Scanning the Cosmos: The Search for Life in the Universe

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ABSTRACT

The utter vastness of the universe makes it seem possible, perhaps even very probable, that there is life thriving on other planets. The cosmos, governed everywhere by the same laws of nature, are teeming with the very material that composes the Sun, the Earth and human beings. Could there be other worlds like our own? Might life exist beyond this planet? To answer these questions, we must consider the specific environments and distinctive circumstances necessary for life to arise. With this information, the detection methods and tools able to scour the great expanse for signatures of life can be determined. They, in turn, can be utilized to gather further data, potentially leading to the discovery of new worlds and new beings.

KEYWORDS

Exoplanets, detection methods, extraterrestrial life

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SCANNING THE COSMOS

THE SEARCH FOR LIFE IN THE UNIVERSE

What is life? A seemingly simple question—yet a universally accepted, all-encompassing definition remains elusive. We must consider this fundamental question if we are to take on the challenge of searching for extraterrestrial life. Part of the challenge is that we have, for now, only on reference: Earth. Though terrestrial life seems impossibly diverse (consider the four biological families: archaea, bacteria, eukaryotes, viruses and all that they encompass), who is to say that life beyond our biosphere is not equally so, if not more? *(1)*

LIFE AS WE KNOW IT

Life on Earth has been shown to be the result of matter organizing itself on various scales and under specific circumstances *(2)* over an extended period of time. Though the specific mechanisms from which life sprung remains a bone of contention, it is known that for life to develop, certain elements are needed: carbon, hydrogen, nitrogen, oxygen, phosphorus, and sulfur *(3)*. These elements, created through the Big Bang and stellar evolution, form the backbone of life, and exist far and wide in our universe.

For life to prosper on a planet, a long-lasting energy source such as a star is required. Even if this requirement is met, life can only flourish in what is called the circumstellar habitable zone:

a range of distances within which the radiative output of the parent star allows for liquid water *(4)*. The habitable zone of a star changes gradually with time—a consequence of stellar evolution. As the nuclear fusion processes that sustain stars begin to produce heavier elements, the central gas pressure changes. The star's output increases, which causes the star to become more luminous over time. This change in luminosity affects the habitable zone. The range of radial distances within which liquid water could be found throughout the entire lifetime of a star is called the continuously habitable zone *(5)*. Life on Earth exists in the Sun's continuously habitable zone. Life on another planet would likely be found in a similar environment.

Additionally, the size of the star must be taken into consideration. More than ninety percent of stars are smaller than our Sun., These smaller stars are less luminous and thus the habitable zone lies closer to the star. Any planets orbiting within this region would become tidally locked to the star, plunging one half of the planet in perpetual frozen darkness and the other in constant scorching light. It is difficult to imagine life in what we would consider such an inhospitable setting. Yet let us not forget the extremophiles of our own planet, found in what are traditionally considered severely hostile environments to living beings. In the case of stars larger than our own, the problem that arises relates to time. The average lifetime of more massive stars is relatively short. Consequently, there may not be sufficient time for matter to organize and evolve into life. Overall, fewer than ten percent of stars in the universe are of a suitable mass to sustain life: between 0.7 and 1.7 solar masses *(6)*.

SHELTER FROM THE COSMOS

What of the planets themselves? Not all planets are created equal. Ergo not all planets provide safe havens for life. A typical star system contains rocky inner planets and gaseous outer planets. Rocky planets tend to be more favourable environments for life, as there exists the possibility of water on their surfaces *(7)*. Many adhere to the theory that the first forms of life on Earth emerged from the primeval oceans. Therefore, importance has been placed upon finding water elsewhere in our solar system, our galaxy and the universe. Water, though necessary for life to arise, is not sufficient for life to thrive. A geologically active planet generates plate tectonics, which hold a crucial role in the carbon cycle. Moreover, geologic activity can provide protection for emerging life. The convective movement present within the molten outer core of such a planet produces a magnetic field that shields the planet and any emerging life forms from incoming solar and cosmic radiation *(8)*.

Other factors important to the habitability of a planet are its orbit's eccentricity and obliquity *(9)*. The amount of thermal energy a planet receives from a star on an annual basis is greatly influenced by the eccentricity of its orbit (a measure of the perihelion and aphelion distances). The more eccentric an orbit, the less hospitable the planet, and vice-versa. Obliquity, the angle between a planet's spin axes and its orbit, influences planetary climate. Depending on the degree of the angle, a planet could experience a multitude of different temperature conditions, some tailor- made to harbour life and others thoroughly unsuitable. An ideal obliquity is one that guarantees a climate befitting the survival of living organisms: not too hot, nor too cold. The obliquity of Earth is 23.5 degrees. Such an incline gives rise to the seasons, ensuring the habitability of all regions year-round. Hypothetically, if Earth's obliquity was more extreme, say near 90 degrees, a large area would become a barren wasteland. Still yet, there is the added influence of the obliquity's stability. Earth's obliquity has remained constant due to its steady relationship with the Moon, allowing life to flourish. Alternatively, the teetering obliquity of Mars (fluctuating between 0 and 60 degrees, currently 25 degrees) has produced a barren landscape, seemingly devoid of life.

Though life might seem to prefer rocky planets (like ours), do not discount the gas giants, for they have their use. In a planetary system, the gravitational influence of larger gaseous planets can reduce the incidence of comet and asteroid impacts *(10)* on the smaller inner planets. This is of significance, considering the frequency of such impacts in space (as evidenced by the multitude of craters on the surface of the moon) and the devastating destruction they can cause.

The development of life boils down to three key points: a stable source of energy such as stars, an Earth-like planet within the habitable zone and the presence of the elemental building blocks of life (C,H,N,O,P,S). One could consider these the framework of the practical search for life in the universe.

LOOKING AND LISTENING

Despite our best efforts (direct imaging, rovers, in situ experiments of the Viking Mars Landers, etc.) even the most promising candidates for life in our solar system have yet to provide proof. Luckily, beyond our own planetary system lies a great deal more to be discovered. According to the online Interactive Extra-solar Planet Catalogue, as of January 2012, a little over 700 extra-solar planets have been detected. This is no easy feat considering planets are much smaller and dimmer than stars, and therefore practically impossible to detect directly. Ingeniously, astronomers have devised a series of indirect approaches by utilizing the effects that planetary bodies exert on the stars they orbit.

The most effective methods are radial velocity and transit photometry. Radial velocity exploits the concept of the Doppler effect. A star orbited by a body experiences a gravitational tug that causes the star to wobble in a small circle or ellipse. Using very sensitive spectrographs, a periodic shift in the star's spectrum can be observed: a blue-shift as the star wobbles toward the observer and a red-shift as it wobbles away. If these shifts are observed regularly, then this is evidence of an orbiting body, perhaps even a planet. This method provides an estimate of an orbiting body's minimum mass, which can determine the nature of the body, planet or otherwise. Unfortunately, this method tends to detect types of planets least likely to have conditions suitable for life since small earth-like planets cause a relatively smaller and less easily detected wobble than their giant gaseous counterparts *(11)*.

Transit photometry measures the tiny dip in brightness of a star as a body passes in front of it. This body is most likely a planet if the diminished brightness moment occurs at regular intervals. The magnitude of the dip is proportional to the size of the transiting body. Combining mass and size data from both the radial velocity and transit methods provides information on the planet's density, which thus sheds light on its composition. Furthermore, the observed absorption spectrum of a transit infers the planet's atmospheric makeup *(12)*. All this information provides key insights into the habitability of a planet.

A third method, microlensing, can be used at much greater distances than radial velocity and transit photometry – thousands of light years away. The immense range of this technique becomes apparent when you consider that Pluto is mere light *hours* from us, whereas the diameter of the Milky Way galaxy is *hundreds* of thousands of light years across. Microlensing is the practical application of Einstein's General Theory of Relativity, which predicts the distortion of light waves due to gravity. When a star passes in front of a more distant star, it will act as a lens, distorting the light waves and amplifying the brightness of the distant star *(13)*. This amplification can last up to about a month, sometimes giving an orbiting planet enough time to reveal itself. In such cases, the telltale result is a momentary spike in brightness.

Astrometry is yet another indirect detection method. Similar to radial velocity, it infers the existence of an orbiting planet through the detection of a wobble. The distinction between the two techniques is that astrometry uses a star's wobble relative to its surrounding stars in the sky instead of to its orbiting bodies.

The detection methods described above demonstrate the creativity and enterprise present within the field of astronomy. However, they do not take into account the possibility of extraterrestrial intelligence equally imaginative and resourceful. We can painstakingly search the skies for planets like ours to get a better understanding of how hospitable our universe is, however, there may be a shortcut: If indeed there exist such beings elsewhere in the universe with similar cosmic agendas, then surely they would have, like us, harnessed the power of science and technology. Radio astronomy, the study of radio waves emitted by distant objects *(14)*, is an exciting tool in the search for extraterrestrial civilizations. Radio waves are not absorbed or scattered by interstellar gas, and thus can travel very large distances unimpeded *(15)*. Listening for radio signals from space garners a significant amount of noise from all regions of the electromagnetic spectrum. Fortunately, within this spectrum lies a comparatively quiet zone: the 21 cm line. Hypothetical advanced civilizations could most certainly use this range for communication. Radiotelescopes calibrated to the 21 cm line and pointed toward extrasolar planets would certainly pick up any extraterrestrial chatter, though this has yet to prove fruitful. Radio astronomy is one of our greatest resources in the search for intelligent life forms in the universe.

The beauty of the pursuit for life in the cosmos lies within the process. The scanning of the skies breeds a plethora of new discoveries and achievements. These in turn give rise to further innovation. Though we may never discover extraterrestrial life forms or achieve contact with intelligent alien civilizations, the knowledge amassed on this cosmic journey is never squandered. We must persevere. Carl Sagan said it best: "Imagination will often carry us to worlds that never were. But without it we go nowhere."

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Science, silly science, and SETI

How realistic is the search for extra-terrestrial intelligence and is it a sensible use of scarce funds? It fails on both counts, in the view of Clive Trotman.

Millions of dollars are being spent on a supreme exercise in futility, the Search for Extra-Terrestrial Intelligence (SETI), to say nothing of the waste of effort, brainpower, resources and electricity by the thousands of distributed enthusiasts with their perversely-called screensavers. What do the operators and funders expect to achieve?

Interstellar communication is hopelessly implausible technically. The inverse square law governing the dissipation of a radio signal makes vast-distance communication impossible unless the beam is virtually parallel and both receiver and sender look directly at where each other was and will be. Domestic omni-directional broadcasts have not the slightest chance of being intercepted. Communication with spacecraft around Saturn requires state of the art antennas pointed at each other. But Saturn is no distance at all at the speed of light; there and back in an afternoon.

All prospective star systems within 100 light years have been dismissed so how are we to pick up signals from thousands, millions, billions of light years away? ET would need to have transmitted a powerful pencil beam, say a millionth of a degree wide, which could be sent in any of about 10^{17} different directions. But sent blindly; because the transmission time completely eliminates any prospect of aiming at a star that has already shifted (and a civilisation yet to exist). To receive the message we need to be positioned in the exact spot in the universe at the exact time when that signal whistles past, millions of years later, never to return.

The best reasons for forgetting SETI are biological. What little we know about life has been learned on planet Earth. Life with the wherewithal to communicate by means of electromagnetic radiation has existed for a century out of four billion years, a microscopic 2.5×10^{-8} of our planet's existence. Evolution is exceedingly slow. The human's genes and hard-wired responses to threat are likely to have changed little in 5000 generations since the Stone Age. It is the repository of knowledge that has grown, not intelligence, with a heavy emphasis on destruction of the environment. This portends a transient existence for any form of life having our definition of intelligence, and if it were completely different, we would not begin to understand each other.

The notion of two civilisations accidentally pointing their antennas towards each other with 10^{17} directions to choose from, coupled with each having its moment of misguided enthusiasm separated by millions of years but miraculously brought into synchronisation by the exact transmission time between two random coordinates somewhere in the universe is, to quote Wolfgang Pauli in a different context, 'not even wrong!' Just silly.

A consensus intergalactic calling frequency is equally imponderable. Why do SETI enthusiasts favour the hydrogen line (1420.40575 MHz), where the only certainty is natural interference from hydrogen? But let such technicalities pass and suppose that we - or they - did receive the other's deranged ramblings. Is there the slightest possibility they could mean anything? What we send, or would seek, in order to unscramble something received, depends totally on human values. What would our DNA mean to a race that does not have any? Or even one that does?

The famous hieroglyphs on Pioneer spacecraft in the 1970s, intended to depict a man, a woman, and 'data' about Earth, are capable of any interpretation you like. The accompanying scribbles of supposed atoms in two spin states are hopelessly unrepresentative. A race disinterested in atoms would be baffled, a race that properly understood atoms would never guess. They might deduce we live near a binary star, but question time is over.

Nothing is impossible, but the prospect of detecting an alien signal ranks alongside swimming the Atlantic underwater, holding your breath. I desperately hope I am wrong.

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Desperately seeking aliens

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Belief that intelligent life is commonplace in the Universe was taken for granted by scholars and scientists until well into the nineteenth century. Space travel since the late 1950s reignited the debate, which even now attracts discussion by serious, professional scientists. And although statisticians might lobby that life must surely exist somewhere in the Universe, the evolution of what we perceive as 'intelligent life' seems utterly improbable — elsewhere as well as on Earth. Can we free ourselves of our animist fantasies and accept that all alien forms of intelligent life are, and always have been, imaginary?

It is easy to imagine the existence of life elsewhere in the Universe. The key word here is 'imagine' — the human mind has been populated with gods and demons since time immemorial, products of an apparently insatiable craving for the exotic. And still we yearn, our dreams turning from the supernatural and animist to the popular culture of such inventions as Mickey Mouse and Bugs Bunny, Klingons and Vulcans, and, of course, the *Alien*. The fruitfulness of our imagination is surprising in view of the fact that the Universe itself has offered no help: so far, our search for signs of alien life has drawn a blank. As far as we know, consciousness has dawned nowhere but on our home planet, Earth. I shall argue the case that — for the moment, at least — all other forms of intelligent life are imaginary, as they always have been.

The case that intelligent life is rare in the Universe is logical, yet it is hardly more than a century old, and showing signs of waning in the face of scientific initiatives such as the founding of the NASA Astrobiology Institute, whose aim is to explore the conditions for life on Earth and elsewhere, and even in the commission of this article for a *Nature* Insight entitled 'Astrobiology — Life in the Universe', in which the possibilities of life elsewhere in the Universe are discussed by serious, professional scientists. In the face of millennia of desperation to find aliens, recent scepticism, such as Brownlee and Ward's book *Rare Earth*[1], might be taken for a *fin-de-siècle* aberration.

A history of belief

Serious speculation about life elsewhere was once commonplace. A few centuries ago, many scholars believed that intelligent life existed everywhere, and that an all-powerful God in his generosity had bestowed life on all the planets of the Solar System. This belief had firmest tenure on our neighbouring heavenly body, the Moon[2]. We cannot tell how ancient this erroneous belief may be, but the first story to be set on the Moon is generally agreed to have been written in the second century AD by Lucian of Samosata, whose *True History* is a satire on travel writing.

Lucian's travellers are carried by a waterspout in a Greek ship to the Moon. There they discover that the King of the Moon and the King of the Sun are at war over the issue of the colonization of Jupiter. Fantastic monsters are employed in battles on both sides. Such adventures have always been popular, at least from recent centuries onwards. One authority, Philip B. Gove, lists 215 books describing voyages to the Moon published in the eighteenth century alone[3]. Modes of transport have varied, from angels to migratory geese.

Science has always provided the most potent fuel for the imagination. Space fiction took off after Galileo published *The Starry Messenger* in 1610, conveying vividly the excitement of the moment when a man first looked through a telescope into space. Not only was the Moon no perfect sphere, as had been always thought, but was "just like the surface of the Earth itself, varied everywhere by mountains and valleys". Following his description of the Moon, Galileo went on to reveal his discovery that "there are not only three, but four, erratic sidereal bodies performing their revolutions round Jupiter". This observation of the four main jovian satellites overturned the old Aristotelian thinking, which had set the Earth at the centre of the Universe. Galileo's name became celebrated beyond his native Italy. No longer was it possible for informed people to believe that the Sun went round the Earth. Henceforth, the heliocentric version of our Solar System would prevail, and bring forth many celestial tales — generally satires or utopias. The telescope fathered both astronomy and fantasy. Just one example was *Man in the Moone* (1638) by the learned Bishop Francis Godwin of Hereford, which remained in print for more than two centuries and was much translated. Possibly because the bishop considered his book went against the teachings of the Church, it had to await publication until after his death.

That life in the Universe was, well, universal was taken for granted in the scientific sphere until well into the nineteenth century. William Whewell, the scientist who famously coined the word 'scientist', found it necessary to dispute the belief in universal life. His book *Of the Plurality of Worlds* was published anonymously in 1855. Not that Whewell's views did anything to stem the tide of aliens in fiction. Since the days of H. G. Wells, when cars replaced horses, writers have propagated aliens with increasing assurance. If aliens do not exist, it seems necessary to invent them. It is a nice irony of modern life that the prospects of finding real-life aliens have dimmed just as the 'realism' of fictional aliens has waxed. Perhaps the two are connected — and yet the pendulum could be swinging back sharply.

By the late 1950s, the idea of intelligent life on Mars or any other planet was unfashionable enough to be the subject of derision. The tide turned just two weeks after the Astronomer Royal, Sir Harold Spencer Jones, announced in 1957 that space travel was bunk — when the Soviet Union sent up the first Sputnik. (Jones later compounded his error by saying that he was talking about science fiction.) Once it was generally realized that large objects could travel through space, propelled by rocket motors, the gates were open for speculation about visits and visitations to and from Earth. It was a technological dream. From then

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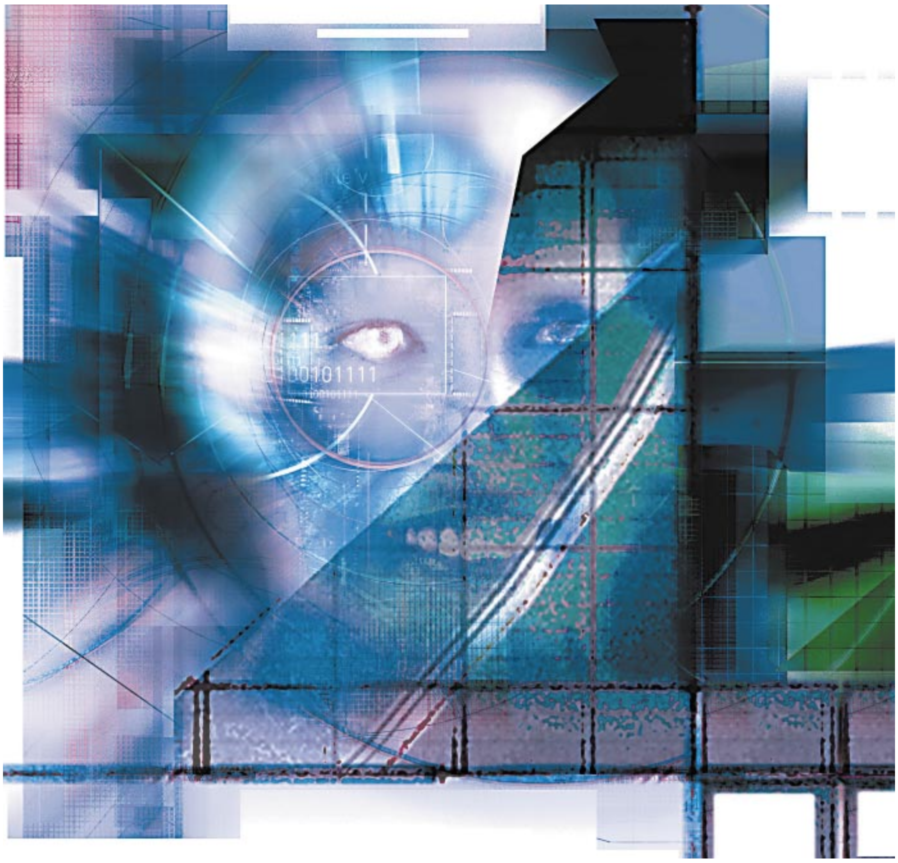

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onwards, it seemed that most people in the West believed — as had the ancients — that all about us were unseen planets of stars abounding with life. For all Whewell's work, the notion of plurality of interplanetary life had returned. By the early 1960s, unthinking scepticism had turned to unthinking belief.

Earth's neighbours and beyond

Nothing except statistics supports the idea that life (or at least intelligent life) exists anywhere else but the Earth. The evidence in our own Solar System is decisively negative. The Moon as an abode of life was ruled out when it was discovered that it had no atmosphere. Elimination next for our shrouded neighbour Venus, of which the Swedish astronomer, Svante Arrhenius, deduced in 1917 that "everything on Venus is dripping wet"[4]. The surface, according to Arrhenius, was covered by swamps, in which low forms of life existed: "the organisms are nearly of the same kind all over the planet". (In a forgotten novel of 1956, *Escape to Venus*, S. Makepeace Lott is nearer the mark, speaking of "the battering of the gas storms which flung the suspended dust particles across the face of the planet at several hundred kilometres an hour".) With a mean surface temperature of 740 K, Venus is an unlikely abode of life.

So to Mars, the planet on which most expectations of finding life were pinned. In 1909, astronomer Percival Lowell — self-delusive finder of martian canals — published the well-reasoned *Mars as the Abode of Life*. It must have seemed reasonable at that period to believe in life on our dry neighbouring planet, when the previous century had uncovered evidence of a staggering abundance of life, never previously dreamed of and flourishing over millions of years, in the strata of terrestrial rock. If a monstrous fossil reptile in the ancient sandstone, why not a little green man on Mars?

But no. Since Lowell's day, Mariners and Vikings have called on Mars. Dust and rocks are all they have found. Mars is a bleak, stony place: dry, with only the thinnest of atmospheres. Viking revealed the martian surface as a highly inhospitable environment for life. The finding of microscopic impressions in a meteorite, believed to be of martian origin, and which might, in some circumstances, have been fossils, has been controversial.

Venus, Earth and Mars lie in the Sun's 'comfort zone'. Beyond Mars stretches a gulf of space, with the gas giants beyond it — surely, there can be no hope for life out there? But the Galileo spacecraft has produced strong evidence that beneath the icy and broken surface of Europa, one of the four galilean Moons of Jupiter, lies an ocean[5], warmed by the gravitational pull of Jupiter. What might we anticipate there? Intelligent shrimps? Intellectual fish? We can but hope — but there is still a line to be drawn between hope and conviction.

And beyond the Solar System? Our Galaxy contains approximately 200 billion stars. Surely some of them must have planets that sustain life? It is not an unreasonable conjecture, given the numbers. Although we have no evidence that any of the now several dozen known extrasolar planetary systems[6] have suitable conditions for life of the kind we might recognize as such, the numbers could give us hope.

Improbable evolution of intelligence

But statistical casuistry works both ways, as is shown by the improbability of intelligent life appearing on the only planet we know well — the Earth. Although life appeared on Earth at least 3.8 billion years ago, not long after the planet itself formed (see the review in this issue by Nisbet and Sleep, pages 1083–1091), it took another 3.2 billion years before the appearance of complex, multicellular life forms large enough to be viewed without a microscope. Intelligence (as we perhaps mistakenly understand it) has developed only in the past few tens of thousands of years. According to Ward and Brownlee[1], microbial life in our Galaxy might be common, but complex, multicellular life will be extremely rare.

Each of the steps — between the appearance of life and the evolution of intelligence — reveals its complexity, helped on or deterred by coincidences and catastrophes. Moreover, there might have been only one time propitious for creating the rudiments of life: later might have been too late. Given its evolution through a number of precarious episodes, we perceive that 'intelligent life' is an uncharacteristic effect, not merely in our own Solar System but more universally. In fact, it seems utterly improbable — elsewhere as well as here.

This knowledge has not deterred serious-minded people from attempting to make contact with intelligences elsewhere in the Galaxy[7]. The Search for Extraterrestrial Intelligence (SETI) programme was set up in the 1960s, although so far no one or nothing has answered its signals (see the review in this issue by Wilson, pages 1110–1114). Nor have we heard any signals from elsewhere.

A challenge to the consensus of universal biological ubiquity was presented in 1986 by John D. Barrow and Frank J. Tipler in *The Anthropic Cosmological Principle*[8], a powerful sequel to Whewell's argument. Using many disciplines, the authors argue that, by an element of design, ours is the only planet that houses cognate beings. Their argument is complex, encompassing the stability of stars and the eccentricities of water, on which life and its origins depend heavily. In sum, it leaves human cognition with a large responsibility for acting as the consciousness of the Universe.

C. O. Lovejoy is quoted as saying: "Man is not only a unique animal, but the end product of a completely unique evolutionary pathway, the elements of which are

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traceable at least to the beginnings of the Cenozoic."[9] This pathway is defined by the evolutionary biologist Ernst Mayr. Speaking of the principal divisions (or phyla) in the animal kingdom, he says that the kingdom "consists of about 25 major branches... Only one of them developed real intelligence, the chordates. There are numerous classes in the chordates, I would guess more than 50 of them, but only one of them (the mammals) developed real intelligence, as in Man. The mammals consist of 20-odd orders. Only one of them, the primates, acquiring intelligence, and among the well over 100 species of primates only one, Man, has the kind of intelligence that would permit the development of advanced technology... An evolution of intelligence is not probable."[10]

The blessing of science

We understand that optimism and imagination help to propel science. Nevertheless, we are entitled to ask whether assumptions about alien life are unscientific. Aliens are the staple diet of modern entertainment, but these are, in the main, contemporary fairy stories, and none the worse for that. However, their relationship with real science is ambiguous. Imaginary aliens are many and diverse, but provide little help in any current comprehension of understanding the Universe: rather than assisting us, aliens impede understanding. Their air of seeming rationality, of being the product of scientific thinking, is spurious. Where, then, do aliens originate, and how has our desperate search for aliens come to find itself on any serious scientific agenda?

An intimacy with the non-human is a fundamental human trait. A vast population of ghosts, ghouls and other mythical creatures has accompanied humankind through the ages, haunting its woods, houses and graveyards. Among their attractions is that they are free of the physical laws that govern humans. In particular, they are at least partly immune to gravity and death (a tradition continued among mythical cartoon creatures such as Tom and Jerry).

Above these minions, as religion outranks superstition, are assembled an even more formidable array of fictitious beings, the gods and goddesses of our inner world. What a collection they are! Belief in them beggers belief: adorned with snakes and skulls, they arrive to impose restrictive laws for human conduct, laws that frequently include whom we should or should not sleep with, and the preservation of life and the sacrifice of it. Coming from a generation which listened to damnation preached every Sunday, brought up to believe in a cloudy Heaven and the fiery torment of Hell (ruled over by a horned and unpleasant Satan), I now recoil from the cruelty of the pulpit, and can but marvel at the entire range of weird deities.

We do not believe in fairies any more, nor do we find it necessary to blaspheme against Baal. But it seems that we are born animists. Parents heap a variety of totemistic animals on their children: *Tyrannosaurus rex* is to be found sharing the cot with Winnie the Pooh. As children talk to their stuffed toys, so adults talk to their pets and pray to one or more members of an invented pantheon.

The latest manifestation of this creaking floorboard in the brain, the alien arriving here from outer space, is the most interesting. Such an event could conceivably happen, and may be regarded indulgently as more supposition than superstition. Much work has been done to render this magical visit plausible. In the 1960s television drama *A for Andromeda*, written by John Elliott and Fred Hoyle, radio signals emanating from the Andromeda Galaxy are picked up by the then new radio telescope at Jodrell Bank, near Manchester, United Kingdom. The signals include directions for the construction of a computer. This computer enables the scientists to build a beautiful alien woman (the first appearance on our screens of Julie Christie). *A for Andromeda*, broadcast hardly an eyeblink beyond the launch of the first Sputnik, marks the emergence of alien life from fantasy into cool scientific reality, given the blessing of a computer. Science fiction infiltrates science itself.

Julie Christie, if memory serves, was gracious and a source of wisdom in her alien avatar. Sometimes, aliens arrive to save us from our own follies. More frequently, they come to invade and destroy us. Such thinking forms a continuity with our ancient dreads of demons, ever hostile to human life.

Let us suppose that aliens are, as I have suggested, merely the latest example of a form of animism at work: or possibly the immature echoes of our own selves, free of time and gravity. So let us suppose further that no one will ever visit or call — because no one is there to call. We, the entire riotous biomass of Earth, are alone on our small planet.

The implications of such a situation are formidable. Scientifically and philosophically, a change of attitude would be demanded. In *A Defence of Poetry* (1821), Shelley states that "man, having enslaved the elements, remains himself a slave". Could we but free ourselves from those atavistic fancies here enumerated, humankind might consider it not impossible that we should go into the Galaxy with the intention of becoming its consciousness. □

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Where are the dolphins?

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Interest in extraterrestrial life has tended to focus on a search for extrasolar planets similar to the Earth. But what of forms of intelligent life that are very different from those found on Earth? Some features of life will not be peculiar to our planet, and alien life will resemble ours in such universals. But if intelligent, non-humanoid aliens exist, where might they be? Would they wish to visit Earth and would we know if they did?

Science currently knows of only one life-bearing world, but our sample is biased, because it is the world we live on. As we learn more about other regions of the cosmos, the prospects for Earth-like aliens seem ever more encouraging: there should be many places in the Universe that are very similar to planet Earth. Current scientific interest in extraterrestrial life is mostly a search for extrasolar planets similar to our own[1]. The main exception is the ocean now thought to exist beneath Europa's icy surface[2–4], but even there the interest lies in the resemblances between this ocean and its terrestrial equivalents.

A more interesting question, however, is the possibility of aliens, especially intelligent ones, that are not like us: which is, after all, what 'alien' means. It is possible to imagine the existence of forms of life very different from those found on Earth, occupying habitats that are unsuitable for our kind of life. Some of those aliens might be intelligent and technological, because technology is an autocatalytic process[5]. It follows that some aliens might possess technology well in advance of our own, including interstellar transportation. So much is clear, but this train of logic begs the obvious question of where these intelligent, non-humanoid aliens might be. Where, then, *are* the dolphins?

Part of the answer is that the question is too parochial in its outlook. Dolphins are the nearest thing to intelligent aliens on this planet, but they are our close evolutionary cousins, and they share many of our own accidental features. There might, perhaps, be dolphin-like aliens, but the dolphin habitat as found in Earth's oceans may not be sufficiently conducive to the development of technology. Nonetheless, we cannot escape the big question[6], raised in 1950 by Enrico Fermi: if intelligent aliens exist, why aren't they here?

Canonical answers[7] to Fermi's question (henceforth 'alien' will imply intelligence unless otherwise stated) include:

- There are no aliens, and there never have been. Humanity is unique in the Universe.
- There have been plenty of aliens, but civilizations only moderately more advanced than ours always blow themselves up in nuclear wars.
- The lifespan of an alien civilization is only a few million years. They visited us ten million years ago, and will turn up again in ten million years' time, but there is nobody around right at the moment.
- Aliens exist, but interstellar travel is impossible because of relativistic limits on the speed of light, or because living creatures cannot survive it.
- Aliens exist, but are not interested in interstellar travel.
- Aliens exist and have interstellar travel, but they are not interested in contacting us[8].
- Aliens exist, but galactic law forbids any contact with us because we are too primitive[9] or violent[10].
- Some aliens see it as their duty to eliminate all other forms of life that come to their attention. Any technological civilization will develop radio and TV, attract their attention, and be eliminated[11]. They are on their way now.
- They are here already (the preferred answer on the Internet's UFO pages).

The evidence for the last assertion, as for the others, is poor. Eyewitness accounts of alien abductions are unconvincing, even when offered in good faith. One of us (J.C.) was on a radio programme with a woman who maintained that aliens had abducted her and stolen her baby. J.C. asked a pertinent question that had eluded everyone else: "Were you pregnant?" Her reply: "no".

Even if we consider, for the sake of argument, that aliens walk among us, we can assume that they are highly intelligent creatures from a technologically advanced civilization and not likely to be swanning around in gigantic machines, kidnapping the natives, or doing weird things to the natives' reproductive organs.

Xeno's paradise

The subject area to which this discussion belongs is often called astrobiology, although in science-fiction circles (where the topic has arguably been thought through more carefully than it has been in academic ones) the term 'xenobiology' is favoured. The difference is significant. Astrobiology is a mixture of astronomy and biology, and the tendency is to assume that it must be assembled from contemporary astronomy and biology. In contrast, xenobiology is the biology of the strange, and the name inevitably involves the idea of extending contemporary biology into new, alien realms.

Upon what science should xenobiology be based? The history of science indicates that any discussion of alien life will be misleading if it is based on the presumption that contemporary science is the ultimate in human understanding. Consider the position of science a century ago. We believed then that we inhabited a newtonian clockwork Universe with absolute space and absolute time; that time was independent of space; that both were of infinite extent; and that the Universe had always existed, always would exist, and was essentially static. We knew about the cell, but we had a strong feeling that life possessed properties that could not be reduced to conventional physics; we had barely begun to appreciate the role of natural selection in evolution; and we had no idea about genetics beyond mendelian numerical patterns. Our technology was equally primitive: cars were inferior to the horse, and there was no radio, television, computers, biotechnology or mobile phones. Space travel was the

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stuff of fantasy. If the past is any guide, then almost everything we now think we know will be substantially qualified or proven wrong within the next 25 years, let alone another century. Biology, in particular, will not persist in its current primitive form. Right now, it is at a stage that is roughly analogous to physics when Newton discovered his law of gravity. There is an awfully long way to go.

Xenobiology seems unusual, because it will require a science of what might happen in addition to the science of what we know. However, many scientific explanations involve contemplating possibilities that do not occur in addition to those that do, so the novelty is less than it seems. (The concept of stability, for example, involves answering a 'what if' question: 'what would the system do if it was perturbed'.) The concept of phase space provides a useful framework for such deliberations[12]. The phase space of a system is the set of all conceivable states of that system, often equipped with a topological structure, in which states that differ only slightly are considered to be neighbours. DNA-space, for example, comprises all conceivable DNA sequences, whereas phenotypic space comprises all conceivable designs for organisms. Xenobiology is an exploration of xenospace, the space of possible aliens, together with alien evolutions, alien cultures, and other associated influences from context or content.

JACEY

Rockets and space elevators

It is important not to let the science of what we do not know be over-constrained by the science of what we do know, or think we know. In particular, life is an emergent phenomenon[5,12] that the Universe 'invented' as it developed. How big is nature's palette? We suspect it is much larger than most people imagine.

Physics is a poor guide here. The spectra of distant stars tell us that physics and chemistry elsewhere in the Universe follow the same principles that they do here. This belief is probably fairly accurate, if only because physics and chemistry are partly invented (human beings choose what contexts to place them in, and those contexts tend to be simple laboratory-based ones, not the 'wild' physics of the real Universe). This leads us to expect biology to be the same everywhere, too. But, even within Earth-like biology, the combinatorial possibilities of carbon compounds compromises this line of argument. Chemists have believed the physicists' claim that chemistry is reducible to physics, but the chemistry in stellar interiors, for example, may not be so reducible in any meaningful way. (We do not dispute that the chemistry in stars is a consequence of physical laws, but it is an emergent consequence, so the laws provide few useful insights.)

Similarly, biology is an emergent consequence of physics and chemistry, making it incomprehensible in terms of the 'tame' physics of the laboratory. This is an appropriate place to introduce two contrasting images: the rocket and the space elevator[13]. Physics places an apparently unbreakable limit on the amount of energy needed to place a human being in orbit: the difference in gravitational potential of an object in orbit compared with that at ground level. The law of conservation of energy implies that it will never be possible to put a human being into orbit cheaply. This argument may seem flawless, but it assumes implicitly a particular context: that the sole traffic is upwards. Instead, consider the space elevator, a cable suspended from a geosynchronous satellite[14–16]. It will be expensive to build, but once it exists one could ride into space very cheaply, powered by minerals from the asteroid belt coming down the elevator for human consumption. The space elevator does not violate the law of conservation of energy, but it demonstrates that in this context that law is irrelevant to cost. Indeed, energy limitations will soon cease to constrain human activities, just as memory limitations constrain our computations less than they once did.

The kind of chemistry understood by contemporary molecular biology is analogous to the rocket; but cells have been using space-elevator chemistry for aeons, which is why life is such an effective trick. Biology results from chemistry that has been corrupted by evolution, and evolution on Earth has been going for at least 3.8 billion years (see review in this issue by Nisbet and Sleep, pages 1083–1091). This is deep time — too deep for scenarios expressed in human terms to make much sense[17]. A hundred years is the blink of an eye compared with the time that humans have existed on Earth. The lifespan of the human race is similarly short when compared with the time that life has existed on Earth. It is ridiculous to imagine that somehow, in a single century of human development, we have suddenly worked out the truth about life. After all, we do not really understand how a light switch works at a fundamental level, let alone a mitochondrion.

For similar reasons, it is probably pointless to search the heavens for radio signals from other worlds, as the Search for Extraterrestrial Intelligence (SETI) project aims to do (see refs 18, 19 and the review in this issue by Wilson, pages 1110–1114). It would be equally sensible to look for smoke signals. Radio did not exist on this planet a hundred years ago, and might become obsolete. If aliens communicate at all, they might use media as yet undiscovered by human technology. Even if radio were their medium of

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choice, they might have encoded their transmissions for optimal efficiency. Moore[20] has shown that an optimally efficient coded message will be indistinguishable from black-body radiation. Imagine a Second World War radio operator picking up one of today's encrypted satellite TV channels: it would sound like static. Is this the true meaning of the cosmic background radiation?

What is life?

An essential component of xenobiology will be a reassessment of the nature of life. The current belief that DNA holds the key to life as a general phenomenon might reflect an unnecessarily narrow perspective. For example, it has been suggested that the concept of the 'gene' might soon be redundant[21]. From a xenobiologist's viewpoint, the problem with life on Earth is that it is a very limited sample, even of DNA-based organisms. DNA space contains about $10^{1,000,000,000}$ different sequences of comparable length to the human genome. Most of those sequences cannot occur in viable organisms, but even if we eliminate an overwhelmingly large fraction we are still left with, say, $10^{1,000,000}$ viable sequences. There are, perhaps, 10^7–10^8 species on the planet today. Although these numbers are the roughest approximations, they are sufficient to make the point — that the phase space of the possible is far greater than is realized by the actual. From this it follows that the detailed genetic constitution of life on Earth is an accidental result of local history, and not the inevitable conclusion of fate.

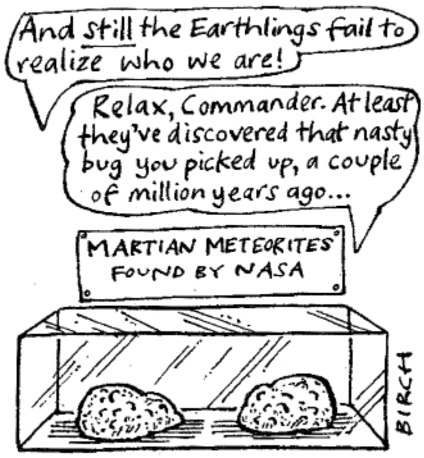
However, despite their seemingly limited diversity, Earth's current life-forms may be more typical in other, more important, ways, such as their relationship with their context. 'Life' is a name we give to certain emergent processes of complex systems[5,22]. Until quite recently we used the word as a catch-all to cover anything on this planet that seemed to have some kind of individual autonomy. It then became evident that everything of that kind was using the same trick — DNA (or RNA) and associated biochemistry. We have therefore assumed that DNA is the sole route to autonomy and self-complication. However, the prevalence of the DNA mechanism on this planet may be just a historical accident. When any one such trick evolves, it quickly dominates — the trick, by its nature, is self-copying, and tends to swamp the competition.

None of this implies that alternatives, especially radical ones, cannot exist. For xenobiological purposes the answer to 'what is life?' cannot be a catalogue of DNA bases. It must involve the recognition that the abstract processes of life possess certain universal features, and that those features might have a large number of possible different physicochemical realizations.

Parochials and universals

Even on Earth, our view of what life is and where it can survive has changed considerably in recent years. Extremophiles survive in environments that would be lethal to humans (refs 23–29, and see the review in this issue by Rothschild and Mancinelli, pages 1092–1101). This suggests that we should not place too much reliance on alleged limitations of living organisms. But our evolution story, even ignoring extremophiles, hints at principles that might also apply to life more generally (see the review in this issue by Carroll, pages 1102–1109). And evolution itself is one such principle: it will apply to aliens as much as to us. Therefore some features of life on Earth will not be peculiar to our planet.

The key distinction lies between features that are 'universal' and those that are merely 'parochial'[30]. The best current test for universality is to ask whether a feature of interest arose more than once, independently, in evolution on Earth. If the answer is yes, as it is for flight, photosynthesis, locomotion, limbs and predation, then the feature is a universal. If not, as for pentadactyl limbs in tetrapods, the feature is a parochial. Alien evolution will resemble ours in universals, but not in parochials. Many disputes about alien life stem from disagreements about which features are universal and which are parochial. Because it is all we know, it is easy to assume that carbon-based molecular structure, genetics based on DNA and an oxygen/water environment are necessarily universal[31]. Xenobiologists, however, would consider oxygen/water to be useful but not essential, carbon-based molecules to be common but not indispensable, and DNA as a strong candidate for a parochial feature that is unlikely to be repeated elsewhere. In contrast, the dual interpretation of DNA as 'instructions' to be carried out and 'information' to be copied, predicted by von Neumann[32] on mathematical grounds just before Crick and Watson discovered the structure of DNA, is likely to be a universal. Many aliens will therefore have their own kind of genetics, because genetics is a useful general trick. But alien genetics might be based on substrates other than DNA. We already know that the double-helix configuration of DNA is only one of many that are possible[33] and that additional artificial bases (now more than twenty) can be included in DNA[34]. It also seems plausible that synthetic transfer RNAs could be constructed to change the genetic code and even to introduce new amino acids[35]. Most standard DNA chemistry is parochial, and aliens will not possess it.



Extelligence

A key question for xenobiology is the status of intelligence. Is intelligence a universal? The answer is unclear. Human-level intelligence has arisen only once on Earth, so by normal criteria it ought to be counted as a parochial. On the other hand, intelligence not so different from our own can be found in the great apes, cetaceans and the octopus. Pigs are excellent at video games, parrots have a surprisingly good grasp of linguistics[36], and even sticklebacks and mantis shrimps can solve problems. Intelligence looks like it should be a universal because it seems to offer major evolutionary advantages, irrespective of context.

However, the most important ingredient for sentient, technically competent aliens is not intelligence, but a property we have elsewhere called 'extelligence'[30]. This is the contextual analogue of individual intelligence. Humanity's assumption of global dominance is a tale of extelligence: language, permanent archives of information such as books, and communication in all its technological forms. When compared with most forms of life, our intelligence is only marginally greater than that of chimpanzees: it is our extelligence that has driven our cultural growth and technology. Human extelligence is far more powerful than any individual, but we can all contribute to it, draw on it and exploit it.

On the existing evidence, extelligence may also be a parochial. But again, it looks like such a useful generalized trick that we might be tempted to think of it as a universal. Technologically advanced aliens will, by definition, possess extelligence as well as intelligence. This is where some intelligent species on Earth seem deficient. Dolphins, for example, are able to communicate with one another, but do not appear to be extelligent — we see no dolphin technology. It remains possible that signs of dolphin technology exist but in a form too alien for us to recognize, but we consider this unlikely at present.

Unearthly habitats

Life is a universal, so it will evolve in any habitat that supports the required complexity of organization. We cannot, as yet, define those properties of habitats necessary to support

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life with the required degree of generalization, but it is likely that our familiar water/oxygen planet is only one of many possibilities. Science fiction has explored many others, including the surfaces of other planets and asteroids, the atmospheres of gas giants, stellar interiors, interstellar space, molecular clouds, and even the surfaces of neutron stars. Some of these locations, conventionally regarded as passive environments, such as stars and molecular clouds, have occasionally been depicted as life-forms in their own right. In fact, it is difficult to imagine a habitat that could not support a suitable form of life. Anywhere that physical matter can exist, and that offers a rich enough energy substrate, can in principle harbour highly organized processes carried out using matter and energy of the same kind. As far as we are concerned, that is alien life. (We modestly propose our own effort[37] as an exploration of the diversity of life when treated as a universal, free from the confines of terrestrial parochiality.)

Where are they, then?

A balloon-like creature floating in the atmosphere of Jupiter would probably regard the terrestrial environment as lethally unattractive. Most aliens would not wish to visit Earth at all, any more than we would care for a ramble across the surface of a neutron star, or to live, as do some extremophiles, in boiling water. We might suppose that the aliens least disinclined to visit us are those who have evolved in an Earth-like habitat, and such habitats might comprise an unknowably small subset of all possible life-supporting habitats. The chances that such aliens exist within 1,000 light years of us at the present time is small. There are plenty of places to visit: why Earth? However, non-humanoid aliens might be keeping a cold, unsympathetic eye on us for their own scientific purposes, writing yet another small footnote in their xenobiology texts.

But if they are here, they will not be easy to spot. As discussed above, they are unlikely to do anything as obvious as abduct gullible readers of supermarket magazines. It is likely that they will possess technology that to us would appear incomprehensible, in accordance with Clarke's dictum[38] that "Any sufficiently advanced technology is indistinguishable from magic." (Or, in Benford's restatement, "Any technology distinguishable from magic is insufficiently advanced."[39]) Aliens would not look like the canonical Little Green Men. They might look exactly like people. Or cats. Or houseflies. Or they are invisible, or lurking just outside our space–time continuum along a fifth dimension, observing our insides like The Sphere in Flatland observing A. Square[40]. Or they are concealed inside atoms. Or they exist only in the gaps when human perceptual systems are in their refractory phase and unable to observe them.

We think it most likely (and less paranoid) to assume that they are not here at all — for reasons of alien extelligence rather than non-existence. Why run the risk of travelling to exotic places when you can put on a headset and walk through Virtual Venice or Artificial Africa? When VR becomes as real as RealR, an actual visit might seem bothersome, expensive, unsafe and even boring.

We can see the germ of this introspective trend within humanity, so far the only extelligent species we know. More than thirty years ago we landed on the Moon. Our last visit was in 1972, and we no longer have a ready capability to land there. A low-Earth-orbit space station is laboriously taking shape, amid little real enthusiasm. We talk of future manned expeditions to Mars, but a projected unmanned probe to Pluto has been cancelled. The question is not about whether aliens have visited us, and if so, why they aren't here. The important question is why we have not ventured further into space. It would be sad if it turns out that the inability (or reluctance) of an extelligent species to leave home turns out to be a universal. □

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