From Stars to Life

How did life originate? Is there life beyond Earth? What is the future of life on our planet? The rapidly growing multidisciplinary field of astrobiology deals with life's big questions. This text harnesses the authors' two decades' experience of teaching acclaimed courses in astrobiology, and adopts a novel quantitative approach towards this emergent discipline. It details the physical principles and chemical processes that have shaped the origins and distribution of molecules, stars, planets, and hence habitable environments, life, and intelligence in the Universe. By synthesising insights from domains as diverse as astronomy and physics to microbiology, biochemistry, and geology, the authors provide a cutting-edge summary of astrobiology, and show how answers to many fundamental questions are drawing closer than ever. Geared towards advanced undergraduates and graduate students in the physical sciences, the text contains more than 150 innovative problems designed to enhance students' knowledge and understanding.

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To our families, with love and gratitude

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Preface

A myriad of multifaceted spectres are haunting humankind: anthropogenic climate change, biodiversity collapse(s), wars and armed conflicts, and artificial intelligences (AIs), to name a few. In these volatile times, the refrain of '*Are we alone?*' – which has echoed through millennia of human history – reverberates and resonates stronger than ever, in the wake of growing alienation and chaos. Against this sober backdrop, seeking answers to this question and others of its ilk might seem a trivial pursuit. And so one may well ask: why write this book, and why undertake it now? There are two responses that spring to our minds: a pragmatic one that we elucidate below and a deeper, philosophical one we defer to the end.

Astrobiology strives to explore three questions of fundamental import: *Where did we come from? Are we alone? Where are we going?* We have witnessed significant progress in the twenty-first century on these fronts, especially within the last decade. Synthetic chemistry and systems chemistry have accomplished a host of breakthroughs in producing and assembling the building blocks of cells. Missions to worlds in our Solar System (e.g., Mars and Enceladus) have revealed several ingredients vital for life, such as liquid water, (free) energy, and bioessential elements. The search for extraterrestrial life and intelligence has also received a major impetus from the exoplanet revolution, which is unearthing a spate of promising targets for future investigations by next-generation telescopes. Lastly, with renewed interest from governmental and private agencies, space exploration is swiftly picking up steam.

Thus, the rapid growth and innate significance of astrobiology constitute a compelling and timely case for authoring a textbook on this subject. There are, however, a number of excellent works in this area, so the question of determining the rationale behind our book remains. Based on an extensive literature survey, the available textbooks are characterised by one or more of the following criteria: (1) they are introductory-level and targeted towards first- or second-year undergraduates; (2) they are qualitative in nature, with an emphasis on the biological aspects; and (3) they are not sufficiently abreast of the latest developments in the field.

In contrast, driven by the remarkable blossoming of astrobiology, universities all over the world are increasingly offering tailored courses at the advanced undergraduate and beginning (post)graduate levels, often in physics and/or astronomy departments, since astrobiology draws heavily on these areas. Despite this fact, a major lacuna in the domain of astrobiology textbooks is discernible: there is no book that evinces a quantitative approach, is pitched towards advanced undergraduates and (post)graduates in the physical sciences, and chronicles the current state of the field. It is our hope and expectation that this textbook will address the above lacuna.

Our book is explicitly intended to be employed in a one-semester course at the forenamed levels, comprising about 30 lectures of 75 minutes each; this is roughly the format adopted in our institutions. We anticipate that 80–90% of the total content in the textbook could be covered within this time frame, with chapters of around 12, 24, and 35 pages warranting one, two, and three lectures, respectively. The prerequisites for comprehending this book are high school biology, two to three years of undergraduate coursework in physics or a closely related discipline (e.g., astronomy), and general chemistry at the freshman undergraduate level. The structure and motifs of the book, divided into six parts, are sketched next.

In Part I, we dive into the astrophysical origins of astrobiology, because it is crucial to understand the phenomena and steps that created the celestial worlds (e.g., planets) for the emergence of lifeforms. We commence with a brief historical introduction in Chapter 1. By starting from the Big Bang, we trace the formation of the Universe, of stars, elements, and molecules in Chapter 2, after which we embark on an in-depth exposition of the multiple stages and processes of planet formation in Chapter 3.

Currently, only a single world is confirmed to host life in the Cosmos: our planet Earth. Taking cue from this simple datum, we focus on Earth in Part II. We describe the potential physicochemical conditions on early Earth in Chapter 4, as they shape the milieu in which living systems originated. This account is followed by a detailed analysis of *how* and *where* the origin(s) of life occurred on Earth in Chapter 5. Building on this narrative, we summarise the co-evolution of life and its environment(s) in Chapter 6.

Habitability is a cardinal notion in astrobiology, since it enables us to determine which settings are conducive for harbouring life, thereby aiding us in target selection for seeking putative signatures of life. Hence, in Part III, we elucidate the set of physicochemical constraints that must be fulfilled at any given moment in time to maintain habitable conditions for life-as-we-know-it (Chapter 7), as well as the physical mechanisms that modulate and/or sustain habitability on geological timescales (Chapter 8).

In Part IV, we centre our attention on the noteworthy matter of astrobiological targets inside and outside our solar system. We report the prospects for life-as-we-know-it on Mars in Chapter 9, and on icy worlds with subsurface oceans of liquid water (e.g., Europa and Enceladus) in Chapter 10. Next, we delve into the possibility of 'exotic' life on worlds like Venus and Titan in Chapter 11. Moving past the solar system, we recount methods of detecting and characterising (rocky) exoplanets in Chapter 12.

Given that one of the key objectives of astrobiology is to look for evidence of extraterrestrial life, we tackle this topic in Part V. We delineate the various techniques and associated concepts that may help us discover markers of non-technological life (i.e., biosignatures) in Chapter 13, and traces of extraterrestrial intelligence (i.e., technosignatures) in Chapter 14. The search for extraterrestrial life is intertwined with our own future on this planet and beyond (e.g., space exploration), owing to which we briefly discuss this aspect in Chapter 15 of Part VI at the end of the book.

Each chapter is accompanied by $\sim$10 problems on average. Instead of regurgitating facts, calculations, or principles in that chapter, we sought to design the problems such that they complement, supplement, or enhance the comprehension of the corresponding material(s). We are quite aware that many, perhaps even most (but *not* all), of the problems could be solved by ChatGPT and its cognate descendants. However, even in this scenario, we trust that the students may still learn something substantive from the AI-generated answers, and that they can duly boost their understanding.

This textbook contains extensive references, albeit without any pretensions of being exhaustive. This unusual decision was made consciously on account of the following reasons: (1) astrobiology synthesises knowledge from a bevy of disparate fields, and it seemed inappropriate to quote data without proper citations; (2) because astrobiology is so diverse, our readership (chiefly advanced students) can peruse these publications to further educate themselves in the domains that interest them; and (3) the references underscore the fast-moving and multidisciplinary nature of astrobiology.

At this juncture, we wish to highlight a couple of important caveats concerning this textbook. In expounding a subject of this scope and magnitude, countless topics had to be either excluded or severely truncated to keep the book within a strict limit (∼400 pages). Needless to say, this winnowing was subjective, and thus coloured to an extent by our limitations and biases. In a similar vein, both of us hail from backgrounds in the physical sciences (NB: the book is also oriented towards such an audience), implying that our coverage of pivotal areas in geology, biology, and chemistry may be insufficiently nuanced and/or inaccurate. We accordingly take this opportunity to gladly solicit corrections and feedback from readers.

We will round off our exposition by circling back to the central question posed at the outset: why compose this book in this disruptive epoch? As a multitude of people experience feelings of estrangement (*Entfremdung*) and loss, humanity is progressively beset by three profound existential questions that have engrossed our species since the dawn of history: *Where did we come from? Who and what are we, humans, and what is our place in the Cosmos? Where are we going?* On comparing this trio with the core goals of astrobiology outlined in the second paragraph, the *fil rouge* or *roter Faden* (i.e., common thread) weaving them together is manifest.

Hence, though our era may seem uniquely ridden with overwhelming difficulties and riven with acute schisms *prima facie*, its anxieties and troubles could be considered universal and ever-present, to a certain degree. Astrobiology, by virtue of grappling with the aforementioned fundamental questions, might have the potential to situate our zeitgeist in a cosmic context, and/or forge bonds and bridges across myriad groups, especially if we unearth evidence that we are not alone in this vast Universe. The eminent biologist Carl Woese (1928–2012) wrote of biology that (Woese, 2004, pg. 185):

> [S]ociety will come to see that biology is here to understand the world, not primarily to change it. Biology's primary job is to teach us. In that realisation lies our hope of learning to live in harmony with our planet.

It is our opinion that astrobiology can assume and fulfil an analogous role for humankind in due time. Therefore, books in this subject are rendered valuable and opportune, arguably all the more so in this turbulent age.

Last but not least, gazing beyond concrete advantages or intangible benefits ensuing from astrobiology in general and our book specifically, we believe that the quest for knowledge and the holistic growth thence kindled is a worthy endeavour in its own right – the human propensity for learning is a wondrous thing, and could ultimately engender its own rewards. This theme was eloquently articulated over a millennium ago by the renowned Japanese writer Lady Murasaki Shikibu (973?–1014?) in her abiding and poignant masterpiece *Genji monogatari* (Shikibu, (c. 1010) 2003, pg. 329), perceived by many as the first 'modern' novel in recorded history:

> No art or learning is to be pursued halfheartedly …and any art worth learning will certainly reward more or less generously the effort made to study it.

We are grateful to the diverse throng of individuals – hailing from multifarious walks of life and sundry locales sprinkled across the world – who have contributed to this textbook, to our ways of thinking, and ultimately to our very psyches. Above all, we are indebted to our families for their profound love, support, and patience: this book is as much the fruits of their labour as it is ours.

We also thank colleagues (faculty, staff, and students) in our respective workplaces for their helpful assistance vis-à-vis our textbook.

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Although the process of writing this textbook was occasionally arduous, it was a deeply rewarding experience. Likewise, we hope that our readers will enjoy their intellectual forays into the fascinating world of astrobiology.