

# Which exo-Earths should we search for life?

In the 15 years since the discovery of the first planet orbiting a Sun-like star, 51 Pegasi (Mayor and Queloz 1995), the detection of habitable planets, and even life, has become a real possibility. The new field of astrobiology has gone from strength to strength, as scientists from a range of disciplines come together to work on the question of how and where to find life beyond the Earth. Unless we are fortunate enough to detect a signal broadcast by another civilization, or detect life *in situ* elsewhere in the solar system, our main route to search for life will be the study of exo-Earths: Earth-type planets orbiting distant stars. Although no such planets have yet been discovered, the first will be found within the next couple of years, and so the time is right to discuss exactly what factors might come together to make such planets more, or less, suitable for life to develop and thrive.

Throughout the history of astronomy it seems that, once the first member of a population of objects has been discovered, many more follow soon after. The faster technology improves, the more rapid the turnover between no objects being known, and many having been detected. Exoplanets are no exception. Since 51 Pegasi was discovered, an increasing number of exoplanets have been found, first at a trickle, and now almost at a flood. At the time of writing, 494 planets are known within 416 planetary systems (data from the *Extrasolar Planets Encyclopaedia*, <http://exoplanet.eu/catalog-all.php>, 15 October 2010). On average, 10 new planets are being announced per month, a rate that is destined to climb further as projects such as Kepler (<http://kepler.nasa.gov>) begin to yield results.

To date, the least massive exoplanet discovered around a Sun-like star is Gliese 581e, with a minimum mass around twice that of the Earth. As new techniques come online, and missions such as Kepler begin to bear fruit, the first true exo-Earths will be detected. Once one is found, many more will quickly follow, and the search for life beyond our solar system will begin. How that search will be carried out is still under some debate – a wide variety of biomarkers have been suggested that might help life be detected – but the observations necessary to give a conclusive result for a given planet will certainly be long and arduous. Although new technologies and telescopes will no doubt be developed to help speed along such work, it is unlikely that we will be able to survey all of the new exo-Earths,

**Jonti Horner and Barrie W Jones work out how to select the most likely targets among planets like Earth, to search for signs of life.**

quickly or efficiently. It is therefore vitally important to ensure that we choose the most promising candidates for initial observations, to maximize our chances of finding life.

## Pick your planet

How do we differentiate between one exo-Earth and the next? What factors help determine which planets are most suited to the development of life? In this article we provide a brief overview of the key factors that are currently thought to influence the habitability of exo-Earths. Although it would be foolish to entirely prejudice where we are likely to find life, it makes sense to concentrate our initial efforts on those that seem most likely to provide a positive detection. We therefore highlight criteria for comparison, in order to determine the best target.

Stars form with a wide variety of masses. The smallest are just 8% of the Sun's mass, below which objects can not sustain hydrogen fusion in their cores. The most massive are over 100 times the Sun's mass. All stars spend the majority of their lives on the "main sequence" – a narrow strip across a plot of luminosity versus surface temperature. A star moves on to the main sequence after its formation (which is a relatively quick process) and remains there for most of its lifetime. Stars leave the main sequence when all the hydrogen in their cores has been used. They then enter stellar "old age", another phase that passes in an astronomical blink of an eye, compared to their main sequence lives.

The luminosity of a star during its main sequence life is roughly proportional to the fourth power of its mass. However, the amount of "fuel" the stars have is simply proportional to their mass. The lifetime of a star is therefore roughly inversely proportional to the cube of its mass. As a result, the most massive stars in the universe live fast and die young. Even if the most massive stars can form potentially "habitable" worlds, they will have such short lives that life on those planets can never truly get started.

Even for those stars of sufficiently low mass to allow the development of a significant biosphere in their main sequence lifetimes, if they are

younger than a few hundred million years then it is likely that life has not yet emerged. Low priority must therefore be assigned to young stars in the search for life.

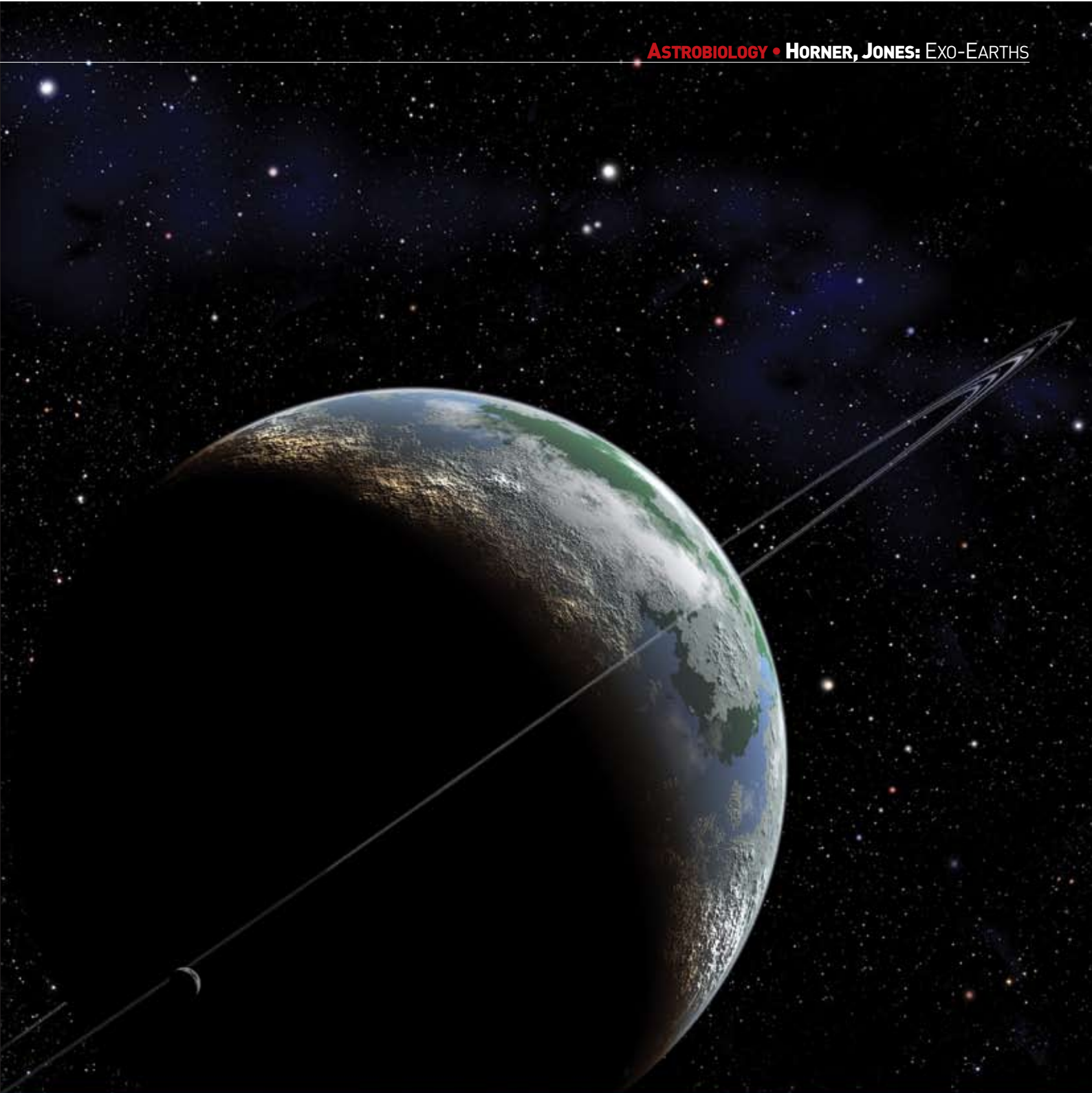
A key concept is the classical habitable zone (HZ). This extends over the range of distances from a star at which an Earth-like planet can have water as a stable liquid over at least part of its surface. The extent of the HZ for a star depends on mass and age.

The luminosity of a star increases throughout its main sequence lifetime. For example, the Sun, now 4.6 Gyr into its 11 Gyr main sequence lifetime, was only about 70% of its present luminosity when it was very young. Consequently, the HZ around a given star will gradually drift outwards. Just because a planet is within a star's HZ now does not, therefore, mean that it will have been there for long enough to have developed a detectable biosphere. Preference must therefore be given to planets that have spent at least hundreds of millions of years in the HZ.

If we adopt 1 Gyr as the minimum age for a planet to have a detectable biosphere, we rule out stars whose main sequence lifetimes are shorter than this – the massive stars that constitute the O, B and A dwarfs. However, the very great majority of stars are less massive, including the Sun. Such a cut, therefore, only rules out a tiny fraction of potential planets. If we extend our 1 Gyr minimum age to all young stars, over 10% of all stellar systems are excluded.

All stars are variable. Our Sun, for example, varies in luminosity by ~0.1% through the 22-year solar cycle. Some stars, though, are far more variable than others: young stars and old stars are particularly prone to significant variability. The variable star Mira (o Ceti), for example, varies in luminosity over a period of ~332 days, by a factor of ~4000, and such behaviour is far from unusual. Other stars, such as our nearest stellar neighbour, Proxima Centauri, are prone to enormous stellar flares. It is clear that such stars would be bad hosts for the development of life. At what point does variability become too great a problem for life to overcome? Whatever the answer, it is surely prudent to focus our initial hunt for life on planets around stars that are comparatively stable

**1: An artist's impression of a watery, ringed exo-Earth, viewed from its largest moon. (David A Aguilar CfA)**



in their output. Fortunately, the detection of planets is significantly easier for quiescent stars, since significant stellar variability can mask any evidence of accompanying planets.

By far the most common stars in the universe are the M dwarfs. These stars have the lowest masses among main sequence stars, and therefore the lowest luminosities and the longest main sequence lifetimes, at many hundreds of gigayears. However, there are a few problems that may limit the habitability of planets in orbit around them. First, the low luminosity of these stars means that their HZs are very close to the star. Even for the most luminous M dwarfs, the HZ only stretches from around 0.2 to 0.4 AU. Exo-Earths located so close to their parent star will rapidly become tidally locked, just as the Moon has about the Earth. It has been suggested that such an exo-Earth, keeping one face pointed permanently toward its host star, would be inimical to life. Indeed, some authors have suggested that the entire planetary atmosphere would freeze on the dark side of the planet, leaving it airless and uninhabitable. However, such a scenario is not as likely as once thought. Heath *et al.* (1999) showed that an atmosphere just a tenth of the density of Earth's would be sufficient to prevent this, were it mainly composed of CO<sub>2</sub>. With denser atmospheres, the conditions could even support liquid water somewhere on the planet's surface.

Secondly, M dwarfs exhibit variations in luminosity that are far greater, relatively speaking, than those experienced by more massive stars, ranging from the giant flares of stars such as Proxima Centauri, which can increase their luminosity by a factor of 100 over minutes, to the large, cool star-spots which can reduce their luminosity by several tens of percent for months at a time. However, even if the X-ray and UV flux from an M dwarf were to increase by a factor of 100, the total flux would still be relatively feeble – and should certainly pose no great problem to life on the surface. Similarly, short-term variations of stellar luminosity of a few tens of percent should pose no problem to any planetary biosphere, so long as the planet has even a moderate atmosphere. All in all, it seems that M dwarfs could be a promising places to look for life.

A significant fraction of stars form in multiple star systems. The exact fraction is unknown – widely separated stars are hard to associate with one another. When we look at our nearest stellar neighbours, roughly half are in multiple star systems, though it is likely that some stellar companions, even among those nearest stars, remain undetected. Whatever the true frequency of multiple stars, they are sufficiently common that any discussion of habitability beyond the solar system must consider such systems. Indeed, roughly a quarter of all known exoplanets are in multiple star systems (Horner and Jones 2010a). Typically, the separation of

the stars in those systems is significantly greater than the orbital radius of the planets that orbit about one or other of them.

Several studies have considered the orbital stability of such planets. David *et al.* (2003) consider the stability of an exo-Earth in the HZ of a Sun-like star. They found that a planet in such an orbit could remain within the HZ for at least the age of our solar system for a surprisingly wide range of binary scenarios, provided that the orbital eccentricity of the binary companion was low. The greater the eccentricity, the wider the mean separation needed to keep the system stable. Similarly, it appears that planets orbiting in the HZ beyond a close binary system can be stable, if the stars are sufficiently close to one another (Holman and Weigert 1999). It seems, that habitable exo-Earths could exist in a binary star system. If dynamical studies indicate orbital stability of an exo-Earth in the HZ, then such systems would be worthy of scrutiny.

The likelihood of stars hosting planets will vary as a function of the position of the star in our galaxy. However, given that we are likely to find many exo-Earths in our galactic backyard, it is certain that the first planets we survey for life will be in our local neighbourhood, and so a discussion of the galactic habitable zone is beyond the scope of this short review. For more information, see our recent lengthier review, Horner and Jones (2010a).

### Dynamical effects and debris

Many of the exoplanetary systems discovered to date are vastly different to our own. Systems have been found where the planets move on tightly packed, or highly eccentric, orbits. Many giant planets have been found orbiting far closer to their host star than Mercury orbits our Sun, while other systems feature planets on mutually resonant orbits. With such a wide variety of systems, it is vital that the orbital stability and evolution of an exo-Earth be examined in some depth before conclusions on its habitability are drawn. The key point here is that, just because a planet's orbit makes it currently appear habitable, it does not necessarily follow that that planet's orbit will have been the same for a protracted period of time. It is easy to imagine, for example, planetary systems in which an exo-Earth's orbit is periodically driven from being sufficiently circular for it to be habitable, to being eccentric enough to be a hostile environment, and back again, on geological timescales. The only way to check for such behaviour is to run suites of dynamical simulations of the planetary system in question, and follow its evolution on gigayear timescales. Any decision on which exo-Earth to study must take into account the long-term dynamical variation of the orbit of the planet in question.

Even if the long-term stability of a planet's orbit appears to ensure its habitability, distant

perturbations applied by the other planets in the system might play a significant role in ensuring that an exo-Earth is less hospitable than would otherwise be expected. Subtle variations in the inclination and eccentricity of an exo-Earth's orbit, coupled with variations in the tilt of its rotation axis, can combine to modify the climate of the planet. On Earth, these Milanković cycles are linked to recent glaciations and interglacial periods. Were our solar system laid out differently, it is quite possible that these variations would be significantly larger, less regular, or happen over a shorter timescale, all of which could lessen the habitability of our planet.

Fortunately, Earth experiences only fairly small variations, over relatively long timescales. Waltham (2010) has used Monte Carlo simulations to show that approximately 98.5% of randomly generated versions of our solar system would result in the Earth experiencing significantly more rapid and extreme Milanković cycles. This suggests that Earth might be unusually favourable for the development of life!

The calculations needed to determine the frequency and size of the Milanković cycles in a given system are not particularly computationally intensive, and therefore, so long as we have a reasonable degree of knowledge about the makeup of an exo-Earth's planetary system, it should be relatively straightforward to draw quick conclusions about the degree to which the planet is habitable. While these cycles are not a key determinant of habitability, it is certainly well worth considering them – at least as a tie breaker between otherwise “optimal” planets.

For many years, it was thought that a key ingredient of planetary habitability was the presence of a large, Jupiter-like planet, orbiting beyond the HZ. Such a planet, it was argued, would shield an exo-Earth, protecting it from an overly punishing flux of hazardous objects from the outer reaches of the system. In a recent series of papers, we showed conclusively that this idea is, simply, wrong. In fact, giant planets in a planetary system are more of a double-edged sword: what they give with one hand, in terms of protection from impacts, they can easily take away with the other, by drawing small bodies closer. We described our results in detail in a recent issue of *A&G* (Horner and Jones 2010b), where the interested reader will find a detailed discussion of this issue. It is certainly the case that the impact regime of any exo-Earths should be considered – dynamical studies of the regimes are relatively straightforward to carry out (although computationally intensive), and would definitely help the selection of the best target for the search for life.

All other things being equal, a system with more debris would deliver a greater impact flux to an exo-Earth. However, not all such systems are equal. Surveys of the sky using infrared telescopes (such as IRAS and Herschel) have

revealed debris discs around a wide variety of stars. The discs span a wide range of masses, and occur at a large variety of distances from their hosts. Note, however, that the dust we observe is strongly influenced by a variety of non-gravitational forces which result in it being removed on astronomically short timescales. Systems that contain large amounts of dust must therefore have some mechanism by which that dust is replenished, which suggests that kilometre-sized objects are continually grinding one another down. This infers either a very large population of such objects or some significant instability in a reservoir containing them, resulting in increased collision velocities and frequencies.

Alternatively, one can imagine systems with massive reservoirs of kilometre-sized objects that remain unperturbed from the dynamically cold orbits (with low mean eccentricities and inclinations, as in protoplanetary discs) on which they formed. Such systems would not, necessarily, show any significant infrared excess, because their low rates of collisional grinding would result in little dust, and would experience little collisional threat. Systems that show a huge infrared excess would, at least initially, seem to pose more of a collision hazard for exo-Earths within them. However, if a debris disc that is somewhat stirred, and therefore very dusty, is a long way from an exo-Earth, and there are no massive planets between the two to source material from the reservoir to the exo-Earth, then the abundant debris will pose little threat.

Infrared data on some systems indicate large amounts of hot dust (which therefore is close to the host star), and could represent systems in which the impact regime would be inimical to the development of life. It might be that these systems simply have so much debris left over that planetary accretion is essentially still in progress. Alternatively, such systems might be in the process of undergoing a Late Heavy Bombardment episode, in which the impact flux through the inner planetary system has undergone a recent significant increase. Such episodes could be the result of the long-term migration of the giant planets in the system destabilizing any reservoirs of kilometre-sized objects.

Information from infrared observations of exo-Earth host systems will no doubt prove invaluable in assessing the local impact regime. However, such observations should be used with dynamical simulations, to check whether the debris associated with an observed infrared excess truly poses a risk to the planet.

It has been suggested that the Moon has played a pivotal role in the development of life on Earth. Compared to the other satellites in our solar sys-

tem, the Moon is unusually large and massive relative to its host planet. It is thought to have formed during the latter stages of the Earth's accretion, when a Mars-sized object collided, at relatively low velocity, with the proto-Earth. Such events are, however, stochastic, and there is no guarantee that an exo-Earth would play host to a similarly large satellite. Does having a large satellite affect the potential habitability?

The supposed beneficial effects of the Moon can be broken down into two roles – the creation of significant tides (which might have facilitated the transfer of life from the oceans to the land), and the stabilization of the Earth's axial tilt. The first does not, necessarily, appear to be a prerequisite – it is easy enough to imagine a planet with oceans teeming with life, and uninhabited continents, providing sufficient evidence for a firm detection of life. Furthermore, even if the Moon was not present, the Earth would still experience tides from the Sun's gravitational pull.

Secondly, the tilt of the Earth's axis rocks back and forth by a degree or two – enough variation to contribute to the Milanković cycles, but not sufficient to cause catastrophic climate changes. The axial tilt of Mars, however, experiences far greater excursions, sometimes even reaching (or exceeding) 60°. If this happened on Earth, the Arctic circle would pass through Cairo and south of Shanghai, and the Antarctic circle to the north of Perth and Santiago, with significant consequences for the climate! It has been suggested that the Moon provides the main reason for the Earth's axial stability. Waltham (2006) found that the mass of the Moon is remarkably close to the maximum for which the host planet's axial tilt would be stable.

Above that mass, a large "Moon" would destabilize the spin axis of the planet, potentially making it less, rather than more, habitable.

While the precise role of giant satellites in determining planetary habitability is still under debate, it would be premature to write off the potential benefits of such a satellite to the development of life. That said, we consider that the role of such satellites may well prove less significant than many of the other features discussed in this review.

### Planetary features

The presence of liquid water is often considered the key ingredient for the development of life on an exo-Earth, as evidenced by the definition of the HZ. Some models suggest that Earth's water was accreted from local hydrated minerals, while others suggest that the source was material that came from beyond the "ice line", the boundary in the protoplanetary nebula beyond

which water ice was able to condense. The latter models come in two versions: early and late arrival of ice – see Horner and Jones (2010a) for more information.

The amount of water possessed by exo-Earths will depend on the dynamical processes involved in the formation of systems significantly different to our own. For example, it is feasible that exo-Earths will have formed in systems that also feature a "hot Jupiter" – a Jovian planet orbiting much closer to its parent star than the exo-Earth. Models examining the formation of such planets suggest that the Jovian planet must have formed much further from the Sun, and then migrated inwards, dragging icy materials with it. This could result in exo-Earths that are covered with a planet-wide ocean tens, or even hundreds, of kilometres deep. Would such planets be habitable? It is often suggested that, in addition to planetary oceans, the presence of continental regions also plays an important role in the development of life. As the continents weather, they provide a constant source of minerals and metals that would otherwise rapidly be lost from the ocean. Without these materials, it is suggested, the development of life would be significantly stymied (e.g. Ward and Brownlee 2000). Equally, it is just as feasible that the late giant impacts at the end of planetary formation could strip an exo-Earth of its watery veneer, leaving it as an uninhabitable desert planet.

So, we come to our "ideal" exo-Earth. Clearly, we want to search for a planet that has liquid water on its surface, so orbits within the HZ. However, we probably want to avoid any planet that is too dry, or too wet, and focus on those that are just right.

As noted above, the weathering of material from the continents might play an important role in providing key chemicals for life in the oceans that would otherwise be depleted over time. A good example of this is calcium – a vital ingredient in shells, bones and teeth. Over time, the calcium in the oceans is sequestered as calcium carbonate, and were it not replaced, would eventually be exhausted. The removal of calcium from the oceans also removes carbon dioxide from the atmosphere. If there were no way to return that sequestered gas to the atmosphere, it is probable that continued removal would gradually cool the planet, as the greenhouse effect lessened, until the planet became uninhabitable. It is fortunate, then, that our planet is tectonically active, with plate tectonics acting to return sequestered carbon to the atmosphere (and calcium to its surface).

These examples highlight the importance of tectonic activity in ensuring the ongoing habitability of the Earth. Were plate tectonics absent (as is believed to be the case for Venus and Mars), then the Earth would certainly be a different place. There is evidence that the ongoing tectonic activity of our planet is due

**“Weathering of material from continents might be important for providing key chemicals for life in the oceans”**

to the lubricative effects of the Earth's water on plate motion. Recent research suggests that dry planets would have to be significantly more massive than the Earth in order to support long-term tectonic activity. Without our water, these studies suggest, the Earth would instead exhibit the "stagnant lid" behaviour of Venus and Mars, a significantly less efficient method of cooling the planet's interior. As we discuss below, the ramifications of such a tectonic scenario might stretch beyond the maintenance of a clement climate.

The combined action of plate tectonics (which helps maintain the continental crust) and weathering (which attempts to rub it away) acts to both mediate our climate, and keep the oceans sufficiently nutrient-rich that life can thrive. Therefore, any exo-Earth should be expected to be tectonically active. This could be determined by long-term observations following the brightness and colour of the planet as a function of time. If the planet has large continents, and broad oceans, it seems likely that it would also be tectonically active (or the continents would weather to nothing).

Tectonic activity also plays a role in the generation of the magnetic field, through the flow of liquid iron in the core. As discussed earlier, all stars expel prodigious amounts of material in the form of their stellar wind and more violent coronal mass ejections. If that material was unimpeded, it would directly interact with the atmospheres of any orbiting exo-Earths, resulting in gradual but unceasing erosion. In addition, the continual rain of fast moving particles from the star would penetrate the atmosphere, doing further damage to the habitability of the planet. Fortunately, the Earth has a relatively strong magnetic field, which acts to protect it from all but the worst vagaries of the solar wind. Without that magnetic field, the flux would be orders of magnitude higher, stripping our atmosphere, irradiating the planet's surface, and likely destroying the ozone layer which protects us from excessive solar UV radiation.

The role of the magnetic field in preserving a planet's atmosphere is particularly important when the system is young. Young stars are particularly active, and have powerful stellar winds. As time goes by, the strength of the stellar wind decreases, and the efficiency with which it could remove a planet's atmosphere falls away. In the case of Mars, observations suggest that the planet's dynamo ceased to operate about 4 Gyr ago, after which the atmosphere has slowly been stripped away, leaving today's tenuous atmosphere, over a thousand times less dense than the Earth's. By contrast, it is thought that the young Venus had plate tectonics and a magnetic field for long enough to retain its atmosphere when the Sun was young and especially active. As the planet warmed, due to the Sun gradually becoming more luminous, the oceans would eventually have boiled, leading to the loss of the

planet's water, and the shutdown of tectonics. Outgassing of carbon dioxide from volcanoes would then have increased the atmosphere and warmed the planet further, with strong positive feedbacks. Lundin *et al.* (2007) suggest these two planets as extreme examples of the effects of loss of magnetic shielding.

It is very likely to be the case that plate tectonics greatly increases the probability that a habitable exo-Earth is, in fact, inhabited. Given that water might be essential for plate tectonics, this strengthens the argument that the first exo-Earths we search for life should be those that have a significant water budget. Without sufficient atmospheric pressure, it is impossible for water to exist as a liquid on the surface of a planet – below a surface pressure of 6.1 millibars, any ice will pass directly to the vapour phase, without ever being stable as a liquid. As the atmospheric pressure increases above this value, the range of temperatures over which water can be liquid increases, such that on Earth, with a mean pressure of 1013 mb, water is liquid between 0 and 100 °C.

The atmosphere also plays a central role in determining the temperature required for water to be liquid. Too cold, and the water will freeze out, too warm and it will boil away (and potentially even be lost via photodissociation). Maintaining this balance is not as straightforward as it seems. When life first appeared on the Earth, the Sun was shining with just ~70% its current luminosity. Had the Earth's atmosphere at that point been the same as that today, the planet would have been frozen solid. Similarly, if the modern Earth had the same atmosphere as it had in the early days of life, then the greenhouse effect would be so severe that our water would have boiled away long ago. As the Sun has brightened, the Earth's atmosphere has evolved (in part, due to the biosphere) in such a way that the mean surface temperature has enabled most of our planet's water to be liquid.

Uniquely among the terrestrial planets, Earth's atmosphere has a major temperature inversion at the top of the troposphere. This inversion helps "cap" the water content of the atmosphere, keeping the great bulk of water vapour below that level. Over the aeons, this effect has prevented the otherwise crippling loss of water due to the vapour reaching sufficiently high altitude that solar UV can photodissociate it. At the Earth's mass, hydrogen easily escapes from our atmosphere, so once water is dissociated in this manner, it is essentially lost.

What about other planets? Imagine the scenario where Mars, instead of being a fraction of Earth's mass, was instead somewhat more massive than our planet. As such, the young, wet Mars would have been able to maintain its tectonic activity, keeping up a dynamo that would prevent the loss of its youthful atmosphere. Suppose also that it had a thicker atmosphere than

the Earth's and a correspondingly greater greenhouse effect. With such an atmosphere to offset the lower insolation received, such a "Mars" would be habitable at the current epoch, despite its position on the very outer edge of the present day HZ; in this scenario our solar system could feature two planets with thriving biospheres, rather than just the one.

These considerations are clearly relevant to choosing exo-Earths that are the best candidates for being habitable, or even inhabited.

## Conclusion

In the coming years we will for the first time discover potentially habitable planets orbiting distant stars. Despite the fact that it has taken so long for us to find the first, we will rapidly move to a situation where tens, hundreds, or even thousands of such planets are known. Once these planets are found, the scramble to detect the first evidence of life upon them will begin. Unfortunately, the observations needed to provide a conclusive proof of life beyond the solar system will be lengthy, expensive and arduous; it is almost certain that we will not be able to study more than a small fraction of the planets we discover in sufficient depth to search for life. As such, it is vital that we direct our efforts with care, and select those planets which represent the most promising targets for a positive detection.

In this review, we present a number of the major factors which are thought to play a role in determining the habitability of exo-Earths. In the coming years, it is imperative that scientists from the varied fields that make up astrobiology come together to prepare a template for "optimal habitability", to help determine which of the exo-Earths we discover should be the first target for an intensive search for life. We have just a few short years to prepare ourselves for that search, which promises to yield the most exciting result science has ever witnessed – the detection of life beyond the Earth. ●

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