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BOOK REVIEW

From Stars to Life: A Quantitative Approach to Astrobiology

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From Stars to Life: A Quantitative Approach to Astrobiology by Manasvi Lingam and Amedeo Balbi, Cambridge University Press, Cambridge, 2024, pp. xiv + 400. Scope: textbook, £59.99, ISBN 9781009411257(Digital) 9781009411219 (Hardback). Level: senior undergraduates, graduate students, professional researchers.

Where did we come from? Are we alone? Where are we going? Astrobiology poses and explores these age-old questions about the human situation. There is as yet no answer to the second one, but a lot can now be said about the first and, to some extent, the third of these questions. One of the great triumphs of the twentieth century was the joining up and coalescence of cosmology, particle physics, astronomy, chemistry, geology, palæontology and biology, enabling us to understand a great deal abut how we came to where we now are. Of course there are still minor gaps in the narrative, like details of how the first self-replicating molecule arose, but the story that science has constructed is both thrilling and compellingly plausible.

Manasvi Lingam and Amedeo Balbi tell the story in considerable detail. They explicitly intend their book to support a one-semester course in astrobiology for advanced undergraduates or beginning postgraduates in the physical sciences, especially in physics or astronomy. I believe that it can also be read for interest and pleasure by almost any professional scientist, though they will need to allocate significant time to the enterprise, for it is a big book.

Of course, the story has been told before, most notably perhaps by Armand Delsemme in *Our Cosmic Origins: From the Big Bang to the Emergence of Life and Intelligence* (English edition, Cambridge University Press, 1998). But Lingam and Balbi's new book differs in several important respects. Not only does it reflect the impressive scientific progress of the last three decades, which has filled in a lot of missing detail, but it is also quantitative to a fault. There are innumerable small calculations in the text, demonstrating that most of the arguments are actually not all that complicated and can readily be handled by the reader, leaving less to be taken on trust.

The book includes 15 chapters divided into 6 Parts and seemingly discusses every aspect of astrobiology that bears on their title. If anything, the authors exceed their self-imposed brief at both ends because they start from the Big Bang, before there were any stars and close, not with the emergence of life, but with its extinction on Earth in about 2.8 Gyrs from now and the ultimate disappearance of the Earth as a distinct entity as it melts into the expanding Sun in about 7.5 Gyr. The questions posed at chapter ends are integral to the exposition, and their solutions are frequently referred to in the text. There are extensive references for further reading or more detailed justification of ideas and statements made.

Part I on Astronomical Origins opens with context-setting discussions about astrobiology and

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its history, admitting at the outset that the only biology we know of is that on Earth. It also provides the astronomical background, with details of the expanding universe, and the formation of stars, molecules and planets.

In Part II, Earth, the focus moves to our own particular planet. It describes the early Earth, definitions of life, the synthesis of the biomolecular building blocks for life, and various paradigms for the origin of life. The possibility of *panspermia*, whereby life perhaps in the form of bacteria arrived from elsewhere, e.g. on a meteorite, is constantly in the background, though it only affects the question of where life originated, not how. The evolution of life, its co-evolution with its geological environment, and the influence of mass extinctions are discussed.

The narrative moves on smoothly to the question of a planet's habitability. Part III considers the physical and chemical constraints and the circumstellar habitable zone – assuming, with numerous and continuing caveats, that we are speaking of life as we know it (LAWKI) based on carbon and water. So the habitable zone requires conditions where liquid water can in principle exist: for the Solar System, it currently encompasses the orbits of Earth and Mars.

Fittingly, therefore, Part IV on Astrobiological Targets, opens with a detailed chapter about the possibility of life on Mars. Beneath a very thin atmosphere (0.6% of terrestrial atmospheric pressure), with an average temperature of 215 K, and subject to fierce solar irradiation, the waterless surface of Mars offers an extremely hostile environment for life. Yet there is persuasive geological evidence for a warmer Mars with flowing water in the past. Might there have been life at that stage? If so, might some of it have survived the subsequent climate change and still be persisting deep underground? Answering these questions is clearly a priority for interplanetary space probes over the coming years.

Other Solar System targets considered are "icy worlds" that have a solid outer shell of ice covering a watery subsurface sea kept in the liquid state by the warmth from radioactive decay and the tidal heating of differential gravitational forces. Prime examples include Enceladus, Titan (moons of Saturn), Europa, Callisto and Ganymede (moons of Jupiter). Icy worlds are very different from the rocky planets on which, by analogy with Earth, one would naturally expect go looking for evidence of life. The outer shell effectively blocks radiation from reaching the ocean so that life cannot rely on photosynthesis; but chemotrophy is still a possibility as an energy source, and the authors discuss some of the options, together with the likely constraints on the availability of nutrients.

Icy worlds may actually be very common in the Universe, and not necessarily just as planets or their satellites: it can be estimated that there might perhaps be 1,000 Moon-sized icy worlds per star, either bound or free-floating. Even if they do not all possess sufficient water to support subsurface oceans, their existence substantially increases the availability of plausible environments for life.

Going beyond LAWKI, the authors also include a chapter considering "exotic life". They discuss the plausibility and implications of replacing the LAWKI solvent (water) with eight possible alternatives including ammonia, hydrogen cyanide and methane; and replacing the carbon with silicon, boron, nitrogen, phosphorous, sulphur or germanium, although most of these have significant drawbacks. They consider the possibility of exotic life relatively close to home, in the clouds of Venus and in the lakes and seas of Titan, as well as in extreme habitats on the Earth itself.

The final chapter in Part IV is devoted to detecting and characterising exoplanets. This is inherently difficult, in view of the tiny angle that they subtend at terrestrial telescopes. Nonetheless, the authors describe critically, and in quantitative detail, a multiplicity of different approaches and conclude that "Looking ahead, the future of exoplanet characterisation is undoubtedly rosy", in the context of the new ground- and space-based telescopes that are being built or are under consideration.

Part V is devoted to the biosignatures and technosignatures of life that may be sought or detected in, especially, exoplanets. Biosignatures can be sought by remote sensing (e.g. spectroscopy) or they can be sought more directly, either by sample-return or through in situ analysis by an instrumentation package. In almost all cases there is unavoidable ambiguity: e.g. might the apparently biological molecule, or seeming microfossil, or unexpected isotope ratio, or even motility have arisen though inanimate agency? So judgement is needed and as many positive indications as possible.

There is a chapter on the possible technosignatures of intelligent life. It includes discussion of the Drake equation for the expected number of planets with remotely detectable technosignatures. On reasonable assumptions for its parameter values, the number seems very large. One might guess that a significant proportion of the advanced species producing the technosignatures would have developed capabilities for interstellar travel, bringing one naturally to Fermi's paradox: "But where is everybody?" The authors suggest ways of attempting to resolve this conundrum, concluding that arrival at a scientifically sound answer will need "sustained empirical observation". They introduce the Kardashev scale, quantifying how advanced a species is by their ability to harness energy on a planetary, stellar, or galactic scale and then discuss the technosignatures that can be sought.

Finally, Part VI looks to the future, addressing the third of the questions posed at the beginning: "Where are we going". The destiny of the Earth is, of course, inextricably entwined with the future of our star, the Sun. A lot is known about stellar evolution from observation and modelling, and we can anticipate that the Sun will enter its red giant phase in about 5.5 Gyr from now. It will cool, while its radius and luminosity increase, and it will shed about a third of its mass. When the correspondingly decreased gravitational attraction is accounted for, together with dissipation, the earth's orbital radius is expected to stay at about 1.0 AU, whereas the Sun will expand to about 1.1 AU, thereby engulfing the Earth in about 7.5 Gyr from now. Long before that, of course, all life will have been extinguished.

The authors describe how the expected evolution of the Earth, and its degradation as a habitat for life, will lead to the sequential extinctions of different species. They discuss how unicellular, anaerobic, extremophiles might possibly survive for a while in subsurface habitats, or high-altitude regions, thus allowing the retention of a residual biosphere until about 2.8 Gyr from now, which is the plausible end of the Earth as a habitable world. Unless there is life elsewhere, or humans have emigrated to other worlds by then, it will also mark the end of life in the Universe.

The book is clearly written and very well-designed and produced, though some of the diagrams would have been rendered better in colour. It is warmly recommended, not only to support the undergraduate teaching of astrobiology, but for physical scientists more generally. Almost everyone will find interesting information and ideas that are new to them.

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