

She was found nine days later, crewless and intact, drifting in the light of a cold December morning — her cargo undisturbed, her provisions untouched, her log-slate carrying its last notation in a doomed man's hand.

Benjamin Briggs had not panicked. He had not lost his mind. He had not conspired in any crime, nor suffered any mutiny, nor made any foolish error. He had done exactly what any sane, sober, experienced captain would have done.

Unavoidable though it was, he had simply made the wrong choice.

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REVIEWS

Out of This World, by Peter Bond (Reaktion), 2026. Pp. 376, 24.5 × 16.5 cm. Price £25 (hardbound; ISBN 978 1 83639 199 9).

Is there a need for another book about humans' adventures in space? As the author Peter Bond recognizes in the acknowledgements, many books have been written about the Space Age, and indeed as he says those have provided much of the background information for this book. Bond's book is a bit different: although it covers much of the same ground as many others, it deals with the subject matter thematically rather than directly historically as is usual. In nine readable chapters, he deals with the particular issues and concerns that must be answered in order to enable humans to live and work in space.

There are chapters covering such topics as the development of suitable rockets, astronaut selection and training, crew health and happiness, and one emphatically dealing with the risks involved. Within each chapter a particular topic is covered semi-historically, illustrated with examples chosen from all of the nations either currently involved or who have previously contributed to the project of humanity's efforts in space. That is an interesting approach which allows for a wide-ranging appreciation of each country's ambitions and concerns, to act almost as a glimpse of national philosophies as well as building a much more global overview of human achievements in space. Some light asides from that international approach involve the food choices available to those early space pioneers — in 1982 the French astronaut Jean-Loup Chrétien brought French cuisine to the Russian three-man Soyuz spacecraft; that included jugged hare, crab soup, and lobster pilaf and must have been an interesting zero-g eating experience. Two years later the first Indian to fly in space, Rakesh Sharma, provided curry, Ravi Shankar music, and Bollywood films, another atmospheric experience. Bond does not record any menu items supplied by Britain's first astronaut, Helen Sharman, who spent a week on the *Mir* space station in 1991 — maybe a couple of those dense, calorie-rich chocolate bars manufactured by Mars, her employer at the time?

Peter Bond tells us that at the time of writing this book, in 2025, 637 people have orbited around the Earth, and another 119 have taken suborbital flights beyond the 80-km altitude recognized by the US as the boundary to space, with many of those above the higher internationally recognised 100-km Kármán line. Those people came from most varieties of humanity, ranging in age from 18 to 90 and from almost all walks of life — artists, pop singers, politicians, as well as the expected cohort of test pilots, scientists, and engineers. The one excluded exception would seem to be the poor — although as Bond reminds us, for their initial flights the Russians used the homeless as test subjects: the stray dog Laika became the first living creature to orbit the Earth, and within a few hours, the first to die there from shock and heat exhaustion. Spaceflight, as well as being dangerous, is an expensive business, so those without government funding, or who are not the CEOs or friends of one of the world's tech giants, must spend vast sums of money to buy a seat as a tourist. \$20 million is reported as the ticket price Dennis Tito, an investment manager, paid for Star City training and a trip in a *Soyuz* craft to spend eight days on board the *ISS* in 2001. At the government-employee end of the business, US astronauts do their work on a salary of up to \$152 258 per year.

Outside the relative safety of their spacecraft, astronauts have made 483 space walks, in space jargon EVA (Extra Vehicular Activity), into the raw, unforgiving, vast vacuum of space; 277 of those space walks were related to the assembly and maintenance of the *ISS* which totalled thousands of hours in that unimaginably challenging immensity. There have also memorably been 12 men who walked on the surface of the Moon, in a total of 14 excursions, some lasting more than seven hours. In Bryan Burrough's book about working in the *Mir* space station, *Dragonfly*, one astronaut describes the first moments of paralysing fear on stepping out from the spacecraft into the constant falling nothingness of orbit and the extreme effort of will required to overcome that brain-numbing effect. Some very dangerous EVAs are described by Bond — for example the Gemini astronauts getting to grips with docking procedures in preparation for the Apollo Moon-landing missions. Those exercises involved practising linking with the seemingly unreliable Agena rocket upper stage. On one occasion, NASA astronaut Richard Gordon had to grasp the Agena and bring it under control by mounting it much as a cowboy on a wild bronco. Several times astronauts have rescued stricken satellites, including on occasions those in which a live rocket motor has failed to fire. Did those guys never read the instructions on the back of a packet of fireworks about never returning to a failed firework?

For all of the seemingly everyday, run-of-the-mill nature of spaceflight which seems to exist in the current era of the space station, Bond's book constantly reminds us just how dangerous that endeavour actually has been and indeed still is. The last two chapters on going to the Moon and the risks involved in human spaceflight are engrossing reads full of

additional detail about Apollo, and other more current programmes, and it has to be said some rather ghoulish accident information.

After over 60 years of human excursions beyond the atmosphere of our planet, perhaps it is time to make an evaluation of what we have learned; what benefits have accrued to those left on the ground, and to make a judgement on whether it has all been worth the vast outlay of earthly resources and to answer the question; is the project worth continuing? With his wide experience in communicating space science, Peter Bond is perhaps a well-placed writer to do that. I lost count of the number of times he reports astronauts taking part in experiments to do with human physiology, or making use of various furnaces and electron guns to study metallurgy or crystallography, although rather few results are described. Experiments to test antibacterial and antiviral materials are apparently useful for application in the design of lift buttons. However, other than those examples and some generic statements about the development of high-tech industry and associated jobs and of course the few satellite-repair missions, this book does not address any major developments that have resulted from people doing science in microgravity.

Space research is currently being funded by national governments and the four wealthiest private-enterprise organizations the world has ever seen. This book does not tell us how any of those organizations suggest putting people into space will assist in solving the major problem currently facing humanity: the relentlessly warming planet. In the 65 years since Gagarin's flight the world annual CO₂ emissions from fossil fuels have increased from around eight billion tonnes to 38 billion tonnes and the average global temperature during the summer months has increased from 15.6 °C to 16.8 °C and with each decade that increase is accelerating. Space research has certainly been absolutely central to our knowledge of those numbers but almost exclusively by the use of sophisticated unmanned satellites. There is a very good case to be made that humanity has gained enormous benefits from the use of unmanned satellites through all sorts of remote sensing: Earth observation, astronomy, telecommunications, navigation, *etc.*, *etc.* — it is less clear that such obvious returns can be seen from manned spaceflight.

The case is not made in this book, which does not claim to be a book of analysis but a very thorough compilation of historical facts arranged in thematic chapters and as such it is a very good and often surprising resource. One must admire the research involved in assembling this detailed listing of components, processes, and interactions; there is, however, no attempt at understanding of purpose other than getting done the job of putting humans into space — there is no 'why'. It is a book of comprehensive listing and description of salient facts without addressing the current overarching purpose, and perhaps that is a true reflection of the space agencies' and private-enterprise ambitions. To use the coarse language of our times: is manned spaceflight any more than expensive 'willy wagging'?

In a book so full of facts I spotted just a few errors, and really only one worthy of comment. Unfortunately, it is on the first page of the first chapter, where we read that rocket propulsion is based on the principle of "Sir Isaac Newton's third law of *thermodynamics*" [my emphasis]. I guess an autofill-suggested word had slipped in, unnoticed by the author, it was then missed by the copy editor, and also missed again at the pre-publication proof stage. Maybe it is churlish to complain that in a book overflowing with facts I found only a few that bothered me — but but but, "Newton's third law of thermodynamics". Mr. Bond, I was "shaken and not stirred". Hopefully it will be corrected for the paperback edition of this thoroughly enjoyable, excellent compendium of the whole range of human space adventures. — BARRY KENT.

The Physics of Interstellar Travel, by Coryn A. L. Bailer-Jones (Cambridge University Press), 2026. Pp. 358, 26 × 21 cm. Price £55 (hardbound; ISBN 978 1 009 68392 8).

For many years now, unmanned space probes have been traversing the Solar System. Some have landed on, or gone into orbit around, some of the planets and their satellites. The very

earliest, *Voyager 1*, is already (since 2012) moving into the interstellar medium (ISM) but will take some 77 000 years to get to the distance of our nearest star. Manned spaceflight is currently largely confined to the Moon, although there are ambitions to build a base on Mars.

Interstellar travel is still a dream, despite *Voyager 1*, but of course if humans are ever to emulate science fiction and journey to other stars then we should be thinking about what it would involve. That's precisely what Bailer-Jones's book addresses. The author makes a systematic study of the physics of the medium through which any space probe would pass and the hazards that it would encounter. The treatment is mathematical and is suitable for a reader with a good understanding of physics at the level of an undergraduate degree.

There is a short introductory chapter, setting the scene and outlining the contents of all 17 chapters, before moving on to Chapter 2, which considers motivations for interstellar exploration, gives essential background information, and talks briefly about the nearest stars and time-scales. It becomes clear that any chance of reaching other stars in a reasonable time requires interstellar probes to be moving at some fraction of the speed of light, say $0.1\ c$.

Chapters 3 and 4 cover the theory of rockets and discuss orbital mechanics while chapters 5, 6, and 8 discuss various types of rocket engine, from thermal- and ion- to nuclear-powered, with relativistic effects on motion (with a clear discussion of the twin paradox) and on their effects on what we see (aberration and the Doppler effect) covered in chapters 7 and 9. Chapter 10 introduces the concept of solar sails, with a clear discussion of the practical difficulties. The next chapter considers using a laser rather than the Sun as a driving mechanism for the sails.

Of course, that kind of probe is light and easily affected by the ISM so the author here inserts a chapter on the ISM, considering the effects of impacts and the resultant drag and explaining the principle of the ramjet, which he regards as very speculative at this stage. Chapter 13 covers more exotic forms of sails, involving magnetic and electric fields.

The next question that arises is how to make sure the interstellar probe goes in the right direction and knows where it is in some inertial frame. Bailer-Jones spends Chapter 14 discussing navigation in general. Within the Solar System, where light-travel times are relatively short, it is a solved problem, with an agreed reference frame (ICRF — the International Celestial Reference Frame) based on the Solar System barycentre (SSB), using radar ranging. Out in the ISM ranging becomes impractical and the probe must do its own navigation. Instead of ranging, the probe must use other reference points, such as bright stars with precisely known positions and velocities in the ICRF. Alternatively, it is possible to use pulsars, but that is more complicated, as he explains.

Back on Earth, meanwhile, we would like to know what the probe is finding, so the final problem is getting the information back. Once the probe is well out into the ISM, two-way communication is unrealistic and even getting data back is slow — it may take months or years to send the information back at a low bit rate because the probe doesn't have the power to transmit faster. Chapter 15 discusses all the ramifications. Chapter 16 discusses possible payloads, including what instruments might be used. The mass of those instruments would have to be small, especially for sail-driven probes, so one option might be to send out swarms of probes, each with a different instrument, and some redundancy built in to avoid losing everything if a probe is lost.

Finally, Chapter 17, 'Outlook', starts by considering very briefly (and dismissing) wilder ideas such as wormholes before going on to real-life challenges and possible solutions. Bailer-Jones then considers broader issues: Should we undertake interstellar travel? Is it ethical? Is it dangerous? And — where do we go from here? None of the technology required currently exists, but some is within reach in the next half-century or so.

This book is clearly written, with useful summaries at the end of each chapter. The mathematics is deliberately simplified to enable the basic principles to be explained without obscuring them by the detail that would be needed in a realistic description. One comment

is that, although he does occasionally mention the power needed to make and send such probes, he does not discuss the fact that it is well beyond current world power usage. But that would be straying into politics, so he's probably wise to avoid that. The book is really an answer to the question: if we want to send out probes into space at $0.1c$, what are the physical requirements? This would be a useful book for anyone thinking about a career in astronautics, and is also of general interest. — ROBERT CONNOR SMITH.

The Multiverse: When One Universe Isn't Enough: Uncovering a Universal Mystery,

by Brian Clegg (Icon Books), 2025. Pp. 190, 20 × 13 cm. Price £10.99 (paperback; ISBN 978 1 8377 3236 7).

Brian Clegg is a well-known popular-science writer and I've reviewed^{1,2} a couple of his previous books^{3,4} in these pages. The Multiverse is the subject of several books⁵⁻¹⁰ reviewed¹¹⁻¹⁶ in this *Magazine*, so this book was an obvious choice for one of the dozen books I bought at an English-language bookstore after attending a thesis defence in Amsterdam a few weeks ago. Already in the acknowledgements (which is mostly a preface), Clegg mentions his sceptical stance on the Multiverse. Perhaps because he is not trying to convince the reader of the reality of the Multiverse, the chapters illuminate various ideas related to the Multiverse rather than working together towards some goal. We get brief descriptions of a motley collection of topics: the idea of the Multiverse, our Universe (one definition of the Multiverse is the sum of observable universes — the sum being Tegmark's Level I Multiverse —, each of which is smaller than the (possibly infinite) ensemble, though usually as used by other authors 'Universe' refers to Tegmark's Level I Multiverse), the simulation hypothesis, imaginary numbers and quaternions, fine-tuning, inflation, the many-worlds interpretation of quantum mechanics, string theory, the ekpyrotic model, the holographic principle, Tegmark's mathematical universe, and pop-science YouTube personality Sabine Hossenfelder. Sometimes I agree with Clegg's sceptical take, *e.g.*, when discussing inflation (though he omits the strongest argument for inflation: a mechanism for the origin of primordial density fluctuations). More often, though, his scepticism seems to be due mostly to a matter of taste (in the acknowledgements/preface, he mentions his sadness when the Steady State model was ruled out, possibly because he was a fan of Hoyle's science fiction).

The book is well-written with few typos; Clegg knows his trade. On the whole, the book is a good (but very brief) introduction to the topics mentioned above. However, whether intentionally or not, the combination of the trivially true, very speculative, and everything in between tends to cast a too sceptical light on things which are almost consensus; maybe Clegg hopes that the reader will come to dislike the same things he does once they've become tainted by association with the Multiverse. There are also a few common misconceptions, such as the ideas that dark energy causes the expansion of the Universe (and it seems to be implied that a negative cosmological constant would lead to contraction) and that inflation is basically faster-than-light expansion. The discussion of the Strong Anthropic Principle is confusing at best. His discussion of the inverse gambler's fallacy is somewhat unorthodox, perhaps to aid his comparison of it to the idea of the Multiverse (while at the same time not even mentioning other reasons for believing in some sort of Multiverse). That discussion is inspired by Philip Goff, who is known primarily for his belief in panpsychism. While people can be right about some things and wrong about others, Goff seems like a strange bedfellow for someone like Clegg pushing a less speculative and more down-to-Earth view.

There are a few footnotes, no photos, and the main text is followed by three pages of suggestions for further reading (many by Clegg, but also many presenting different points of view on the idea of the Multiverse) and a four-page small-print index.

In a review of another book by Clegg, I wrote "I would like to give the book a better recommendation, since it is generally well written and manages to give a good overview". My desire with regard to this book is somewhat less, because in addition to mistakes I detect an agenda. It's not a problem that I disagree with his opinion; rather, my impression is that

the account is intentionally somewhat biased. On the other hand, it's an easy introduction to some complicated topics and sometimes it is good to be exposed to a different point of view.
— PHILLIP HELBIG.

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Gravitation for Theorists, by Piljin Yi (Cambridge University Press), 2026. Pp. 338, 24·4 × 17 cm. Price £70 (hardbound; ISBN 978 1 009 57564 5).

This book grew out of a single-semester graduate course taught by the author at Seoul National University and at the Korea Advanced Institute of Science and Technology (the author's affiliation is the Korea Institute for Advanced Study). To allow comparison with other books on General Relativity (GR) which I've reviewed in these pages, I assign it a relativity-book signature of 000+++.* As such, it is good for someone who wants to work through the mathematical details at a fairly high level. It is atypical for GR books in that Part III (three chapters) is about 'Canonical Field Theories with Gravity' (including a chapter on the ADM formalism) and there is an appendix on 'Fiber Bundles'; much more than most broadly similar books, it highlights connections between General Relativity and other branches of physics. (Parts I and II are 'Relativity and Geometry' and 'General Relativity', five and six chapters, respectively.) Except for some background on Special Relativity and Maxwell's equations, the book has practically nothing on the history of General Relativity.† I can't improve on the author's summary: "This book is intended as a self-contained handbook on the foundation of General Relativity. The content shies away from a comprehensive treatise that would cover all the nooks and crannies of gravitational phenomena. The emphasis is instead given to incremental developments of the underlying mathematics, explicit derivations of key formulae, and, in particular, examples and sidetracks that are meant to solidify the concepts and to prepare the readers for further applications."

Although, as expected, Chapter 7 on 'Cosmology in Brief' is indeed brief, there is nothing misleading or wrong in it. Non-flat cosmological models are also discussed, and even the Multiverse gets a few paragraphs. The discussion of the flatness problem (though restricted to the fine-tuning problem, *i.e.*, why was the Universe extremely flat immediately after the

*The characters indicate maths-first or physics-first, breadth, depth, level, difficulty of maths, mathematical detail shown. (+ indicates maths-first or more than average, – physics-first or less than average; o neither or about average.)

†For that, see another book¹ reviewed² in these pages.

Big Bang) and the effects of inflation is good (though I disagree that the flatness problem is actually a problem (e.g., ref. 3 and references therein)). In my review⁴ of a cosmology textbook⁵, I praised the author for explicitly introducing various forms of the Robertson–Walker metric. Something similar is done in this book for various representations of S^3 in the chapter on the Maurer–Cartan description (and the connection to the RW metric in cosmology is mentioned). The author is also aware that it is the Lorenz gauge (though there is no such entry in the six-page small-print index, though there are three Lorenz-related entries.) Apart from the usual topics and those already mentioned, the discussion of black holes (Schwarzschild, Reissner–Nordström, Kerr, Kerr–Newman) also includes the cosmological constant, and there is an entire chapter on the Maurer–Cartan description.

The book is a good introduction at a reasonably high level for someone who wants the work shown and is happy to forego the history of the topic. However, I found the book rather difficult to read, primarily because of the lack of definite and indefinite articles when they should be there and *vice versa*. In general, the book could have benefitted from editing by a native (or otherwise very good) speaker of English. There is also one instance (p. 223) where some text has obviously been left out. Similarly to the previous book on General Relativity⁶ I reviewed⁷ in these pages (also from Cambridge University Press), the wider margins are always on the left; more practical is to have them always on the outside. Several pages of my copy also became unattached; hopefully that is a one-off problem and doesn't affect the entire print run.

There are only a few black-and-white diagrams, scattered throughout the text. There are neither footnotes nor endnotes nor any sort of bibliography; only preface, main text (including appendix), and index. This is a no-frills detailed introduction to General Relativity and good for those who want to learn the subject by following worked-out derivations — PHILLIP HELBIG.

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Radio Universe: How to Explore Space Without Leaving Earth, by Emma Chapman (John Murray), 2026. Pp. 242, 23.5 × 15 cm. Price £18.99 (paperback; ISBN 978 1 529 39899 1).

I've read many popular-science books on astronomy, but this is probably the first which is mainly about radio astronomy. The author is a Royal Society Dorothy Hodgkin Research Fellow at the University of Nottingham and recipient of several awards; this is her second popular-science book about astronomy (thus only two books so far; there is another author named Emma Chapman; to add to the confusion, in the US this book is entitled *Echoing Universe*). Chapman was raised on radio, but in the BBC sense; she became interested in radio astronomy as a result of her PhD project, which involved radio observations from the Netherlands. An introduction mentions that project, tells a very brief history of radio astronomy, describes how radio telescopes work, and offers a somewhat longer exposition of the electromagnetic spectrum (including an obsolete reference to the colour indigo on p. 7). There is little about radio astronomy in the technical sense in the book; rather, it discusses the science which can be done *via* radio astronomy, sometimes containing asides about other radio-related topics.

The first six chapters are confined to the Solar System: the Moon (Apollo programme, radar, radio communications), the Sun (sunspots, James Stanley Hey, coronal mass-ejection events), Mercury (detailed discussions of its rotation, the presence of ice, why there have been only three missions), Venus (temperature, rotation, vulcanism, craters, lack of plate tectonics, high-resolution mapping), Mars (extraterrestrial life, orbital mechanics, the ill-fated *Beagle 2* lander), and the asteroid belt (introduced *via* Saturn's rings, Saturn being the current limit of radar astronomy), detecting potentially dangerous asteroids, and some history involving (later Sir) Bernard Lovell at Jodrell Bank. We then move further away to the Milky Way (the *Voyager* probes, Grote Reber, the 21-cm line, the structure of the Milky Way, astrophysical masers, *Meerkat*), black holes (detection, gravitational waves, Special and General Relativity, Schwarzschild's life (and death) and work, the *Event Horizon Telescope*, stellar-mass black holes), neutron stars (discovery of pulsars, neutron-star physics, pulsar astronomy, controversy around Jocelyn Bell (Burnell)), gravitational waves (the Hulse–Taylor binary pulsar, *LIGO*, the *Pulsar Timing Array*, kilonovae), exoplanets (formation, T Tauri stars, *ALMA*, molecular clouds), contact with extraterrestrial intelligence (SETI, TRAPPIST 1e, the Drake equation, the *Allen Telescope Array*, funding, Sagan, Tartar, METI), the high-redshift Universe (discovery of the CMB, 20th-Century astronomy including some wrong turns and dead ends, radio-source counts, physics of the CMB, first stars, the *Square Kilometre Array*), dark matter (cosmology, history of dark matter, Purcell & Ewen, modern structure-formation simulations), dark energy (more cosmology, baryon acoustic oscillations, intensity mapping), and the 'dark' side of the Moon (putting a radio telescope on the far side of the Moon). Finally we get a tourist's guide to radio telescopes, with brief descriptions of eleven such potential travel destinations. There are no figures and a few footnotes. The back matter includes extensive acknowledgements, notes (which are actually numbered references corresponding to numbered citations in the text, about eight per chapter), suggestions for further reading (both in general and a few suggestions for most chapters; I noted five which I intend to read; some should be updated to reflect more recent editions), and a ten-page small-print index.

While the topics are chosen because of the role played by radio astronomy in them, that is a jumping-off point for more general descriptions, such as a detailed account of the determination of the rotation of Mercury and Venus and the mapping of the latter.* While much of the material was familiar, I was happy to get more details on Hey and Purcell & Ewen. It is also good to have a nice overview of SETI and related topics; Chapman notes that some authors shy away from such discussions for no good reason. (Recently, SETI has become more respectable, and Michael Garrett, a prominent SETI advocate, has been the Sir Bernard Lovell Professor of Astrophysics and Director of the Jodrell Bank Centre for Astrophysics since 2016, after having been Director of the Joint Institute for VLBI in Europe and the General & Scientific Director at ASTRON.) Considering the large number of diverse topics, balance might be hard to achieve, but she does a good job, usually going into more depth only when mentioning less common (but important) details. A minor point is that I found there to be a bit too much detail on the physics behind the CMB (and to some extent on the history of the topic), but too little on why it is so important for cosmology today, *i.e.*, what one can learn from the power spectrum, though arguably that is too much physics and too little radio astronomy.

I noticed only a few mistakes. Some are easy to explain. For instance (p. 40), "Six missions carried a total of twenty-four American men to lunar orbit between 1969 and 1972, and of those, twelve set foot on the surface." There were eight, not six missions, but only six included a Moon landing. (The ill-fated *Apollo 13* went around the Moon, but didn't orbit it in the

*The most recent space-probe mapping is from the *Magellan* mission 1990–1994, with a resolution of 100 m. In 1978, the *Pioneer Venus Orbiter* had achieved one of 2 km. Amazingly, only ten years later, technology at the *Arecibo Telescope* was able to achieve that from Earth.

stricter sense.) Some are common misconceptions, *e.g.*, Special Relativity (SR) cannot deal with acceleration (p. 157) — the main difference is that SR is restricted to (flat) Minkowski space and General Relativity (GR) allows for curved space–time (to be sure, gravity curves space–time, and the Equivalence Principle relates acceleration and gravity, but nonetheless SR can describe acceleration). It is at least implied that Schwarzschild died on the battlefield; he died in hospital, away from the front, and of an auto-immune disease, not war wounds (p. 160). (She does get the history of the term ‘black hole’ correct, crediting Dicke and not Wheeler, p. 160.) Bell wasn’t yet Bell Burnell when she discovered pulsars (p. 172). The last sentence in the first paragraph of the last section in the chapter on neutron stars (p. 182) states “Sadly, Bell Burnell is less known for her scientific breakthrough than for the controversy that surrounds it.” That might well be true, but I wonder if devoting eight paragraphs to said controversy will improve the situation. At the risk of doing the same, I note that the actual discussion agrees with my assessment and correctly differentiates the question of whether she should have received a share of the Nobel Prize (including placing the decision in the context of the time and Bell Burnell’s own take on the matter) from the silly reporting by many journalists at the time. While GR indeed describes changes in the gravitational field propagating at the speed of light, not all such changes correspond to gravitational waves as usually thought of (p. 189). Since this is the third book in which I have noticed it, the idea that astronomers can somehow *measure* the radial velocity of extragalactic objects is becoming a common misconception (p. 248).

Others are more bizarre: Drake’s choice of 1679 pixels for his Arecibo message was due to it being the product of the two primes 23 and 73, but of course 1679 itself is not prime (p. 235). The description of the Hubble law is at best confused (p. 247). It is at least strongly implied that Einstein was aware of Friedmann’s work (which was done some years later) when the former added the cosmological constant in order to have a static universe (p. 248). The history of dark matter is at best too brief. P. 263: “Dark energy was proposed in the 1990s, when observations of distant supernovae revealed that the expansion of the Universe is not slowing down as expected, but accelerating.” That is literally true, but it was not *first* proposed (which seems to be implied) then, and though the *term* ‘dark energy’ was proposed then the idea is older. (Sometimes ‘dark energy’ is used to contrast it with a cosmological constant, the former having an equation of state other than $p = -\rho$ and/or the value or even the equation of state changing with time, though none of those were needed in the 1990s and probably none is needed today.) Further discussion of supernova cosmology is at best muddled (pp. 278–279).

However, most of the mistakes are related to cosmology, with which only a small part of the book is concerned, and are rather common, both of which are true of many books reviewed in these pages. I think that it is important to mention them, but at the same time the space devoted to them in this review exaggerates their importance. The rest of the book is not only (as far as I can tell) technically correct, but is well written and conveys the author’s love of radio astronomy, a topic which should get much more attention in books at this level; perhaps this book can be a step in that direction. I certainly enjoyed reading it and, despite being an honorary radio astronomer, learned many new things. — PHILLIP HELBIG.

On Time: The Physics That Makes the Universe Tick, by Jim Al-Khalili (Princeton University Press), 2026. Pp. 359, 24 × 16 cm. Price £28/\$32 (hardbound; ISBN 978 0 691 26703 6).

Al-Khalili is a well-known popular-science writer and presenter on radio and television with a background in theoretical nuclear physics; he is a professor of physics at the University of Surrey, where he also holds a chair in the public engagement of science. This is the first book by him that I have read. I’ve read many books on the nature of time and reviewed some in these pages, though they were usually more technical and/or edited volumes with several authors. In particular, this book — with an important exception mentioned below —

could be seen as something like a popular-science version of a book¹ reviewed² in the 2026 August issue of this *Magazine*. It's more than just a typical popular-science book, though, as some of its contents reflect research done by Al-Khalili and colleagues in the context of a large research grant, in an area (the philosophy of time) somewhat removed from his earlier specialization. While there are many popular-science books on time itself (including an excellent one³ reviewed in these pages⁴), there are few on the philosophy of time.

The preface notes that the book is concerned with physical time, not “mystic or poetic notions”. That does not exclude our perception of time, ‘manifest time’. That and basic questions are discussed in the introduction, such as whether time is an illusion, whether (and if so how) it flows, whether it is continuous, why it has a direction, and so on. The two philosophical problems of time are why we perceive it to flow and why we perceive the past to be different from the future, given that those facts aren't obvious from the equations of physics. The two physical problems are the connection between the coordinate time of classical or quantum physics and the time which is part of space–time in relativity, and reconciling time-symmetric dynamical equations with the irreversibility of thermodynamics.

There are so many concepts involving (the philosophy of) time that some structure is needed. The four parts of the book provide some of that, reflecting time as a label, as a dimension, as an arrow, and the reality of time. The first, with four chapters, discusses the basic concept of time as a coordinate which indicates when something happened, as in Newtonian or quantum mechanics, and how it is measured. The philosophy of time becomes important when psychological time and the question of free will *versus* determinism are discussed. The second, with five chapters, covers Special and General Relativity, including cosmological time, the idea of the block Universe, and the fact that ‘now’ is not clearly defined in a relativistic context. The third (four chapters) discusses various arrows of time: psychological, entropy, causal, cosmological, quantum, *etc.* Al-Khalili sees statistical mechanics on an equal footing with Quantum Mechanics (or dynamical physical equations in general) and Relativity with respect to its role in the foundations of physics, and there is a good discussion of various types of entropy, Loschmidt's paradox, and so on.

The closest thing to a consensus on the topic of the arrow of time is that all arrows of time are ultimately derived from the cosmological arrow of time, which is due to the Universe having started in a state of very low entropy, which is difficult to explain. (One might think that radiation would have a high entropy; that is true in the absence of gravity, but with gravity the high-entropy state is with everything in black holes.) Thus, the importance of the Past Hypothesis, which is just a statement of that fact, without explanation. Most discussions, at least most I am familiar with, are concerned with ‘traditional’ entropy (*e.g.*, that of particles of matter or radiation) or gravitational entropy. Al-Khalili emphasizes the importance of a third type of entropy, namely that connected with nuclear fusion. It is the increase of entropy as the result of fusion which ultimately responsible for most entropy-related phenomena. Since the possibility of such fusion is merely one of many aspects dependent on the fine-tuning of our Universe (*e.g.*, ref. 5 and references therein, reviewed⁷ in these pages), Al-Khalili also introduces the interesting twist that no extra Past Hypothesis is actually needed; it is merely one aspect of the fine-tuning of our Universe for life, which is hard to dispute, though there is disagreement about its explanation (*e.g.*, refs. 5,6). Considering that many have deemed the problem of the origin of the low-entropy Big Bang the most important outstanding problem in physics, such a simple explanation — which I haven't seen anywhere else — is at least very interesting.* With the beginning out of the way, the reader is then presented with various ideas about a possible end of time. Contemplating extremely long periods of time leads to the idea of ‘Boltzmann brains’, conscious observers which arise due to fluctuations. Whatever one thinks of them (the author apparently doesn't think much of the idea), as a serious area

*Al-Khalili does point out what are the author's own ideas and what is his summary of the field, always something worth doing when a popular-science book includes the former as well as the latter.

of research I would have liked to have had a bit more discussion than the short shrift they are given here.

The fourth part is intended to convince the reader that time is real, with one chapter discussing the idea of time as an emergent concept within the context of quantum gravity, and the other introducing Al-Khalili's concept of entanglement entropy. The interrelated concepts of quantum measurement, entanglement, and decoherence are discussed. It is, correctly, pointed out that entanglement is not limited to the special cases we read about in laboratory experiments, but is actually the rule, and that decoherence is extremely important. The two chestnuts that the laws of physics are time-symmetric and that entropy almost always increases both apply only to isolated systems. Of course, no system in the Universe is truly isolated, but that is not appreciated enough. I remember John Barrow's example of aiming a cue ball at the other 15 balls at the start of a game of pool with the maximum precision allowed by the uncertainty principle; after just 15 collisions the uncertainty in the balls' positions would be larger than the size of the table. We are reminded of a similar but more impressive argument due to Michael Berry already mentioned in Chapter 4: Take the classic molecules-in-a-box thought experiment from a typical discussion of statistical physics, which is alone in the Universe except for one electron at the limit of the observable Universe — but we don't know in which direction. Even if we could measure the position and momentum of each molecule in the box *exactly*, after 50 collisions, *i.e.*, within a tiny fraction of a microsecond, we would lose predictability due to our lack of knowledge of the position of the electron. With the smallest imaginable perturbation having such an effect so quickly, no system can be described as even approximately isolated, thus giving great importance to decoherence. The irreversibility of quantum decoherence, together with an initially non-entangled Universe is thus the ultimate source of arrows of time. The fly in the ointment is that a new Past Hypothesis regarding a non-entangled Big Bang seems to be needed, since fine-tuning doesn't seem to explain it as it does the traditional Past Hypothesis. (After such heavy going, the bonus chapter on time travel after the afterword is almost light relief! There is nothing novel here, but it is included because it seems to belong in a book on time.)

As with many books I've reviewed, there are a few blunders relating to cosmology, but fewer and more harmless than is usually the case and not important for the main narrative. There are a few black-and-white drawings scattered throughout the book and a few footnotes; the nine pages of small-print endnotes after the acknowledgements are references — unusual for a popular-science book, but appreciated. The two pages (also in small print) of about 50 suggestions for further reading are particularly interesting: I've reviewed some of the books, just read others, some were already on my ever-growing list of books to read, others I've added to it. A nine-page small-print index and a note on the type end the book. The book is a nice combination of the familiar and the new, well researched, and thought-provoking; anyone interested in time should find the time to read it. — PHILLIP HELBIG.

References

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- (5) G. F. Lewis & L. A. Barnes, *A Fortunate Universe: Life in a Finely Tuned Cosmos* (Cambridge University Press, Cambridge), 2017.
- (6) P. Helbig, *Found. Phys.*, **16**, 93, 2023.
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