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 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.

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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 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.

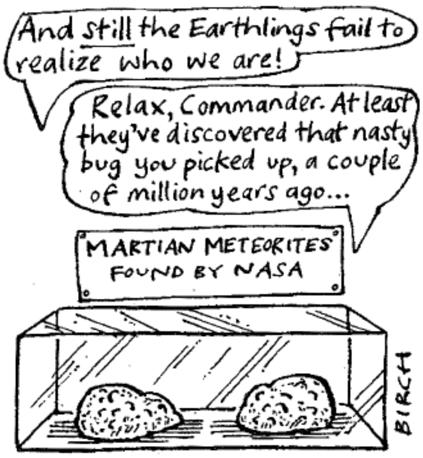
However, despite their seemingly limited diversity, Earth's current life-forms may be more typical in other, more important, ways, such as their relationship with their context. 'Life' is a name we give to certain emergent processes of complex systems[5,22]. Until quite recently we used the word as a 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 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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