Astronomy + biology

Charles S Cockell reviews the eventful history and exciting future of astrobiology: the collaboration between astronomers and biologists.

In the 200 years since the Royal Astronomical Society was founded, astronomy and biology have never been natural allies – not because they are in conflict, but because there seems little common ground on which a deep and coherent relationship might be forged. One characteristic common to both that we can observe, however, is that they deal in immensities. Astronomers peer back over 13.8billion years of history and attempt to fathom where the material in the universe came from and to piece together the origin of stars that likely number at least ~10^{20} in the known universe. Microbiologists stare into a less deep abyss of time. Yet beginning 4.54billion years ago, when our planet congealed out of the incandescence of the protoplanetary disc, there have come to exist on this tiny speck of rock we call Earth about 10^{29} microbes (Kallmeyer *et al.* 2012). Astronomers and biologists have never been shy of large numbers.

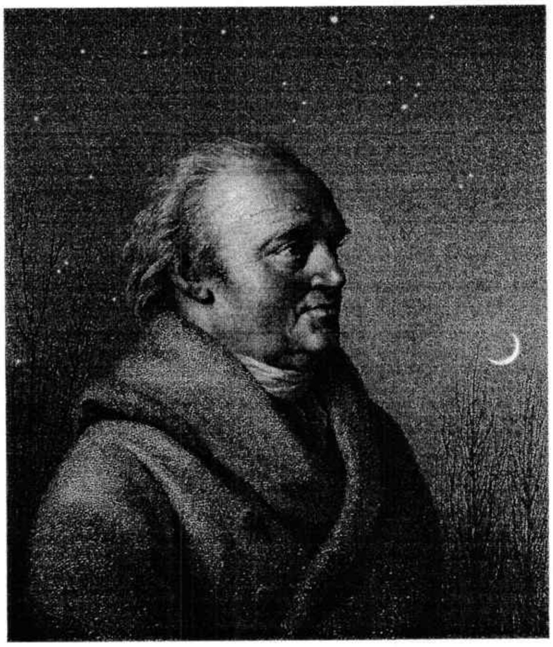
Yet astronomers with their telescopes are looking outwards to vastness, seemingly in the opposite direction to microbiologists who, with their microscopes, look inwards to similarly unfathomable numbers. But over the past two centuries, these two apparently antipodal groups of people have come together in a similar quest. This is an alliance forged in the fire of a simple and unambiguous scientific question: is the material that swarms and swims beneath a microscope slide something unusual, even unique to this planet, or can such a phenomenon be observed on and within similar lumps of material elsewhere across the cosmos?

Moon towns

This apparently simple scientific question, first posed long before the birth of the RAS, became indissolubly linked with the question of whether an intelligent version of the material under a microscope slide can be found elsewhere. As intelligences might be creatures we could talk to, it is perhaps unsurprising that the question of whether any extraterrestrial life existed became overshadowed by the quest to find such entities, and with it the alliance between astronomy and biology often slid into the realms of what many would soon regard as fringe science. When William Herschel (figure 1) famously wrote, in an age when the reason for the uncannily circular structure of impact craters was not understood, that those "numberless small Circuses we see on the Moon are the works of the Lunarians and may be called their Towns" (Herschel 1778), he was only one in a long line of scientists fascinated by intelligent life, who imagined civilizations in our neighbourhood.

Eighty years after the founding of the RAS, in 1900, the French Academy of Sciences offered 100000 francs to the first person to communicate with alien intelligence – apart from on Mars, because that was considered too easy. In our modern times, it strains the imagination to conceive of a time when many considered civilizations on Mars to be an incontrovertible fact. Camille Flammarion's 1892 tract, *La Planète Mars et ses Conditions d'Habitabilité*, had put paid to any suggestion that talking to the martians was a challenge worthy of the Prix Pierre Guzman. But in this slight to martian conversationalists was an example of the poisonous mixture of the fascination with extraterrestrial civilizations and the perceived credibility of scientific institutions. It was further inflamed by Percival Lowell and his acolytes who, even in the early 20th century, imagined

"Images of the dead surfaces of Venus and Mars quenched centuries of optimism"



1 *Sir William Herschel, first president of the RAS, speculated about Lunarians in the 18th century.* (SPL/RAS)

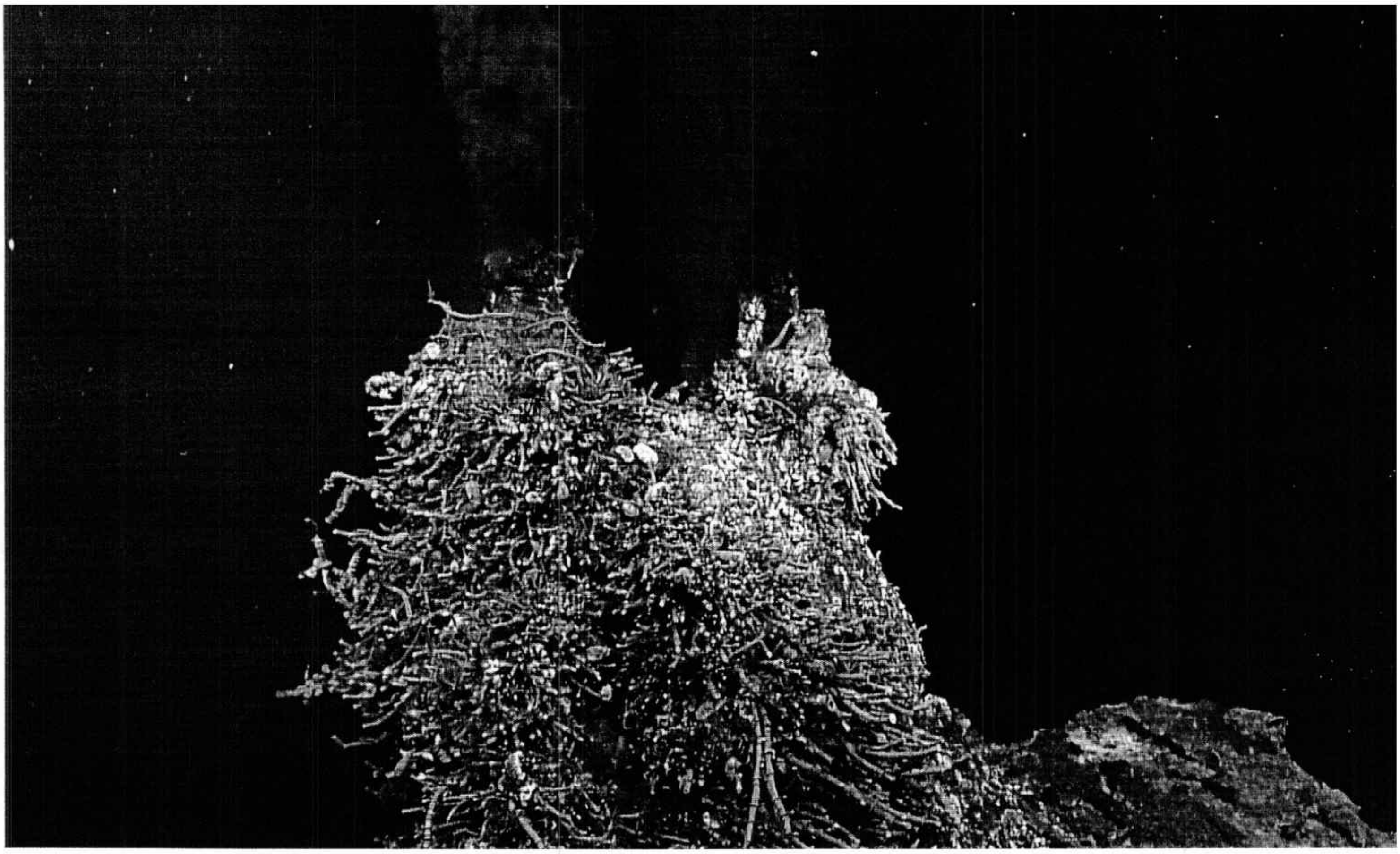
that they saw canals on Mars and wrote prolifically about the suitability of that planet as a home to intellects that, as H G Wells famously fantasized, were "vast and cool and unsympathetic" (Wells 1898).

When the beginning of the space age and the efflorescence of planetary exploration using robotic spacecraft got into full sway in the 1960s, images of the dead surfaces of Venus and Mars quenched centuries of optimism; biology then retreated from astronomy. What was now perceived as scientific over-optimism of the past scorched the fingers of the biologists and astronomers: no serious biologist would henceforth admit to their colleagues that they were in cahoots with astronomers to search for alien life, and no astronomer wanted the opprobrium of being seen to dabble in biology. It also crushed any serious professional support for funding such endeavours.

Down but not out

But like a relationship that goes awry for reasons not down to malice, but because of some ineffable incompatibility, biologists and astronomers still wistfully gazed at each other across the room with a twinkle in their eyes, wondering whether, under different circumstances, they could really fall for each other.

That day would eventually arrive, but not before biologists had strengthened a link with a relatively new ally of astronomy – planetary sciences. For buried in the grainy pictures of the martian surface returned by the Mariner spacecraft, and later in the much-improved imagery of the Viking orbiters, were the unmistakable signs of liquid water that had flowed copiously across the martian surface. Although the mid-1970s Viking Landers seemed another stalled attempt to engineer a meeting of biology and astronomy – no life, not even a metabolizing microbe, could be found in the soil that had been home to Lowell's canals – the orbital data brought the unmistakable realization that Mars was once a wet planet. Rivers and lakes once adorned a volcanic world. But if these places did ever



harbour any form of life, what would it have been like? What sort of life should one look for? How can life exist in such extreme conditions? The planetary scientists wanted answers from biologists.

In the late 1960s and 70s, the biologists themselves were experiencing a renaissance in their view of life. Microbiologist Thomas Brock investigated the volcanic hot springs in Yellowstone National Park in the USA and, observing microbes flitting and flexing in their waters, he demonstrated the astounding fact that they were able to grow at temperatures exceeding 70°C (Brock & Freeze 1969). As biologists investigated the envelope of physical extremes, they discovered life everywhere. Even in the boiling waters of the newly discovered hydrothermal vents that spew crustal waters into the deep oceans at plate boundaries (figure 2), microbes would eventually be found that not merely tolerated temperatures greater than 100°C, but had adapted to require them. Environments with high and low pH, radiation levels far higher than will kill a human, and pressures more than a thousand atmospheres all yielded their haul of microbes (Stan-Lotter & Fendrihan 2012, Harrison *et al.* 2013). New genetic insights had revealed the domain archaea, a group of microorganisms as diverse and biochemically remarkable as their better-known cousins, the bacteria. These creatures radically expanded our knowledge of the reach and capacities of the microbial world.

Biosphere limits

As these new vistas emerged, the biologists began to wonder about the limits of the biosphere and whether it might tell us about the potentialities for life elsewhere. Did the menagerie of microbes that inhabited the hydrothermal vents suggest that deep in the oceans of distant worlds, biological adaptability and profligacy might also bring life to these bodies? Of course, they also realized a point that is often poorly understood. The permissiveness of life on a planet, once it does get started, does not imply that the origin of life is also flexible in its requirements. If the origin of life requires very specific conditions and is therefore rare, then the universe might be full of environments suitable for life, but these locations might be uninhabited. Nevertheless, that important point does not detract from the intriguing observation that physical and chemical conditions in some extreme environments in space might overlap with similar conditions on the Earth known to support life.

Thus, inexorably, the biologists began to form a bridge to planetary scientists, which would lead them eventually back to astronomers. One did not have to propose alien races, artificial canals or even the presence of life itself to see merit in a growing conversation between these different groups.

The realization that understanding the origin and distribution of this replicating, evolving matter that we call "life" required interdisciplinary collaborations was not entirely new. We are often remiss in forgetting the efforts of non-Western scientists. As early as 1953, Gavriil Tikhov (1875–1960) wrote a full-length book with the title *Astrobiology* (Tikhov 1953) and even founded an "astrobotany" sector allied to the Kazakhstan Academy of Sciences. It is too easy to dismiss him as an eccentric. He proposed that spectroscopic signatures of vegetation might be used to look for life in our solar system. Although we have long since given up the quest to map seasonal vegetation on Mars, the Vegetation Red Edge, that abrupt increase in infrared reflection observed in chlorophyll-containing organisms on Earth, has more recently been considered as a potential surface biosignature for life on exoplanets (Seager *et al.* 2005). There have been a number of speculations on how the spectral characteristics of stars might influence the type of pigments (figure 3), and thus biosignatures, associated with alien photosynthetic organisms (Kiang *et al.* 2007). Tikhov's influence looms large.

In the 1960s, Joshua Lederberg, a molecular biologist who won a Nobel Prize for discovering that bacteria could mate and thereby transfer genes, known today to be a central factor in the spread of antibiotic resistance, became involved in NASA's biological interests in the United States. He brought the term "exobiology" to the fore (Lederberg 1960). Like the Soviet term astrobiology, exobiology was focused on the search for life beyond

2 *Hydrothermal vents. In these and other extreme locations, biologists found organisms that would eventually energize their collaboration with astronomers and planetary scientists.* (Ocean Networks Canada/Ocean Exploration Trust nautiluslive.org)

Earth and it dominated NASA's biological efforts to explore the universe for life. Under the umbrella of this term, a range of groups, for example the Exobiology Branch at NASA Ames Research Center in northern California, convincingly brought biologists, planetary scientists and engineers together to tackle the question of life beyond the Earth. The work was not merely speculation. From these collaborations came the Viking Lander missions to search for life on Mars (Klein 1992). Their experimental packages, which included ingenious crucibles for adding nutrients to martian soil collected by a scoop and mass spectrometers to hunt for the signatures of biogenic gases produced by microbes, were the first biological experiments implemented on another world. They found a dead, but chemically active soil that nevertheless still stirs controversy in the community. Indeed, the ambiguity of the Viking data caused NASA to recoil, for decades, from missions that explicitly stated as their objective the search for extant life.

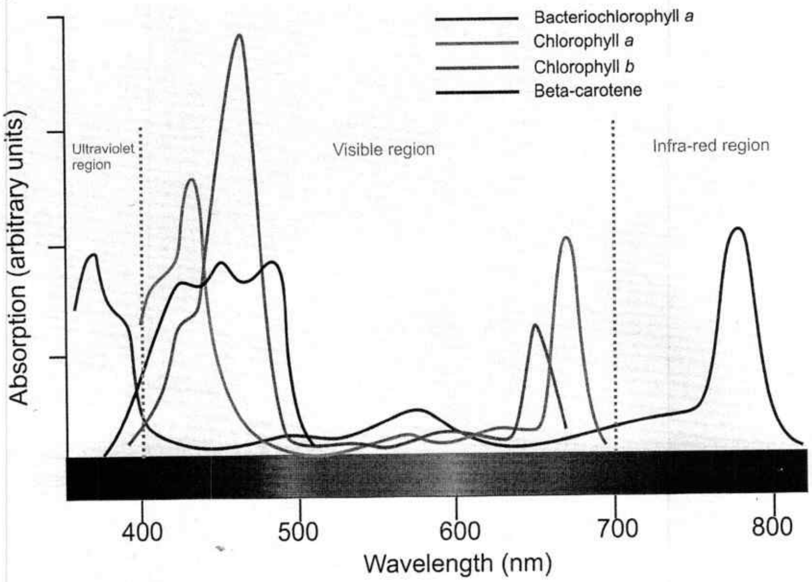
Convergence

In hindsight, one can pick out a convergence that was unseen at the time. Biologists, knowing more about life in extreme environments, its proclivities and limits, were well placed to consider how to search for this life elsewhere and whether in fact extraterrestrial environments had any potential to host similar life to that being discovered in the Earth's extreme Mars-like environments such as Antarctica. In the meantime, planetary scientists, on account of the new planetary missions that were snapping images of distant worlds and gathering chemical knowledge about their surfaces and atmospheres, were better placed to make accurate statements about the conditions in these distant bodies, data that could be used in turn by the biologists to make assessments about habitability. In some sense, one might simply observe in a crude way that at last biologists and planetary scientists had some data that they could compare and contrast, rather than sitting together in rooms speculating about distant life, intelligent or not, with no recourse to information. Things had finally got empirical.

Yet even as this intersection between planetary scientists and biologists developed, astronomers and biologists had not yet got together in any serious manner beyond their brief fling in the light of alien civilizations.

All this would change in the 1990s. I was undertaking a postdoctoral fellowship at NASA Ames Research Center in 1995 and was able to watch the emergence of the NASA Astrobiology Institute. The furore that surrounded the 1996 *Science* paper by David McKay and co-workers (McKay *et al.* 1996) about purported biogenic signatures in the martian meteorite ALH84001 is often cited as the impetus that pushed astrobiology into centre field at that time. I sat in the café at Ames and watched US President Bill Clinton on the White House lawn laud the new discovery. While it was exciting, I think such media frenzies are, in the broader scheme, mere tinsel that never launches a scientific field – that takes much greater seismic activity. If I was to offer an opinion on what happened on a wider scale at that time that might have been sufficient to stimulate NASA's interest, I would cite two particular developments.

In the early 1990s, extrasolar planets were discovered, first orbiting pulsars and later, main-sequence stars (Perryman 2012). A new age of astronomy had been launched. But buried within this thrilling new landscape for our understanding of the formation of solar systems and their planets, there was a new potentiality. Just as planetary scientists had successfully gathered information from Mars and other locations through our solar system, information that gave empirical foundation to a collaboration with biologists, so the astronomers had now gathered information on more distant worlds that would furnish them with reasons for a new discussion with biosciences, one that would take those two communities beyond their ancient speculations about civilizations. Now they could discuss how many of these planets might host liquid water, a fundamental requirement for life. They could calculate what radiation was reaching the surfaces of these distant planets and what this might mean for life. They could ponder on the stability of planetary orbits in binary star systems and search for habitable zones in such systems, and so on. An ancient relationship between biologists and astronomers that had gone sour in the fetid canals of Mars was reborn.



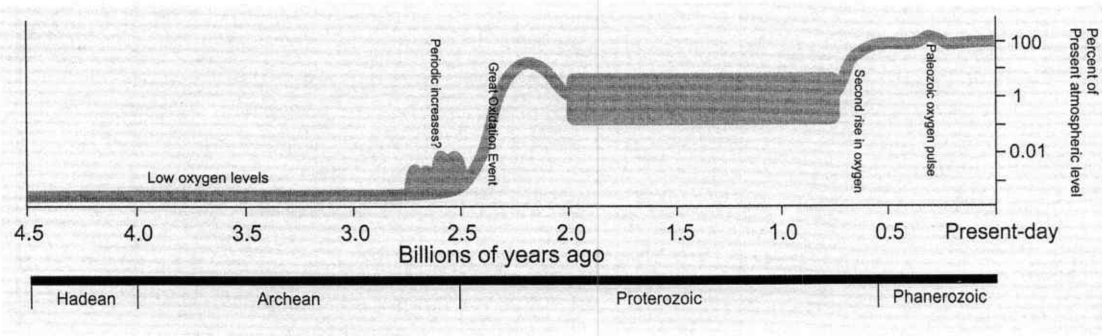
3 *Different organisms contain pigments that have different absorbances, such as these examples of photosynthetic chlorophylls and carotene. These pigments raise questions that have persisted for decades on whether such biological absorbances could be used as signatures for life on distant worlds. Such questions, when asked about exoplanets, have brought biologists together with astronomers.*

Rock records

Yet there was more. Quietly in the background, biologists were working with geologists more than ever before. From their mutual explorations of ancient rocks emerged new insights about the antiquity of life and its provenance. These much-debated fossils raised questions on the conditions for the appearance of life and the environment of the ancient Earth. Great paroxysms in the history of the Earth, such as the rise of oxygen about 2.4 billion years ago, were also revealing their secrets in the rocks (figure 4). Why did the oxygen concentration rise so quickly, who was to blame? It was clear that life, cyanobacteria, were the culprits of the rise, yet cyanobacteria had apparently appeared in the rock record long before. What took them so long? As the detective story unfolded, the rise in oxygen became a textbook exemplar of the co-evolution of life and a planet (Kasting & Siefert 2002). Reduced gases, among other factors, had prevented the initial rise of oxygen. As if in a waltz, the action of Earth influenced biology and vice versa. The Earth and life have advanced through time in an inseparable dance.

"The rise in oxygen became a textbook exemplar of the co-evolution of life and a planet"

As the fields of geobiology, then geomicrobiology (focused on the role of microbes in shaping the Earth), emerged, so the co-evolution of life and planet became clearer. Yet again, it raised obvious questions about distant worlds. Were all these interlocking feedbacks mere serendipity? Was the rise of oxygen that led to aerobic respiration and thus the energy required for intelligence one of many possible planetary paths, the majority of which would end with not a brain in sight, or was the trajectory of Earth a template for any small rocky planet with liquid water in the universe? On this compelling question of the



4 *The history of oxygen in Earth's atmosphere. A detective story involving biologists and geologists has led to a timeline of the history of this gas. It would lead to a collaboration with astronomers who will now seek this gas on distant exoplanets as a signature of biological activity.*

contingency, or chanciness, of Earth's trajectory, we still do not have an answer (Ward & Brownlee 2000, Waltham 2014), but the field of geobiology provided an empirical basis to make this question answerable.

So, if I had to explain why in the 1990s the conditions seemed propitious for a collaboration between biologists and astronomers, I would guess that the discovery of exoplanets and the emergence of geobiology provided two of the key structural girders that made the edifice look robust.

Of course, the zeitgeist of this new interdisciplinary environment demanded a name. Soviet astrobiology and American exobiology were concerned exclusively with the search for alien life and that was too narrow. The new collaboration certainly did seek to know how unusual life was in the universe, but it was equally interested in the origin of life on Earth, its co-evolution with the planet and what we might learn about life in general from the history and trajectory of our own biosphere. The possibility that such a cosmic theme might be repeated elsewhere could be investigated only with better knowledge of our own world. A name was needed to capture this idea. When NASA formed the NASA Astrobiology Institute, which consolidated in institutional form this new sense of an interest in the origins, evolution and distribution of life in the universe, then astrobiology it was (Blumberg 2003).

Misnomer?

Although there is complexity in the way in which new sciences are named, including areas such as exobiology and astrobiology (Cockell 2001), which have been additionally confused by words such as xenobiology, cosmobiology and bioastronomy, astrobiology seems sensible enough. There are those linguistic purists who will rightly point out that, as far as we know, there is no life on stars, so the prefix of the word (star, which is *aster* in Greek, *astrum* in Latin) makes the world a misnomer. However, if physics is broadly conceived as the study of matter and energy, and astrophysics is the study of this with a more cosmic twist, then it seems to me that if the study of the matter that replicates and evolves is called biology, then the study of this with a cosmic twist is astrobiology.

While we are on the topic of scientific definitions, there are those who ask whether astrobiology is truly a separate field that merits its own domain. It is worth remembering that all scientific fields are human inventions. For example, there is no such natural entity as physics. When you examine an atom you will not find a small label wrapped around a proton that says "this material should only be studied by someone with a physics degree". Nature is indifferent to human pride and administrative boundaries. There is merely a universe about which we can ask questions using the scientific method – that is all. If the word astrobiology was to achieve nothing more than gathering a few biologists and astronomers in the same room once in a while to talk about questions of common interest and write papers, then its purpose in the world would be as much justified as neurobiology, geophysics, chemistry or any other word dreamt up by humanity. There is really nothing deeper or more profound to be said on this matter.

What of the future of this fertile link between biologists, astronomers and planetary scientists? The Royal Astronomical Society has been witness to the past 200 years in which this conversation has grown in maturity, but if we were to consider the 200th anniversary a midpoint, what will this essay look like in the year 2220, when Fellows gather in the futuristic megalopolis of London to celebrate 400 years?

It is a notoriously dangerous thing to make predictions, so I will not fall into that trap. However, one might attempt to outline some directions one could wish for, states of knowledge one might hope will seem mundane to the RAS of the year 2220. By that time, one would hope that we have much more substantial knowledge of the surface and subsurface conditions of many bodies in our solar system, especially with respect to their biological potential. The subsurface of Mars down to many kilometres, the oceans of Europa, Enceladus and Titan, the salty brines beneath the surface of Ceres, and potentially even the interior of Pluto. Are these bodies of water uninhabitable, too extreme for life, or do they contain fluids that are habitable? If they are habitable, do they contain life? One might hope that answers to these basic questions will be present for all these bodies, and more.

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Armed with this information, we will be able to set out the contours of habitability in the universe at the largest scale. Are habitable environments common in the universe, but devoid of life, or is the presence of habitable conditions always associated with life? Perhaps, in contrast, there are many bodies of liquid water that fall short in one aspect of their physical and chemical conditions as suitable places for life. Perhaps we live in a universe full of aqueous environments that sit just outside the boundaries of biology. In using our own solar system to gain generalized insights into life elsewhere, we would hope that our knowledge of life in the cosmos will be greatly advanced and, in many respects, settled, by this future date.

Perhaps, by 2220, astrobiologists will have access to many spectra from Earth-mass planets and then we will have a definitive answer to the question of whether there are clear biosignatures on other worlds, and we will have a statistical appreciation of their occurrence across wide expanses of our own galaxy, if they exist. Equipped with this knowledge, we will first be able to say whether we are alone in the universe, at least with respect to any biology, and second we will be in a strong position to make statements about the distribution of habitable conditions across large swathes of the known universe. We are not so far away from realizing these objectives today. Another 200 years should see them safely home.

We might hope that our knowledge of the interiors of extrasolar rocky worlds, the structure and composition of their atmospheres and the evolution of the stars around which they orbit will not only be advanced, but augmented by many examples, allowing us to answer

that profound question that still eludes us: is the trajectory of the Earth and its biosphere a mere contingent event, so dependent on so many variables that it would never be repeated elsewhere, or is it typical of many worlds that share broadly the same features? An answer to this question, likely to be known to those who attend the RAS's 400th anniversary celebration, will allow us to know how special or common the Earth is in the cosmos, even if we are still ignorant as to whether such distant worlds harbour intelligences.

Alongside this growing cosmic appreciation, we can hope that, as has happened in the last 100 years, this knowledge will be further enriched and advanced by our understanding of the history of life on Earth. At this future date, we should be able to say with greater certainty when life emerged on the Earth and in what form. How long was the span of time between the accretion of the planet and the emergence of life? The answer to this question may forever be shrouded by the simple fact that we may never be able to find chemical fossil evidence of the first replicating molecules on Earth in exactly the place that they occurred, given that the rocks from this time are long since destroyed. However, greatly advanced chemical knowledge of the origins of life, coupled with a growing understanding of the chemical and physical conditions of the young Earth and the formation of the solar system, may narrow this time considerably and with it we will be better able to assess the prospects that other worlds could support such a process.

Carbon and water

In the field of chemistry and its collaboration with astronomers and biologists, it remains a fascinating question to know whether the fact that life on Earth is carbon-based and uses liquid water as a solvent is merely because of the abundance of these raw materials in the universe, or whether it reflects a more fundamental chemical barrier to any alternatives. Answers to this question will come from a greatly expanded grasp of the nature of carbon compounds and water in the varied conditions of the universe; further laboratory adventures to study complex compounds made of alternative elements such as silicon in exotic solvents such as ammonia or liquid methane will, one hopes, enrich our understanding of the peculiarity or not, as the case may be, of life on Earth.

5 *Do planets in the Andromeda Galaxy exhibit biosignatures of life? How can extragalactic astrobiologists assay planets for life outside our own galaxy and eventually beyond the Local Group?* (Adam Evans/ Wikimedia Commons)

Going much further afield, we might wonder about the prospects for a field of "extragalactic astrobiology". Will we build telescopes large enough to search for exoplanets in distant galaxies and investigate them for biosignatures? Andromeda, or another galaxy in our Local Group, might become the focus of such a stupendous astronomical and engineering project (figure 5). When we reach the 600th anniversary of the Society, might astronomers exchange ideas and information about the habitability of planets in these distant galaxies, making our search for life a truly cosmic endeavour? Might professors of extragalactic astrobiology spend their time considering how they could assay for life even outside the Local Group?

There are many other directions one can envisage in the years ahead, but what is thrilling is that the last 200 years of astronomy and its on-and-off alliance with biologists has now blossomed into a permanent scientific friendship. One might hope, and indeed expect, that the next 200 years, however unpredictable the minutiae of particular discoveries or insights, will in broad outline bring us closer to a deeper understanding of the origin of the replicating, evolving material we call life, the distribution and prospects for life across the cosmos and our own place in this small, but immensely interesting phenomenon of the material universe. ●

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REFERENCES

Brock T D & Freeze H 1969 *Journ. Bacteriol.* **98** 289

Blumberg BS 2003 *Astrobiology* **3** 463

Cockell CS 2001 *Interdisc. Sci. Rev.* **26** 90

Harrison J P *et al.* 2013 *Trends Microbiol.* **21** 204

Herschel W 1778 microfilm (reel 17) of the RAS Herschel MSS, W. 3/1.1 p8

Kallmeyer J *et al.* 2012 *Proc. Natl. Acad. Sci.* **109** 16213

Kasting J F & Siefert J L 2002 *Science* **296** 1066

Kiang NY *et al.* 2007 *Astrobiology* **7** 222

Klein HP 1992 *Origins Life Evol. Biosph.* **21** 255

Lederberg J 1960 *Science* **132** 393

McKay DS *et al.* 1996 *Science* **273** 924

Perryman M 2012 *Astrobiology* **12** 928

Seager S *et al.* 2005 *Astrobiology* **5** 372

Stan-Lotter H & Fendrihan S 2012 *Adaption of Microbial Life to Environmental Extremes* (Springer, Berlin)

Tikhov GA 1953 *Astrobiology* (Molodaya Gvardiya Publ., Moscow)

Waltham D 2014 *Lucky Planet: Why Earth is Exceptional and What that Means for Life in the Universe* (Basic)

Ward PD & Brownlee D 2000 *Rare Earth: Why Complex Life is Uncommon in the Universe* (Copernicus)

Wells HG 1898 *The War of the Worlds* (William Heinemann, London)