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INTRODUCTION

The detection of extra-terrestrial life and the consequences for science and society

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Astronomers are now able to detect planets orbiting stars other than the Sun where life may exist, and living generations could see the signatures of extra-terrestrial life being detected. Should it turn out that we are not alone in the Universe, it will fundamentally affect how humanity understands itself—and we need to be prepared for the consequences. A Discussion Meeting held at the Royal Society in London, 6–9 Carlton House Terrace, on 25–26 January 2010, addressed not only the scientific but also the societal agenda, with presentations covering a large diversity of topics.

Keywords: origin and evolution of life; extra-terrestrial life; extra-solar planets; astrobiology; search for extra-terrestrial intelligence; science and society

1. The quest for exploration

A thin layer around the surface of Earth is teeming with life of huge diversity: from micro-organisms to plants and animals, and even intelligent species. Up to now, this forms the only known sample of life in the Universe. However, observing the pinpoints of light on the night sky has probably always inspired humans to speculate about the existence of other worlds. It is, therefore, not surprising that there is a long history of thoughts about such a proposition (e.g. [1–5]). Despite the fact that it is straightforward to imagine that stars other than the Sun would also host planets, speculations turned into evidence only fairly recently: in 1992, the first planet around a special type of stellar remnant, namely pulsars, was found [6], and in 1995, the first detection of a planet around a star of similar composition to the Sun, namely 51 Peg b, was reported [7]. The enormous progress in this field is reflected by the fact that, as of 1 June 2010, more than 450 extra-solar planets[1] are known. While most of these are gas giants like Jupiter and Saturn, some spectacular discoveries of about 20 planets of less

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[1]This number is likely to be out of date already by the time this paper is published, but the reader is referred to the 'Extrasolar Planets Encyclopedia' at http://exoplanet.eu.

One contribution of 17 to a Discussion Meeting Issue 'The detection of extra-terrestrial life and the consequences for science and society'.

than 10 Earth masses (e.g. [8–13]) have already indicated that rocky planets with conditions considered suitable to harbour life are probably rather common. The discovery of a true sibling of our home planet, therefore, seems to remain only a question of time (cf. [14,15]).

The active quest for extra-solar planets has opened a new chapter in the book of the search for extra-terrestrial life. This was already an active field of science with the exploration of the Solar System by means of space probes, which gave rise to a 'space age' from 1957 when Sputnik-1, the first Earth-orbiting artificial satellite, was launched. Current technology allows us to land a robotic chemistry laboratory on other Solar System bodies, or return samples to Earth, the latter coming with the advantage of being able to adapt analysis strategies to unexpected findings. Based on our current understanding, Mars, Europa, Enceladus and, if we consider life based on a liquid other than water, Titan are the most promising places for finding life signatures (cf. [16]). A direct search for life on Mars, rather than searching for evidence from fossils, was carried out as early as 1976 with the two *Viking* landers. However, the outcome of these experiments is still subject to an unresolved controversy (cf. [16,17]). A further opportunity to find alien life forms is given by the study of meteorites found on Earth (cf. [17]), where it is now well established that some of them originate from Mars [18]. However, the exchange of biological material between Solar System bodies might also mean that such life is not distinct from ours, but rather shares a common origin.

Only shortly after the advent of the space age, it was proposed to use radio telescopes to search for signals arising from extra-terrestrial civilizations [19], while independently preparations for such an experiment, 'Project Ozma', were already under way [20]. This marked the birth of a scientific venture known as the 'Search for Extra-Terrestrial Intelligence' or 'SETI' for short (e.g. [21]).

Exploration of the unknown, making use of previously unavailable technology, led to 'ages of wonder' [22], where prevailing concepts have been challenged and new ideas and insight emerged. The study of the origins, evolution, distribution and future of life in the Universe, for which the term 'astrobiology' has been coined (following up on the earlier used 'exobiology'), plays a critical role in a continuing era of enlightenment.

2. Universality or uniqueness?

We readily accept that the concepts of physics and chemistry apply throughout the cosmos and are valid for all time, but should this not make us wonder whether biology is universal as well [22], and not just a special feature that only applies to planet Earth?

There is actually no lack of the building blocks of life; the number of molecules fundamental to Earth's biochemistry that have already been found in the interstellar medium, planetary atmospheres and on the surfaces of comets, asteroids, meteorites and interplanetary dust particles is surprisingly rather large. Giant 'factories', where complex molecules are being synthesized, appear to make carbonaceous compounds ubiquitous in the Universe (cf. [23]).

We are however left with a fundamental gap in understanding just at the point where molecules become 'alive'. Nevertheless, it has been conjectured that life resembling that on Earth in its biochemistry is a cosmic imperative [24,25], following from the deterministic and reproducible nature of chemistry under given environment conditions, and the reproducibility of optimization by selection [26] from a large number of variants. The latter is strongly supported by the observed evolutionary convergence in the biological history on Earth, but it cannot be ruled out with certainty that our existence is a fluke arising from a highly improbable chance event (cf. [27]).

A strong case for the genesis of life being a 'cosmic imperative' would arise from the detection of a 'shadow biosphere' on Earth with a distinct 'tree of life' [28–30].

So if there are alien civilizations at a comparable stage of evolution, one might expect that they do not differ that much from our own (cf. [27]). However, with the Sun just about half-way through its lifetime as a main-sequence star, with about 4.5 billion years remaining, that 'comparable stage' might constitute a rather short transient episode, and advanced extra-terrestrial life might be inconceivable to us in its complexity, just as human life is to amoebae.

3. Our lack of knowledge and the arising challenges

The current state of the study of life in the Universe sees us being confronted with many questions cutting across various traditional fields of science, while leaving us with almost no answers. The inherent interdisciplinarity does not come as a surprise when realizing that we are investigating ourselves,[2] our origins and future, and our role in the cosmos.

Our ignorance is most famously quantified by the Drake equation [30–32]

$$N = R_\star f_\mathrm{p} n_\mathrm{e} f_\mathrm{l} f_\mathrm{i} f_\mathrm{c} L, \tag{3.1}$$

which describes the number of civilizations N that are detectable by means of electromagnetic emissions (more particularly, radio signals) as a product of various factors, namely the rate $R_\star$ of formation of suitable stars, the fraction f_p of those with planetary systems, the number n_e of planets per such system with conditions suitable for life, the fraction f_l of such planets on which life actually develops, the fraction f_i of life-bearing planets on which intelligent life emerges, the fraction f_c of emerged civilizations that develop technologies for propagating detectable signals and finally the time span L over which these civilizations disseminate such signals. Rather than as a product of numbers, the Drake equation should more appropriately be seen as a product of random variables with their respective distribution functions [33–35]. Interestingly, the uncertainty among the different factors in the Drake equation increases from left to right. The 'astronomical factors' $R_\star$, f_p and n_e are rather well determined as compared with the 'biological factors' f_l and f_i, while the 'technological factor' f_c and even more the 'societal factor' L are the great unknowns. Despite the fact that the Drake equation has been devised for SETI, only the last three factors are specific to intelligent life or its detection by means of electromagnetic signals, whereas the others are relevant to any astrobiological context.

[2]As Frank Drake likes to point out.

Let us suppose that life beyond Earth does exist. In order to detect it, we encounter substantial difficulties when aiming to define its characteristics, and in selecting signatures that are certainly incompatible with an abiogenic origin. Organic molecules with a carbon skeleton that are stable on geological time-scales form 'chemical fossils' that constitute an early record of life on Earth. Moreover, measured carbon isotope ratios in sedimentary rocks suggest the presence of microbial life already 3.8 billion years ago ([36]; cf. [17]). It, however, requires biological material to determine whether life is truly 'alien', i.e. belonging to a 'tree of life' distinct from that of life on Earth. Evolutionary selection is likely to result in the use of a set of basic organic molecules, but it is a subject of debate whether there is a strong evolutionary convergence either to the one and only optimum or in such a way that the process of natural selection always leads to the same global optimum for all environments under which life can evolve, or whether a weak evolutionary convergence accounts for the possibility of ending up with different optima for the realization of life or its features. Strikingly, a system of life based on molecules just of opposite chirality but otherwise identical to those that form the building blocks for life known on Earth appears to be a viable distinctive alternative (cf. [16,17,27]).

Out of the vast number of places in the Universe to look for life, what should guide our search? With no other account for life other than that on Earth and a lack of understanding of the properties and preferred environments of life as we do not know it, one readily tends to accept the null hypothesis that an efficient search should be oriented towards the set of conditions that is defined by the variety of terrestrial life forms. Therefore, a widely adopted strategy is to search for liquid-water habitats, given that terrestrial biochemistry relies on liquid water as solvent (cf. [16,27]). Moreover, given the requirements of metabolism, energy is a more universal imperative for life, providing a further criterion to narrow down searches, and opening an opportunity to go far beyond characteristics that might be specific to life as we know it [37]. While it was the porphyrin nucleus, central to the structure of chlorophyll, that paved the way for using chemical fossils as biomarkers ([38]; cf. [17]), even before the age of photosynthesis life may have been living on energy sources bound within rocks, such as iron. Rather than just the presence of water or energy, it is the kinetics of water flows that constitute the crucial criterion for such processes to succeed (cf. [39]).

Not only has Earth initially provided an environment for life to develop, but also the resulting living organisms have subsequently shaped the planet. In particular, the large abundance of oxygen in the Earth's atmosphere is the result of biogenic photosynthesis. Such feedback mechanisms gave rise to the idea of describing the Earth's biosphere, atmosphere, oceans and soil as a complex entity in what is referred to as the 'Gaia theory' [40,41]. In fact, it emerged from thoughts about simple signatures of life on another planet [42], and given that planets outside the Solar System cannot be explored by spacecraft, measurements of the abundance of molecules in the planetary atmosphere from related spectral features in order to construct a biosignature are the very limited 'bits and pieces' of information upon which we can draw conclusions about life. Such efforts mark one of the greatest challenges ever undertaken in observational astronomy (cf. [15]).

4. Societal relevance and political action

The detection and further study of extra-terrestrial life will fundamentally challenge our view of nature, including ourselves, and therefore the field of astrobiology can hardly be isolated from its societal context, including philosophical, ethical and theological perspectives (cf. [43]).

With the detection of extra-terrestrial life being technically feasible, one needs to address whether perceived societal benefits command us to search for it, or whether such an endeavour may rather turn out to be a threat to our own existence (cf. [44]). Modelled after the Torino Scale for asteroid/comet impact predictions [45] and the Rio Scale for a putative discovery of extra-terrestrial intelligence [46], the London Scale index (LSI) with values ranging from 0 to 10 together with an independently evaluated level of risk or biohazard [47] provides an assessment of the scientific importance, validity and potential risks associated with putative evidence of extra-terrestrial life discovered on Earth, on nearby bodies in the Solar System, or in our Galaxy.

Various scenarios of encounters with extra-terrestrial life have already been portrayed in the science-fiction literature and films, some of these being more scientific, others more fictional (cf. [48]). Imagination, however, must not be underestimated as a valuable means to advance knowledge towards new frontiers, and is not at all an unscientific concept. It is also valuable that a broad public has been given the opportunity to reflect on this topic. Similarly, scientists involved in relevant research themselves should engage with journalists and the public (cf. [49]). Media reports and weblogs debating extra-terrestrial life, including those that relate to this very Royal Society Discussion Meeting, also provide some evidence on public opinion and reactions that can be expected.

If data are absent or ambiguous, we tend to argue by retreating to analogies or theories about universalities. Historical examples, however, need to be well understood before these can serve as a guide, which is demonstrated by the fact that history is full of misinterpretations and misconceptions of itself (cf. [48,49]). Rather than aliens invading Earth, most likely detection scenarios will involve microbial organisms and/or extra-terrestrial life at a safe distance that prevents physical contact. As far as exploring other life forms is concerned, any strategy applied must exclude biological contamination—not only to protect ourselves, but also to preserve any alien life discovered as part of an overall commitment to enhancing the richness and the diversity of life in the Universe [16]. For such scenarios with well-contained risks, the dominant human response is unlikely to be one of fear and pandemonium [48]. Human perceptions and representations of alien life will not only derive from science, but, given that humanity is more than just a collection of logic and facts, they will be highly influenced by cultural and psychological factors. Therefore, reactions will not necessarily be homogeneous, and reality may defy common myths [49]. It is believed by some that establishing the presence of extra-terrestrial life as a fact will cause a crisis for certain religious faiths. A survey, however, shows that followers of all the main religious denominations as well as atheists declare that it will not be a problem for their own beliefs [50].

While scientists are obliged to assess benefits and risks that relate to their research, the political responsibility for decisions arising following the detection of extra-terrestrial life cannot and should not rest with them. Any such decision will require a broad societal dialogue and a proper political mandate. If extra-terrestrial life happens to be detected, a coordinated response that takes into account all the related sensitivities should already be in place. In 1989, the International Academy of Astronautics (IAA) approved a SETI post-detection protocol [51], which was developed by one of its committees. Despite the fact that it has subsequently been endorsed by the International Institute of Space Law (IISL), the Committee on Space Research (COSPAR) of the International Council for Science (ICSU), the International Astronomical Union (IAU) and the International Union of Radio Science (URSI), the procedures laid out in that document are not legally enforcible. If it remains a voluntary code of practice, it will probably be ignored in the event to which it should apply. Will a suitable process based on expert advice from proper and responsible scientists arise at all, or will interests of power and opportunism more probably set the scene (cf. [52])? A lack of coordination can be avoided by creating an overarching framework in a truly global effort governed by an international politically legitimated body. The United Nations fora constitute a ready-made mechanism for coordination. Member States of the Committee on the Peaceful Uses of Outer Space (COPUOS) will need to place 'supra-Earth affairs' on the agenda in order to take it further to the General Assembly, with the goal of establishing structures similar to those created for dealing with threats arising from potentially impacting near-Earth objects [53].

5. Outlook

So far, there is no scientific evidence for or against the existence of life beyond Earth. All arguments about whether life is common and universal or whether we live in a unique place in the cosmos are rather based on philosophical beliefs and assumptions. Consequently, there is no way of predicting the outcomes of searches for extra-terrestrial life. This, however, surely drives the scientific imperative to test the hypothesis.

The year 2010 marks the 50th anniversary of the first search for radio signals originating from other civilizations, a remarkably optimistic endeavour in 1960, particularly bearing in mind that up to now all SETI experiments have provided a negative result. One, however, has to realize that these have probed only our neighbourhood, up to about 200 light-years distant, whereas the centre of the Milky Way is 25 000 light-years away from us. And even if there is no other intelligent life in the Milky Way, it could still be hosted in another of the remaining hundreds of billions of other galaxies.

Advanced efforts are now on the drawing board or already under way for the further exploration of the Solar System and the search for biomarkers in the atmospheres of extra-solar planets, while searches for signals of extra-terrestrial intelligence are entering a new era with the deployment of the next generation of radio telescopes.

The study and understanding of life in the Universe encompasses many, if not all, of the fundamental questions in biology, physics and chemistry, but also in philosophy, psychology, religion and the way in which humans interact with their environment and each other. While we cannot be prepared for the unpredictable, the careful development of a societal agenda alongside a scientific agenda for the search for life elsewhere becomes mandatory.

Frequently, things are only seen in the proper context if observed from a far enough distance. The image of Earth taken by Voyager 1 from as near as about 40 AU, i.e. still within the outer regions of the Solar System, which depicts just a 'pale blue dot', proves insightful. As Carl Sagan [54] (p. 9) worded it: 'Our posturings, our imagined self-importance, the delusion that we have some privileged position in the Universe, are challenged by this point of pale light.'

For the first time in human history, living generations are now given a realistic chance to find out whether we are alone in the Universe. Should an answer be found one day, we will still be left with deeper questions to be answered: where do we come from, why are we here and where will we be going?

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