,019 m/s, $T = 2.37 \times 10^6$ s = **27.4 days**. ✓

5.1 · Gravitational time dilation on Earth

$\Delta t/t = GM/(rc^2) = 3.986 \times 10^{14}/(6.371 \times 10^6 \times 9 \times 10^{16}) = \mathbf{6.95 \times 10^{-10}}$. Over 80 years ($2.53 \times 10^9$ s) that is **1.8 seconds** of accumulated difference. Small, real, and routinely measured.

6.1 · Magnitudes

Sirius (−1.46) vs Polaris (+1.98): $\Delta m = 3.44$, ratio $= 10^{0.4 \times 3.44} = \mathbf{23.8\times}$. Sun vs full Moon: $\Delta m = 14$, ratio $= 10^{5.6} \approx \mathbf{400{,}000\times}$ — which is why moonlight will not let you read. Betelgeuse and Rigel: absolute magnitudes work out to about −5.6 and −7.0, so **Rigel is roughly 3–4 times more luminous**, despite looking slightly fainter, because it is further away.

7.1 · Wien's law as a thermometer

Human 310 K → **9.3 µm**, mid-infrared. Sun 5,772 K → **502 nm**, visible. Betelgeuse 3,600 K → **805 nm**, near-infrared (hence red). Rigel 12,100 K → **240 nm**, ultraviolet. CMB 2.725 K → **1.06 mm**, microwave. Cluster gas 5×10^7 K → **0.058 nm**, X-ray. Inverting for a 100 µm source: T = **29 K** — visible only to a cold infrared telescope such as JWST or Herschel.

8.1 · Doppler velocities

656.05 nm: $\Delta\lambda = -0.23$ nm → $v = -0.23/656.28 \times 3 \times 10^5$ = **−105 km/s, approaching**. 662.94 nm: $\Delta\lambda = +6.66$ → **+3,045 km/s, receding**. Distance = 3,045/70 = **43.5 Mpc** ≈ 142 million light-years. A 0.0001 nm precision corresponds to **46 m/s** — about 500 times too coarse to detect the Earth's 0.09 m/s effect on the Sun, which is why Earth-analogues remain out of reach for radial velocity.

9.1 · Neutrinos through you

Taking a cross-section of ~0.7 m² = 7,000 cm²: $\mathbf{4.6 \times 10^{14}}$ **per second**, 4×10^{19} per day, and about $\mathbf{1.2 \times 10^{24}}$ **over 80 years** — roughly one ten-thousandth of the 7×10^{27} atoms in your body. Super-Kamiokande holds 50,000 tonnes of water for exactly this reason.

10.1 · Pair-production temperatures

Electron: $mc^2 = 8.20 \times 10^{-14}$ J, so $T = mc^2/k_B = \mathbf{5.9 \times 10^9}$ **K**. Proton: $mc^2 = 1.51 \times 10^{-10}$ J → $\mathbf{1.1 \times 10^{13}}$ **K**. Compare with Figure 10.1: protons condense out at about 10^{-6} s (10^{13} K) and electron–positron pairs stop being made around 1 second (10^{10} K). Both land exactly where the timeline says.

11.1 · Sixty e-foldings

e^{60} = **1.14×10^{26}**. (For contrast, $2^{60} = 1.15 \times 10^{18}$ — eight orders of magnitude smaller.) A proton at 10^{-15} m grows to about **1.1×10^{11} m**, roughly the radius of the Earth's orbit. Sixty e-foldings in 10^{-32} s means each took about **1.7×10^{-34} s**. For the flatness question: the Earth's surface drops about 8 cm per km; inflate it by 10^{26} and that deviation falls to ~10^{-27} m per km — undetectably flat.

12.1 · Stretching the microwave background

T_{then} = 2.725 × 1,101 = **3,000 K**. ✓ Wien: then λ_{max} = **966 nm** (near-infrared, just past visible red); now **1.06 mm** (microwave). Density has fallen by $1{,}101^3$ = **1.3×10^9**. For T = 300 K: $1 + z = 300/2.725$, so **$z \approx 109$** — an era when the whole universe was at room temperature and no star had yet formed.

13.1 · Auditing your atoms

A 50 kg person: hydrogen 10% = **5 kg** of primordial material; the other **45 kg (90%)** was made in stars. The 4 g of iron is $0.004/1.2 \times 10^{30}$ = **3×10^{-33}** of one Type Ia supernova's output. At one merger per 100,000 years, the galaxy has hosted roughly **136,000** neutron-star mergers — which, at several Earth-masses of gold each, is comfortably enough.

14.1 · Free-fall time of a molecular cloud

10^4 H_2 per cm³ = 10^{10} per m³, so $\rho = 3.35 \times 10^{-17}$ kg/m³. $t_{ff} = \sqrt{(3\pi/(32G\rho))} = 1.15 \times 10^{13}$ s = **360,000 years**. Real clouds survive tens of millions of years — roughly a hundred times longer — which tells you that turbulence and magnetic fields are supplying most of the support, not thermal pressure.

15.1 · The Sun's fuel bill

$dm/dt = L/c^2$ = **4.25×10^9 kg/s** — 4.25 million tonnes per second, or 1.3×10^{17} kg per year. Hydrogen consumed = $4.25 \times 10^9/0.007$ = **6.1×10^{11} kg/s** (610 million tonnes). With 10% of the Sun's mass available, lifetime = $1.99 \times 10^{29}/6.1 \times 10^{11} = 3.3 \times 10^{17}$ s = **10.4 billion years**. ✓ A 2 $M_\odot$ star: $L = 2^{3.5}$ = **11.3 $L_\odot$**, lifetime = $(2/11.3) \times 10^{10}$ = **1.8 billion years**.

16.1 · Stellar radii

Betelgeuse: $\sqrt{90{,}000} \times (5772/3600)^2 = 300 \times 2.57$ = **771 $R_\odot$** = 5.4×10^8 km — larger than Mars's orbital radius of 2.28×10^8 km. Sirius B: $\sqrt{0.056} \times (5772/25000)^2 = 0.237 \times 0.0533$

= **0.0126 R$_\odot$** = 8,780 km — slightly larger than the Earth. Proxima: **0.148 R$_\odot$** = 103,000 km, about 1.4 times Jupiter.

17.1 · White dwarf conditions

V = 1.44 × 10^{21} m³; ρ = **8.3 × 10^8 kg/m³** = 0.83 tonnes per cm³, about 37,000 times denser than osmium. g = **1.6 × 10^6 m/s²** = 165,000 g_{Earth}; a 50 kg person would weigh about **8,300 tonnes**. Escape velocity = 4.8 × 10^6 m/s = **1.6% of *c***.

18.1 · Supernova energetics

The Sun's lifetime output = 3.828 × 10^{26} × 3.16 × 10^{17} s = **1.2 × 10^{44} J** — essentially the same as one Type Ia releases in a month. Average power = 10^{44}/2.6 × 10^6 = 3.8 × 10^{37} W = **10^{11} Suns**, so yes, comparable to an entire galaxy. Neutrino fluence at 10 pc = $10^{46}/(4\pi(3.1 \times 10^{17})^2)$ = **8 × 10^9 J/m²** — enough, at closer range, to strip an atmosphere.

19.1 · Spinning up a stellar core

T_2 = 30 days × (10/10,000)² = 3 × 10^{-5} days = **2.6 seconds**, or 0.39 rotations per second — the right order of magnitude, and faster still for a more compact or faster-spinning progenitor. Equatorial speed at 716 Hz: 2π × 10^4 × 716 = 4.5 × 10^7 m/s = **15% of *c***. Escape velocity: 1.93 × 10^8 m/s = **64% of *c***. Setting it equal to c gives $R = 2GM/c^2$ = **4.15 km** — you have derived the Schwarzschild radius.

20.1 · Schwarzschild radii

Sun **2.95 km**. Earth **8.9 mm**. Sagittarius A*: 4.3 × 10^6 × 2.95 km = 1.27 × 10^7 km = **0.085 AU**, about a fifth of Mercury's orbit. A 50 kg person: **7.4 × 10^{-26} m**, eleven orders of magnitude smaller than a proton. Densities: 1 M$_\odot$ → **1.9 × 10^{19} kg/m³**; 4.3 × 10^6 M$_\odot$ → ≈ **1,000 kg/m³**, the density of water. Because $R_S \propto M$ but volume ∝ M^3, mean density falls as $1/M^2$.

21.1 · Resolving a black hole

θ = 1.22 × 1.3 × 10^{-3}/10^7 = 1.59 × 10^{-10} rad = **33 microarcseconds**. M87*'s horizon subtends 3.8 × 10^{13}/5.2 × 10^{23} = 7.3 × 10^{-11} rad = **15 μas**, and the shadow — enlarged by light bending — is around 40 μas, so the EHT just resolves it. Hubble at 500 nm: **0.052 arcsec**, about **1,600 times coarser**. The long wavelength is survivable only because the baseline is 4 million times larger than Hubble's mirror.

22.1 · Weighing the galaxy

$r = 2.46 \times 10^{20}$ m, $v = 2.3 \times 10^5$ m/s. $M = v^2r/G$ = **1.95 × 10⁴¹ kg ≈ 1 × 10¹¹ M⊙**. Period = $2\pi r/v$ = **213 million years**. ✓ Visible stars account for about 5×10^{10} M⊙ — roughly **half** the required mass, and the shortfall grows rapidly further out.

23.1 · Why stars miss

$n = 0.1/\text{pc}^3 = 3.4 \times 10^{-51}$ m^{-3}; path 30 kpc = 9.3×10^{20} m. Expected collisions = $6 \times 10^{18} \times 3.4 \times 10^{-51} \times 9.3 \times 10^{20}$ = **2×10^{-11}** — one chance in fifty billion. Repeat with gas clouds of radius 10 pc and the cross-section rises by a factor of ~10^{17}, giving **many collisions**. That single change of scale is the whole difference between "stars pass through" and "gas slams together".

24.1 · Weighing Sagittarius A*

a = 970 AU = 1.45×10^{14} m; $T = 5.07 \times 10^8$ s. $M = 4\pi^2a^3/(GT^2)$ = **7×10^{36} kg ≈ 3.5×10^6 M⊙** — close to the published 4.3×10^6, the difference coming from the more precise orbital elements now available. R_S = **1.05×10^7 km = 0.070 AU**, so S2's closest approach of 120 AU is about **1,700 Schwarzschild radii**. Packing that mass into 120 AU gives a density far above any stable star cluster, which is what rules out every alternative.

25.1 · The Boötes Void

Radius 165 Mly = 50.6 Mpc; V = **5.4×10^5 Mpc³**. At 0.004 bright galaxies per Mpc³ that predicts about **2,200** galaxies. The observed ~60 is **under 3 per cent** of the expectation. From its centre, the nearest galaxies would be over 100 million light-years away — far beyond the reach of 1920s telescopes, so the Great Debate would have been unresolvable and cosmic expansion undiscoverable for decades longer.

26.1 · The dark matter halo

At 60,000 ly (5.68×10^{20} m) with v = 220 km/s: M = **4.1×10^{41} kg ≈ 2.1×10^{11} M⊙** — roughly **twice** the mass inside the Sun's orbit, over a region where the starlight has all but vanished. If v is constant then $M = v^2r/G \propto r$; and since $M = (4/3)\pi r^3\rho$, that requires **$\rho \propto 1/r^2$**.

27.1 · The age from Hubble's constant

H_0 = 70 km/s/Mpc = 2.27×10^{-18} s^{-1}; $1/H_0 = 4.41 \times 10^{17}$ s = **14.0 billion years** — within 2% of the true 13.8, because early deceleration and recent acceleration very nearly cancel. With H_0 = 67.4 you get **14.5 Gyr**; with 73.0, **13.4 Gyr**. The Hubble tension is therefore also a one-billion-year disagreement about the age of the universe.

28.1 · Deep time

We are **1.4×10^{-5}** — about one thousandth of one per cent — of the way to the degenerate era. Against black hole evaporation at 10^{67} years, the current age is **1.4×10^{-57}** of the way. Compressing cosmic history so far into one second makes 10^{100} years equal to about **2×10^{82} years** — a number with no physical comparison available, since the observable universe contains only about 10^{80} atoms.

29.1 · Kepler's third law

Jupiter: $T = 5.20^{1.5}$ = **11.9 years**. Neptune: $30.1^{1.5}$ = **165 years** — discovered 1846, so it completed its first full orbit since discovery in **2011**. Halley: $a = 75.3^{2/3}$ = **17.8 AU**, out past Uranus. An 8-year period gives $a = 8^{2/3}$ = **4.0 AU**.

30.1 · Sizing a transiting planet

1.0% dip on a Sun-like star: $R_p/R_\star = 0.10 \rightarrow$ **69,600 km**, almost exactly Jupiter. 0.0084% → ratio 0.00917 → **6,380 km**, the Earth. On a red dwarf of 0.15 $R_\odot$ (104,400 km) a 0.7% dip gives **8,740 km** = 1.37 Earth radii. Small stars produce far deeper dips for the same planet, which is exactly why TESS targets them and why TRAPPIST-1's seven planets were findable at all.

31.1 · The Drake equation, twice

Optimistic: $2 \times 1 \times 0.2 \times 0.5 \times 0.5 \times 0.5 \times 10^6$ = **50,000** civilisations. Pessimistic: $2 \times 1 \times 0.2 \times 0.01 \times 0.001 \times 0.1 \times 500$ = **2×10^{-4}** — meaning we would very likely be alone. The ratio is **2.5×10^8**. Neither set of numbers is better justified than the other, which is the entire point.

32.1 · Aperture

JWST/Hubble = $(6.5/2.4)^2$ = **7.3**× the light. Against a 200 mm amateur telescope: **1,060**×. ELT/JWST = $(39/6.5)^2$ = **36**×. ELT resolution at 500 nm: $1.22 \times 5 \times 10^{-7}/39 = 1.56 \times 10^{-8}$ rad = **0.0032 arcsec**, so adaptive optics must beat 1-arcsecond seeing by a factor of about **310** for the mirror to be worth building. Cost scaling: $800 \times (40/10)^{2.5}$ = **₹25,600 crore** — the right order of magnitude against the ELT's real budget.

33.1 · The size of a strain of 10^{-21}

Over LIGO's 4 km: ΔL = **4 × 10^{-18} m**, about **1/400 of a proton diameter**. Over the Earth's diameter: **1.3 × 10^{-14} m**. Over the distance to Proxima Centauri: **4 × 10^{-5} m** = 40 μm, about half the width of a human hair. Energy: three solar masses = **5.4 × 10^{47} J**; averaged over 0.2 s that is 2.7 × 10^{48} W, and the *peak* was around 3.6 × 10^{49} W — several times the combined light output of every star in the observable universe.

34.1 · The speed of gravity

130 million years = 4.1 × 10^{15} s. The fractional speed difference is at most 1.7/4.1 × 10^{15} = **4 × 10^{-16}**, so $|v_{gw} - c|/c < \sim 10^{-15}$. Because part of the 1.7 s is almost certainly an intrinsic emission delay rather than travel time, the true bound is **even tighter** — the calculation is conservative.

36.1 · Propagating uncertainty

$L = 4\pi d^2 F$: relative uncertainty = $\sqrt{(2 \times 0.10)^2 + 0.03^2}$ = **20%**. Note that the squared distance *doubles* its 10% contribution — this is why distance dominates the error budget in almost every luminosity measurement in astronomy. For the two Hubble values: difference 5.6, combined $\sigma = \sqrt{0.5^2 + 1.0^2} = 1.12$, so **5.0 standard deviations**. Particle physics calls five sigma a discovery, which is precisely why the Hubble tension is taken so seriously.

If your answer disagrees. Work backwards rather than starting again. A factor of 10^3 usually means kilometres and metres; a factor of 10^6 means cm^3 and m^3; a factor of about 3.15 × 10^7 means years and seconds. Getting good at diagnosing your own errors is worth more than getting them right first time.

APPENDIX C

Glossary

> The vocabulary of the field, in the sense each term actually carries in a paper — which is occasionally not the sense it carries in a headline.

Absolute magnitude — how bright an object would appear at a standard distance of 10 parsecs. Compare apparent magnitude; the difference gives distance.

Accretion disc — a flattened, rotating disc of gas spiralling onto a compact object. Friction heats it enormously, making it the most efficient energy source known.

Adaptive optics — deforming a mirror hundreds of times a second to cancel atmospheric blurring in real time.

AGN (active galactic nucleus) — a galaxy centre powered by accretion onto a supermassive black hole. Quasars, blazars, Seyferts and radio galaxies are all AGN seen from different angles.

Astronomical unit (AU) — the mean Earth–Sun distance, defined as exactly 149,597,870,700 m.

Baryon acoustic oscillation (BAO) — a preferred separation of about 490 million light-years between galaxies, frozen in from sound waves in the early universe. Used as a standard ruler.

Big Bang — the hot dense early state of the universe and its subsequent expansion. Not an explosion, and not located anywhere in particular.

Binary — two stars in mutual orbit. Roughly half of all stellar systems.

Blackbody — an idealised perfect absorber and emitter. Its spectrum depends only on temperature, which is why colour measures heat.

Blueshift — wavelengths shortened by motion towards the observer.

Brown dwarf — an object too light (below about 0.08 $M_\odot$) to fuse hydrogen. Neither star nor planet.

Cepheid variable — a pulsating star whose period fixes its luminosity, discovered by Henrietta Leavitt. The foundation of the extragalactic distance ladder.

Chandrasekhar limit — 1.44 $M_\odot$, the maximum mass electron degeneracy pressure can support. Above it, a white dwarf cannot exist.

CMB (cosmic microwave background) — the 2.725 K relic radiation released 380,000 years after the Big Bang. The oldest observable light.

Cosmological constant (Λ) — a constant energy density of empty space; the simplest model of dark energy.

Dark energy — the unidentified 68.3% of the universe driving accelerated expansion.

Dark matter — the unidentified 26.8% that has mass but does not interact electromagnetically.

Degeneracy pressure — outward pressure arising from the Pauli exclusion principle rather than from heat. Supports white dwarfs (electrons) and neutron stars (neutrons).

Doppler shift — the change in observed wavelength caused by motion along the line of sight. $\Delta\lambda/\lambda_0 = v/c$.

Event horizon — the boundary around a black hole from which no path leads outward. Not a physical surface.

Exoplanet — a planet orbiting a star other than the Sun. Over 6,000 confirmed.

Flux — energy received per square metre per second. Depends on both luminosity and distance.

Frost line — the distance from a young star beyond which water can freeze; it divides rocky planets from giants.

Galaxy — a gravitationally bound system of stars, gas, dust and dark matter. Roughly two trillion are observable.

Geodesic — the straightest available path through curved spacetime. What a freely-falling object follows.

Globular cluster — a dense spherical group of hundreds of thousands of ancient stars, orbiting in a galaxy's halo.

Gravitational lensing — the bending of light by mass, used to weigh objects including their invisible content.

Gravitational wave — a propagating ripple in spacetime geometry, produced by accelerating masses. First detected in 2015.

H–R diagram — luminosity plotted against surface temperature. The organising chart of stellar astronomy.

Habitable zone — the orbital range where liquid water could exist on a planetary surface. A necessary condition, nowhere near sufficient.

Hubble constant (H_0) — the present expansion rate. Measured at either 67.4 or 73.0 km/s/Mpc depending on method — a live disagreement.

Hydrostatic equilibrium — the balance between inward gravity and outward pressure that holds a star together.

Inflation — a proposed episode of exponential expansion at $\sim 10^{-36}$ s, explaining the horizon, flatness and monopole problems.

Interferometry — combining signals from separated telescopes so that resolution is set by their separation, not their size.

Kilonova — the optical glow following a neutron-star merger, powered by the decay of freshly made heavy elements.

Light-year — the distance light travels in a year, 9.46×10^{15} m. A distance, not a time.

Luminosity — total energy emitted per second, in watts. A property of the object alone.

Magnitude — a logarithmic brightness scale in which *smaller means brighter* and five magnitudes is a factor of 100.

Main sequence — the diagonal band on the H–R diagram where stars spend their hydrogen-burning lives. Position is set by mass.

Multi-messenger astronomy — combining photons, neutrinos, cosmic rays and gravitational waves from a single event.

Nebula — a cloud of gas and dust. May be a stellar nursery, a planetary nebula, or a supernova remnant — three quite different things.

Neutrino — a nearly massless, chargeless particle that barely interacts. Carries direct information from stellar cores.

Neutron star — the collapsed core of a massive star: ~1.4 $M_{\odot}$ in about 20 km, at nuclear density.

Parallax — the apparent shift of a nearby star as the Earth orbits. The only direct distance measurement in astronomy.

Parsec — 3.26 light-years; the distance at which one AU subtends one arcsecond.

Planetary nebula — the ejected envelope of a dying low-mass star. Nothing to do with planets.

Protostar — a collapsing cloud fragment, glowing from compression, before fusion begins.

Pulsar — a rotating neutron star whose beamed radiation sweeps past us. It does not pulse; the beam does.

Quasar — an extremely luminous AGN, mostly at high redshift, powered by rapid accretion.

Radial velocity — motion along the line of sight, measured by Doppler shift. Used to detect exoplanets.

Recombination — the moment at 380,000 years when electrons joined nuclei and the universe became transparent.

Redshift (z) — the stretching of wavelengths, either by recession or by cosmic expansion. Higher z means earlier and further.

r-process — rapid neutron capture, making the heaviest elements. Occurs in neutron-star mergers.

Schwarzschild radius — $2GM/c^2$, the radius of a non-rotating black hole's event horizon.

Spectroscopy — splitting light into its wavelengths to read composition, temperature, velocity, rotation and magnetic field.

s-process — slow neutron capture in dying low-mass stars, making about half the elements beyond iron.

Standard candle — an object of known luminosity, used to measure distance. Type Ia supernovae are the most important.

Stellar wind — the continuous outflow of particles from a star. The Sun's is the solar wind.

Supermassive black hole — millions to billions of solar masses, at the centre of essentially every large galaxy.

Supernova — the explosive death of a star. Type II is core collapse; Type Ia is a detonating white dwarf.

Tidal force — the *difference* in gravity across an object, falling as $1/r^3$. Causes ocean tides, moon heating, and spaghettification.

Transit — a planet crossing in front of its star, dimming it slightly. Gives the planet's radius.

VLBI — very long baseline interferometry: linking telescopes across a continent or planet for extreme resolution.

White dwarf — the exposed core of a dead low-mass star, Earth-sized and supported by electron degeneracy pressure.

Wien's law — $\lambda_{max} = 2.898 \times 10^{-3}/T$. Hotter objects peak at shorter wavelengths.

APPENDIX D

Where to Go Next

> Specific books, specific datasets, specific institutions. Nothing here is generic advice, and almost all of it is free.

Books, in the order they will be useful

Read next. Carl Sagan's *Cosmos* remains the best written popular science book about this subject, and the chapter on the Library of Alexandria is worth the whole thing. Neil deGrasse Tyson's *Astrophysics for People in a Hurry* covers similar ground to this book in a shorter, breezier form. Katie Mack's *The End of Everything* is the best treatment of Chapter 28 anywhere.

Read in Class 11 and 12. *Fundamentals of Physics* by Halliday, Resnick and Walker — the standard, and worth owning. *Concepts of Physics* by H. C. Verma, in two volumes, which is the best problem book written in India and is used far beyond it. Kip Thorne's *Black Holes and Time Warps* for the history and the physics of Chapters 5, 20 and 33, from someone who won a Nobel Prize for it.

Read as an undergraduate. *An Introduction to Modern Astrophysics* by Carroll and Ostlie is the standard textbook and is genuinely readable. *Astrophysics for Physicists* by Arnab Rai Choudhuri is excellent and written for exactly the Indian curriculum you will be following. *Fundamental Astronomy* by Karttunen et al. is a good cheaper alternative.

On how science actually works, which matters more than any single result: Richard Feynman's *The Character of Physical Law*, and Thomas Kuhn's *The Structure of Scientific Revolutions* — the second is contested and worth arguing with rather than absorbing.

Data you can download tonight

Source	What is in it	Start with
Gaia Archive gea.esac.esa.int	positions, distances, motions and colours for ~2 billion stars	plot your own H–R diagram (Chapter 16)
MAST mast.stsci.edu	all Hubble, JWST, Kepler and TESS data	find a transit in a TESS light curve
NASA Exoplanet Archive	every confirmed exoplanet and its parameters	reproduce the radius valley (Chapter 30)
SDSS SkyServer	millions of galaxy spectra and images	measure redshifts and rebuild Hubble's law
GWOSC gwosc.org	raw LIGO/Virgo strain data, with tutorials	detect GW150914 yourself — the notebook exists
arXiv arxiv.org/list/astro-ph	essentially every astronomy paper, free, the day it is written	one abstract a day
Aladin / SIMBAD / NED	sky atlas and object databases	look up anything named in this book

Software worth learning, in order

Python — the language of the field. Then **numpy** and **matplotlib** for computation and plotting; **astropy** for units, coordinates and FITS files; **astroquery** for pulling catalogues; **lightkurve** for Kepler and TESS data; and **emcee** when you reach Bayesian fitting. **Stellarium** is a free planetarium for the desktop and will teach you the sky faster than any book. **SAOImageDS9** is what professionals use to look at astronomical images.

Indian institutions, and what each is for

Institution	Where	Known for
IUCAA	Pune	cosmology, gravitational waves; excellent outreach and summer programmes
IIA	Bengaluru · Hanle · Kavalur	optical and solar astronomy; runs the 2-m telescope at Hanle
NCRA-TIFR	Pune	operates the GMRT; radio astronomy and pulsars
TIFR	Mumbai	astronomy, particle physics, the VSRP summer programme
ARIES	Nainital	the 3.6-m Devasthal Optical Telescope, the largest in Asia
PRL	Ahmedabad	exoplanets (PARAS), solar physics, planetary science
RRI	Bengaluru	theoretical astrophysics, radio astronomy
ICTS-TIFR	Bengaluru	gravitational-wave theory, data analysis
IISERs	seven cities	the BS–MS route into research (Chapter 37)
IIST	Thiruvananthapuram	ISRO's own institute — the engineering route
HBCSE	Mumbai	runs the olympiad programme, including NSEA and INAO

Things to do that are not reading

- **Join an amateur astronomy club.** Most large Indian cities have one, and they hold free public observing nights. Members will lend you equipment and teach you the sky, which is much faster than learning it alone.
- **Contribute to citizen science. Zooniverse** hosts real projects — Galaxy Zoo, Planet Hunters TESS, Backyard Worlds — where volunteers have co-authored genuine discoveries. It is free, it takes minutes, and it is real data.

- **Watch a total solar eclipse** if one is ever within reach. Everyone who has seen one says the same thing: photographs do not convey it.
- **Get to a dark sky once.** If you have only seen the sky from a city, you have not seen it. Hanle in Ladakh is now a designated Dark Sky Reserve; so are parts of Spiti, the Rann of Kutch and the hills of Uttarakhand. The Milky Way from a genuinely dark site is startling.

> **ONE LAST PIECE OF ADVICE**
>
> Pick one thing from this appendix and do it this week. Not all of it — one thing. The students who end up in this field are not the ones who read the most; they are the ones who finished something small, then something slightly larger, and kept going.

APPENDIX E

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