Is Earth Special?

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Abstract: Peculiar conditions may be required for the origin of life and/or the evolution of complex organisms. Hence, Earth attributes—such as plate-tectonics, oceans, magnetism and a large moon—may be necessary preconditions, for our own existence, that are rare in the general population of planets. The unknown magnitude of this observational bias undermines understanding of our planet. However the discovery and characterization of exoplanets, along with advances in mathematical modelling of Earth systems, now allow this "anthropic selection" effect to be more thoroughly evaluated than before. This paper looks at a number of properties of our Solar System and our planet. It examines their possible benefits for life, whether these properties might be rare, whether they required fine-tuning and whether they have an associated habitability-lifetime. It also discusses additional data likely to become available in the near future.

None of the individual properties considered show convincing evidence for anthropic bias. However, the time-scales associated with habitability— in particular, those associated with solar-warming, with axial stability and with planetary-cooling—are surprisingly similar and this provides tentative support for the view that Earth may be special.

Keywords: Habitability, Habitable lifetime, Exoplanets, Plate tectonics, Magnetism, Oceans, Large moons, Anthropic selection.

1 Introduction

What we can expect to observe must be restricted by the conditions necessary for our presence as observers (Carter, 1974)

There is an observational bias that must be taken into account when we try to understand our own planet; the preconditions required for life to begin and for intelligence to evolve may be extremely unusual. As a consequence, we cannot say whether Earth is a typical, medium-sized, rocky world or one of the oddest planets in the Universe. More specifically, are features such as surface oceans, plate tectonics and long-lived magnetism common properties of planets or rare consequences of a peculiar, but necessary, history? *Rare Earth* (Ward and Brownlee, 2000) brought widespread attention to the contention that Earth may be unusual and it is timely to re-examine the evidence for and against that view.

Carter (1974) called this bias “anthropic selection” and Barrow and Tipler (1996) presented a detailed analysis of its consequences for the properties of our Universe and the properties of our planet. As with “natural selection”, careless language causes confusion. Anthropic selection has not altered any of Earth’s properties. Rather, there is a large population of planets in the Universe which exhibit a wide range of attributes but only those that have all the necessary properties will give rise to observers. Hence, since we are observers, Earth must have those properties even if they are rare in the general population of planets.

These ideas are esoteric and far-removed from the usual concerns of Earth-scientists, but anthropic selection has a concrete consequence for our science; we must be careful when drawing broad conclusions from Earth’s narrow history.

For example, it is sometimes stated that the relatively rapid appearance of life—perhaps 200 My or less after the first appearance of liquid water (Nisbet and Sleep, 2001)—is evidence that life emerges easily and will be found on many other worlds (Lineweaver and Davis, 2002). At first sight this seems a reasonable argument but it is not well-founded (Carter and McCrea, 1983; Spiegel and Turner, 2012); if it takes billions of years for intelligent observers to evolve from simple life, and if planets are only habitable for a few billion years, then worlds where life emerges late will not be habitable long enough for observers to appear. Hence, it is possible that intelligent observers always find themselves living on planets where life evolved early, even if early-life is the exception rather than the rule. This is not an argument against the hypothesis that life really does evolve quickly and easily; it is simply a statement that we cannot draw any such conclusion based solely upon the rapid emergence of life on Earth.

A further consideration is that, within science generally, explanations are considered strong if they explain puzzling correlations and weak if they appeal to chance. For example, part of the evidence supporting mid-ocean spreading is that it explains why coasts on opposite sides of oceans fit together. A counter-example is that, if the currently increasing CO_2 levels in our atmosphere result from natural processes, it is hard to explain why the rise is so highly correlated with anthropogenic emissions (Canadell et al., 2007). Hypotheses are therefore usually rejected if they require unlikely properties, fine-tuning of parameters or implausible coincidences. However, this approach must be used with care when considering Earth-properties that influenced our own evolution; improbable accidents of history may have been necessary to allow the emergence of observers.

Earth's long-lived magnetic field illustrates this issue. There is good evidence that Earth has maintained a strong magnetic field through most of her history (Tarduno et al., 2010) but this longevity may require a geochemically unlikely core composition (see section 6 of this paper). In most areas of science, special-pleading like this would be interpreted as indicating problems with underlying theory but, in this case, such a conclusion cannot be drawn. If a continuous magnetic field is required for habitability, all worlds with observers will possess one even if magnetic longevity is highly unusual. I am not saying that Earth's magnetic field is definitely odd or that it is a definite requirement for habitability—as section 6 will show, these remain open questions—I am simply stating that the mere possibility that there might be an observational bias means that models of Earth's magnetic field cannot be ruled out purely on the basis that they require unlikely, but not impossible, core properties.

The thesis of this review is therefore that a proper understanding of Earth requires us to be aware of the potential for anthropic selection effects. To search for affected properties, an obvious strategy is to search for Earth attributes that are uncommon in the general population of planets. For some properties, exoplanet studies have already given us the necessary data to check for such anomalies whilst, for others, the data will become available in coming decades as a consequence of planned exoplanet-characterization surveys. However, looking for unusual Earth-properties can be criticized on the grounds that every world has its own peculiarities. Planets are characterized by a large number of properties and it is almost inevitable that any given world will have a few attributes that are chance outliers. Every planet, like every pebble on a beach, is unique and it may be difficult to distinguish anthropically selected properties from meaningless statistical fluctuations.

For example, consider the estimate that 20±14% of solar type stars have a planet of approximately Earth-mass within the habitable zone (Traub, 2012; Petigura et al., 2013; Burke et al., 2015), i.e. that orbit at distances from their star compatible with surface liquid water. Our own location within the HZ (habitable zone) of the Sun is an anthropically selected attribute of the Earth (i.e. Earth could not have observers on its surface if it did not lie within the HZ) but this particular property is not rare at even a 5% significance level. Hence, if we use a significance level of, say, 1% as our indicator of anthropic selection, it could result in us missing many anthropically selected properties. If, on the other hand, we use a significance level much above 1% we will unavoidably highlight many properties that are mere statistical fluctuations. The best that might be achieved would be to demonstrate that Earth has more rare properties than expected but we would be unable to decide, using statistics alone, which properties are anthropically selected and which are inconsequential accidents of history.

It could be argued that anthropic effects are only of interest if they concern extremely rare properties; it is neither surprising nor novel to suggest that habitability requires a few common, but not universal, characteristics such as sufficient mass to retain an atmosphere. However the effects of selection for moderately rare properties are cumulative. For example, if Earth has a dozen independent properties that are rare at the 10% level, it will almost certainly be the only planet in our Galaxy with all 12 properties (1 planet in 10^{12} will have all of them but there are only $2x10^{11}$ planets in our Galaxy). Hence, even selection for moderately rare attributes would make Earth special if there are enough such properties.

Identifying anthropically selected attributes that are slightly rare (say 1-10% frequency), rather than exceedingly rare (<<1% frequency), is therefore worthwhile but it requires additional lines of evidence. To begin with, there should be a convincing mechanism whereby an attribute contributes to Earth's habitability (e.g. being at the right distance from the Sun allows the presence of liquid water). Secondly, it may be possible to show that an Earth attribute is fine-tuned. An example of fine-tuning would be if Earth's distance from the Sun maximized its time in the HZ. This particular example is illustrated in Figure 1 which shows how habitable lifetime changes with Earth-Sun separation (after Waltham, 2017). Figure 1 suggests that Earth would be habitable for significantly longer if she orbited at 1.16 AU (where 1 Astronomical Unit is the true Sun-Earth separation) and so, in this case, the evidence for fine-tuning is not strong. Note that this does not mean that the Earth-Sun distance is not anthropically selected (it almost certainly is!) it just means that looking for fine-tuning has not provided any additional evidence in favour of the hypothesis. It should also be noted that different climate models and/or different solar evolution models produce different results and Figure 1 is only shown here to illustrate a general point about fine tuning.

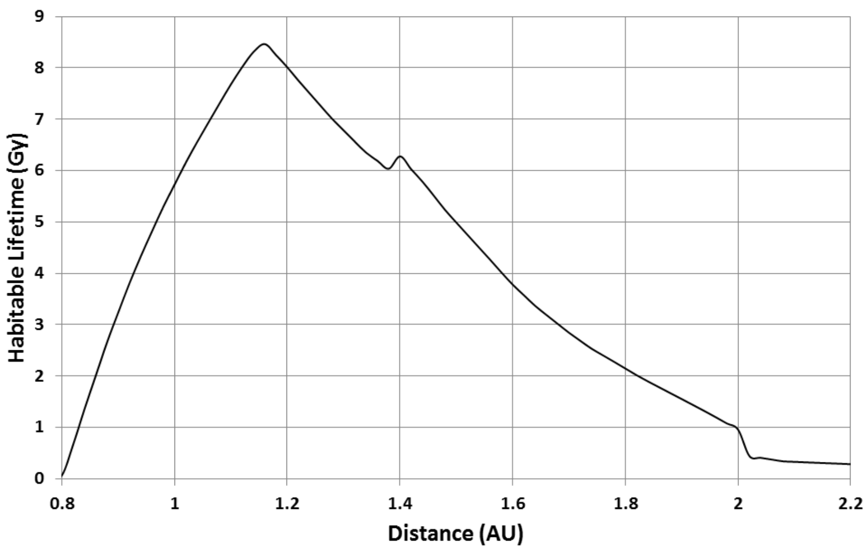

Figure 1. Habitable lifetime of the Earth as a function of its distance from the Sun (after Waltham, 2017). Note that Earth does not appear to be at the optimal distance since a significantly longer lifetime would occur if Earth was 16% further from the Sun. Hence, this model does not provide evidence of fine-tuning for this parameter.

A further test for anthropic selection arises because some habitability-requirements are time-limited. The best known example is that, a few billion years from now, the Sun will become too luminous to allow liquid water on Earth's surface (Kasting et al., 1993). Furthermore, there may be many such lifetimes (e.g. a lifetime for plate-tectonics, a lifetime for magnetism, a lifetime for axial-stability and so on) and these could conceivably be very different from each other since they are controlled by different factors (e.g. star mass controls stellar luminosity history whilst the longevity of plate-tectonics/magnetism is strongly influenced by planetary mass). However, imagine that these lifetimes have a range of possible values which are typically short compared to the timescale needed for the emergence of observers. Under those conditions there will be anthropic selection for planets where these lifetimes are unusually long. Furthermore, planets where some of these timescales are set significantly longer than others will be even rarer than planets where all the timescales are just long enough. Hence, complex life will tend to appear on worlds where such timescales are approximately equal. An important caveat is that some lifetimes might not be independent—e.g. magnetism and plate-tectonics are both driven by planetary cooling—so that the resultant correlation in lifetimes is no longer evidence of anthropic selection. In summary, a possible signature of anthropic selection is the existence of surprisingly long and approximately equal habitability lifetimes; but only if those lifetimes are demonstrably controlled by independent factors.

Given the above analysis, this article has five sub-sections for each Earth property that it considers:

1. Possible benefits: How might the property aid habitability?
2. Frequency: How unusual is the property?
3. Fine tuning: Does the precise value of the property have benefits?
4. Lifetime: How long does the property provide its benefits?
5. Future evidence: What additional information might become available within the next few decades?

The paper starts by considering the masses of the Sun and Moon (sections 2 and 3) followed by the masses and positions of the other planets of our Solar System (section 4). These astronomical influences on Earth's habitability may seem a little out of place in an Earth-science paper but they have the advantage that there is a great deal of statistical data concerning stars, planets and planetary systems. In addition, well established mathematical models describe the evolution of stars and the motions of moons and planets. Geological factors influencing Earth's habitability have neither of these advantages since we currently lack detailed information about the geology of rocky exoplanets and, furthermore, the complexity of geological processes has slowed the development of predictive, mathematical models. Nevertheless, later sections will look at important attributes of Earth herself; they will consider the presence of oceans (section 5), a magnetic field (section 6) and plate tectonics (section 7). The paper concludes by synthesising these astronomical and geological analyses in an attempt to establish whether Earth really is an oddity.

2 The Sun's mass

Stars exist with a wide range of masses. The smallest known star has 7.5% of the Sun's mass (van Biesbroeck, 1944) a record that is unlikely to be substantially broken because smaller bodies do not have the internal temperatures and pressures needed to initiate nuclear fusion (Dantona and Mazzitelli, 1985). At the other end of the range, the largest known star has 315^{+60}_{-50} solar masses (Crowther et al., 2016). Hence, our Sun is often thought of as relatively small since she is an order of magnitude larger than the lightest stars but two orders of magnitude smaller than the heaviest. However, as discussed later, this is misleading because the majority of stars are significantly smaller than our Sun.

A star's mass is important because it determines three major factors affecting any life on its planets; more massive stars are more luminous, they have shorter lifetimes and they radiate light with shorter, more energetic frequencies (LeBlanc, 2010). In addition small stars have more flare, UV and X-ray activity, particularly when young (Scalo et al., 2007). Finally, there would be an indirect effect of star-mass on habitability if there is a tendency for stars in a particular size range to have more planets within their HZ; however the evidence so far does not indicate any strong link of this kind (Traub, 2012).

2.1 Possible benefits

If the mid-range mass of our Sun has been anthropically selected, the implication is that there are habitability problems associated both with smaller stars and with more massive ones. It is relatively easy to find a problem with heavier stars—they burn their nuclear fuel rapidly so that planets orbiting them remain habitable for less time. For example, Kasting et al. (1993) estimated that Earth will remain habitable about 3-times longer than an HZ planet orbiting a 1.5 solar-mass star.

The effect of habitable lifetime on the probability of observers may be dramatic (Waltham, 2017). This arises because, as discussed by Carter and McCrea (1983), there is an interesting order-of-magnitude coincidence between the 4.5 Gy taken for intelligent observers to appear on Earth and the ~6 Gy timescale after which the Sun is too luminous to allow life on Earth. The biological processes giving rise to intelligence are unrelated to the nuclear processes that control the evolution of stars and, hence, there is no obvious reason why these timescales should be of the same magnitude. Carter and McCrea (1983) explain the coincidence by suggesting that the true characteristic timescale for intelligence is actually much longer than 4.5 Gy. Under these conditions, intelligence never appears at all on most living worlds but, when it does, it nearly always occurs close to the end of the habitable period (since earlier appearances are even less likely).

More quantitatively, the model predicts that the time for intelligence to appear (in the rare cases where it does) will on average be $n/(n+1)$ times the habitable lifetime, where n is the number of critical (i.e. unlikely) evolutionary steps required for intelligence. For example, if there are 3 critical steps and Earth has a habitable lifetime of 6 Gy, we should expect intelligence to appear after (3/4) x 6 = 4.5 Gy. This analysis suggests that n is around 3 (e.g. Watson (2008) estimates it as 4) although the precise value is not well constrained (Waltham, 2017). This simple model neatly explains why intelligence has appeared close to (but not quite at) the end of Earth's habitable duration. Critically for the current paper, the model also predicts that the probability of observers emerging increases with t^n where t is time.

This argument leads to dramatically increased probabilities of observers on planets orbiting small stars. The least-massive red-dwarfs have lifetimes approaching 100 times longer than our Sun's and so, by the above argument, are apparently one million (=100^3) times more likely to give rise to observers eventually. The fact that we find ourselves orbiting a solar-mass star is therefore evidence that there is a habitability problem associated with small stars. There are a number of possible mechanisms.

Firstly, low-mass stars take a long time to settle down when they first form; small stars can have pre-main-sequence lifetimes in excess of 100 My compared to only 10 My for a solar mass star (Bressan et al., 2012). During this "T Tauri phase" (Landessternwarte, 1989) small stars are typically two orders of magnitude brighter than they later become whilst solar mass stars undergo a luminosity drop of less than a factor of ten (see graphs in Hillenbrand and White, 2004 and in Bressan et al., 2012). The resulting initial period of high planetary temperatures may be long and severe enough to strip atmospheres (or, at least, water) from planets orbiting in the HZ of stars up to around 0.6 solar-masses (Luger and Barnes, 2015).

Another possibility is that planets orbiting within the relatively tight HZ of a small star are exposed to the high X-ray, UV and flare activity that is associated with such stars when young. This issue affects stars with masses below about 0.36 solar masses (Scalo et al., 2007).

A rather different problem with smaller stars emerges because the stellar tides, experienced by an HZ planet, increase in strength as stellar mass falls (see appendix A). The rotation of habitable planets orbiting small stars is therefore tidally-braked to the point where rotation may even become synchronous with the orbital period. The resultant slow rotation may severely affect climate, reduce magnetic-field strength and increase exposure to radiation (Lammer et al., 2009; Scalo et al., 2007). Waltham (2017) estimated that, if tidal locking is a problem, it will limit the habitable lifetime of planets orbiting stars smaller than 0.84 solar masses. However, all of these ideas for possible problems with small stars have been criticised (Heath et al., 1999; Yang et al., 2013).

A final possible issue for stars of different mass to the Sun is that their peak-wavelength is also different. Massive, hot stars emit much of their radiation in the ultra-violet whilst small, cool stars radiate largely in the infra-red (LeBlanc, 2010). It has therefore been suggested that planets orbiting such stars will receive less photosynthetically active radiation (PAR) (Pollard, 1979) and it is certainly plausible that the absence of photosynthesis would make the appearance of observers less likely. Heath et al. (1999) calculate that PAR could be reduced by an order of magnitude on planets orbiting smaller stars but, nevertheless, conclude that there would still be sufficient light to support photosynthesis. They justified this by the observations that land-plants on Earth are frequently saturated (i.e. get more light than they can use) and that the photic zone in our oceans extends down to depths where solar radiation is only about 1% that at the surface. Similar conclusions have been drawn by other authors (e.g. McKay, 2014; Gale and Wandel, 2017).

In summary, planets orbiting stars larger than the Sun are probably less likely to harbour observers because of short stellar-lifetimes. Plausible suggestions also exist for why smaller stars may have habitability problems but those proposals remain controversial.

2.2 Frequency

The frequency distribution of mass, for newly formed stars, is given by the initial mass function (IMF) (Miller and Scalo, 1979; Chabrier, 2005). The precise form of the IMF, and whether it remains constant with time, is a controversial topic (Kroupa, 2001) but the debates concern details that do not greatly affect the key result that our Sun is a relatively large star. For example, the Miller and Scalo (1979) IMF implies that 87% of all stars are smaller than the Sun whilst the Chabrier (2005) IMF gives 86 % (see Fig. 2). These percentages differ sufficiently from an expectation value of 50% to be interesting but are not different enough to rule out the possibility that this is a statistical fluctuation of no anthropic significance (i.e. 14% of all stars have masses even larger than the Sun's).

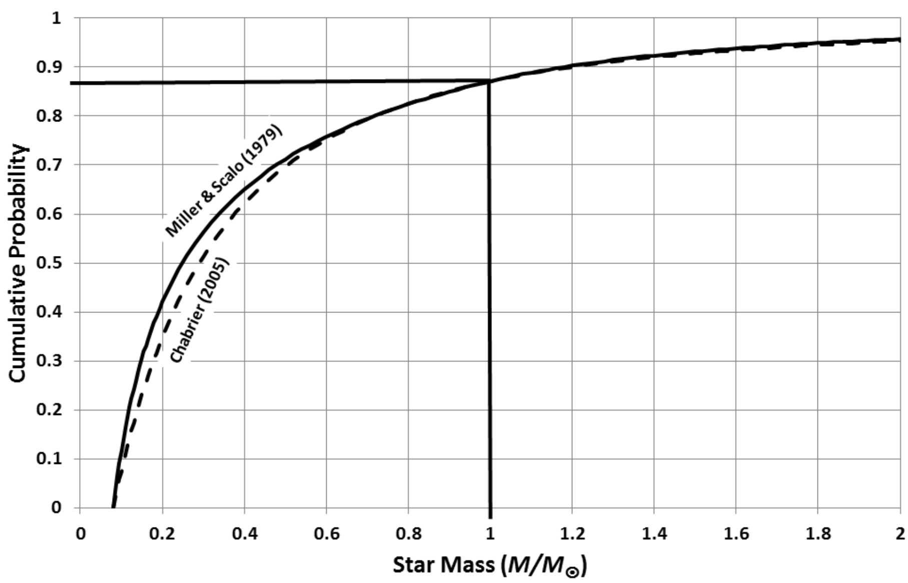

Figure 2. Cumulative mass distribution of stars (after Miller and Scalo, 1979 and Chabrier, 2005). $M_\odot$ is the solar mass. Note that the Sun is relatively large since ~86% of all stars are smaller.

2.3 Fine tuning

There are no habitability-relevant properties of stars, known to the author, which are either maximized or minimized for stars of approximately solar-mass. All relevant properties—such as lifetime, radius and surface temperature—are smooth, monotonic functions of mass.

Waltham (2019, in review) has suggested that the rate at which the evolution of solar-mass stars warm their planets, may be optimum for cancelling geological evolution (principally continental growth and reductions in outgassing/ocean-spreading-rate) which tends to decrease greenhouse gasses in the atmosphere. This proposal depends critically upon estimates of negative climate feedback strength that are too weak to prevent severe cooling (warming) of HZ planets orbiting stars of lower (higher) mass. This is likely to be contentious.

Thus, at present, there is no widely accepted evidence that solar-mass is fine-tuned.

2.4 Lifetime

Like all stars, our Sun becomes more luminous with time and, as a consequence, Earth will eventually become too warm for life. Kasting et al. (1993) looked at this issue using a climate model that underwent run-away cooling at the point where CO_2 clouds condensed in the atmosphere, and dehydration when warming produced atmospheric activity intense enough to transport water into the stratosphere where it underwent photolysis and hydrogen-loss to space. The model predicted a habitable lifetime for Earth of about 5.5 Gy, i.e. that life can survive on Earth for approximately another 1 Gy. In contrast, the model of O'Malley-James et al. (2013) suggests that, whilst there will be a rapid increase in Earth-temperature starting around 1 Gy from now, our planet does not become uninhabitable for another 2.8 Gy. Even longer lifetimes are predicted by Rushby et al. (2013) who give a total lifetime range of 6.29-7.79 Gy (i.e. habitability ending 1.76-3.25 Gy from now). These discrepancies are largely due to differences in climate model although there are also differences in assumed solar-evolution.

Few other authors have calculated a future-lifetime directly but several have calculated a distance to the present-day inner-boundary of the HZ. This can be converted into a lifetime by using a solar-evolution model (e.g. from Girardi et al., 2000) to calculate when illumination at Earth's orbit will have risen to equal present day illumination at the inner-HZ boundary. These inner-boundary estimates are based upon a variety of different climate models, and different mechanisms for how habitability is affected by increased illumination, but they give reasonably consistent answers. Thus Kasting et al. (1993) and Franck et al. (2000) both estimate that the inner HZ boundary lies at 0.95 AU whilst Kopparapu et al. (2014) place it at 0.949-0.964 AU. Hart (1979) suggested forty years ago that it lay at 0.958 AU. The Kopparapu et al. (2014) range encompasses all the others and corresponds to present-day illumination at the inner-HZ boundary of 1.08-1.11 times the illumination at Earth's orbit. Using the solar evolution model of Girardi et al. (2000), this level of illumination will move out to the Earth's orbit when the Sun has an age of 5.45-5.74 Gy, i.e. 1.2±0.2 Gy from now.

There is therefore still scope for debate over the exact future duration before solar-evolution produces a Sun too luminous for life on Earth. For now, a composite estimate is that Earth has a Sun-related habitable-lifetime of 6.5±1.0 Gy (but with most estimates lying towards the lower end of this range).

2.5 Future evidence

The study of planetary systems around other stars (i.e. exoplanets) is a rapidly developing field that will soon allow us to directly study the impacts that different sized stars have on their planets. Techniques for estimating the surface temperature and atmospheric composition of exoplanets are in their infancy but, nevertheless, extraordinary progress has been made (Charbonneau et al., 2008; Seager and Deming, 2010; Swain et al., 2009a; Janson et al., 2010; Bean et al., 2010). At present, results are confined to planets that are significantly larger and warmer than Earth but, over the next decade, upcoming space-based telescopes (e.g. Ariel (Tinetti et al., 2018) and JWST (Greene et al., 2016)) will allow these methods to be used for rocky planets only a little larger and warmer than Earth. These studies should show whether atmospheres are retained by bodies orbiting within the HZs of smaller stars and will provide observational constraints for climate models of terrestrial planets at the limits of habitability. These studies may even detect biosignatures (spectroscopic indicators of life) hence giving direct observational data on the masses of stars conducive to life.

3 Our Moon

There is reasonable consensus that the Earth-Moon system formed following a collision between two proto-planets when the solar system was young (see Stevenson, 1987 for a review). The resultant values for Earth-mass, Moon-mass and total angular momentum were set by the details of this collision (i.e. the masses of the impactors, their collision speed and whether the impact was head-on, grazing or something in between). Such collisions are common when planetary systems are young and it is likely that there is a population of Earth-Moon-like systems across the Universe with a range of angular momenta and a range of component-masses. The effects of a different planet-mass will be discussed in later sections on magnetism, plate-tectonics and oceans and so this section will concentrate on the possible habitability consequences of having a different satellite mass and a different total angular momentum to that of the Earth-Moon system.

3.1 Possible benefits

It is frequently argued that the presence of a large moon helps stabilize Earth's axis (Laskar et al. 1993) and, hence, her climate (e.g. Forget, 1998; Williams and Pollard, 2000; Spiegel et al., 2009; Ferreira et al., 2014). However, evidence to support this contention is surprisingly weak.

It is certainly correct that removing the Moon would result in chaotic obliquity for the Earth. Earth's axis is stable because its precession rate of 50 "/y (i.e. period of 26000 years) is *far from the main planetary resonances, the closest being* s_6*=-26.3302 "/y* (Laskar et al., 1993). Removing the Moon would reduce the tidal forces experienced by Earth and, consequently, reduce precession below the 26 "/y threshold for resonant interactions. The resulting instability could lead to obliquity changes as large as tens of degrees over periods of a few million years (Ward, 1982; Laskar and Robutel, 1993). This much is uncontentious but drawing the conclusion, from this, that a large Moon is necessary for habitability can be criticised on multiple grounds:

(1) Planets may have stable climates even if their axes are unstable (Armstrong et al., 2014).
(2) The amount of axial instability may be less severe than suggested (Lissauer et al., 2012).
(3) Moon-free planets are stable if they rotate sufficiently fast (Ward, 1982).
(4) Moon-free planets are stable if they orbit in the HZ of a smaller star (see below).
(5) Moon-free planets are stable if their planetary systems are more widely-spaced and/or consist of less massive planets (Waltham, 2006).
(6) Large moons may cause, rather than prevent, axial instability (Ward, 1982).

The last three criticisms need to be discussed in a little more depth.

To this author's knowledge, criticism (4) has not been previously highlighted. A planet orbiting within the HZ of a different sized star will experience a different stellar-tide and simple calculations show that the total tidal effect of the Sun-Moon combination is identical to that for a moon-free planet orbiting in the HZ of a star with a mass ~0.8 that of the Sun (appendix A). As already discussed, smaller stars are more common than Sun-sized ones and so stable, Earth-like but moon-free, planets orbiting less-massive stars may be more common than moon-stabilized planets around solar-mass stars.

Criticism (5) needs elaboration as it is relevant to a later section in the paper. As discussed above, axial instability sets in once the Earth's precession rate falls below 26 "/y, but this critical-threshold is set by the masses and separations of the remaining planets in the solar system. More specifically, this cut-off would be lower in a system that was more widely spaced and/or had planets of lower mass. A later section will look at the effects of planetary system architecture and this issue will be returned to there.

Coming now to criticism (6); the suggestion that large moons actually cause, rather than prevent, axial instability goes against received wisdom. This under-reported conclusion arises because the tidal drag from our Moon has two important consequences: (i) tidal friction causes slowing of Earth's rotation through time; (ii) differential gravitational attraction to Earth's tidal-bulges causes the Moon to recede from the Earth. Both of these lead, in turn, to a fall in Earth's precession rate through time (e.g. see Berger et al., 1992). Laskar et al. (2004) and Waltham (2015) estimated how the precession rate has changed in the past and this trend will continue into the future so that, in ~1.5 Gy (Ward, 1982), Earth's precession rate will fall below the 26 "/y threshold and our axis will become unstable. The conclusion that Earth's axis will become unstable in the future is not contentious but it has a frequently overlooked corollary; had our Moon been larger, tidal-evolution would have been faster and instability would have set in sooner (Ward, 1982). If everything else was unchanged, instability would have set in already if our Moon's mass had been as little as ~10% larger (Waltham, 2004, 2011) or no more than ~50% larger (Brasser et al., 2013).

There is therefore a contradiction between the perfectly correct statement that removing our Moon leads to instability (and hence large moons stabilize planetary axes) and the equally correct statement that larger moons lead to earlier onset of instability (and hence large moons destabilize planetary axes).

This discrepancy is easily resolved since both ways of looking at the problem are flawed. The first approach effectively models a planet that has a large moon for 4.5 Gy which suddenly disappears; the fact that this unnatural sequence of events leads to instability is not relevant to understanding how real Earth-Moon-like systems evolve. The second approach is also flawed because larger moons are likely to be associated with more energetic collisions and hence larger angular momentum. Increased angular momentum moves the system away from instability and this could more than offset the effect of increased moon-mass. Hence, it is possible that large-moon systems are, after all, more stable than small-moon ones.

A better approach is to model a large number of moon-formation events to directly investigate the frequency of subsequent axial-instability. Figure 3 shows such a model. The crosses on figure 3 are the results of 500 Monte-Carlo simulations over a range of collision conditions. The model which produced these results was taken from Brasser et al. (2013) but with three minor modifications; the model has used the full range of impactor masses (i.e. down to an impactor of size zero), the full range of impact parameters (i.e. from head-on collision to grazing impact) and it explicitly calculates Brasser et al.'s (2013) β-factor for each impact (rather than assuming a constant value of 1.2). The resulting model produces a wide range of outcomes but these are clustered towards moon-masses significantly less than that of our Moon (in agreement with Brasser et al. (2013)).

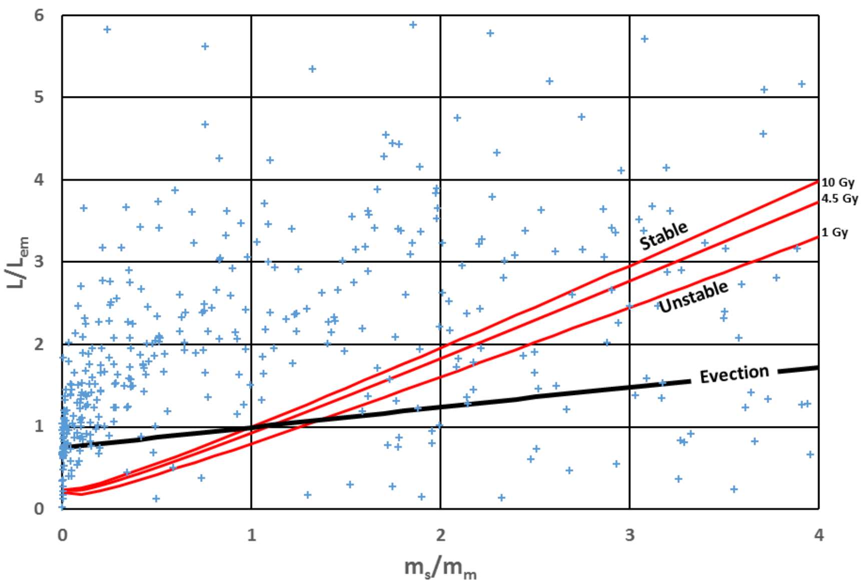

Figure 3. Monte-Carlo simulation of the satellite-masses (m_s) and total-angular-momenta (L) resulting from moon-forming collisions (after Brasser et al, 2013). The actual lunar-mass is m_m and the angular momentum of the real Earth-Moon system is L_{em}. The red lines show the minimum angular-momentum for axial stability after 1, 4.5 and 10 Gy of Planet-Moon evolution (using theory in appendix B). The black line shows the angular-momentum after loss through evection resonance (after Ćuk and Stewart, 2012). Note that angular-momentum loss through evection resonance leads to unstable obliquity for moons much larger than our own.

These model outcomes can be compared to the conditions required for axial stability. The red lines in Figure 3 show the mass/angular-momentum combinations that produce unstable obliquities after 1, 4.5 and 10 Gy of planet-moon evolution (see Appendix B for details). Note that 70% of systems lie above the 4.5 Gy line, i.e. stability for longer than Earth's current age is the usual outcome. However, the chances of retaining stability fall off with increasing moon-mass. Figure 4 shows how the fraction of stable-systems declines with moon-mass and, for systems with moons larger than 2.5 lunar-masses, long-term stability is the exception rather than the rule.

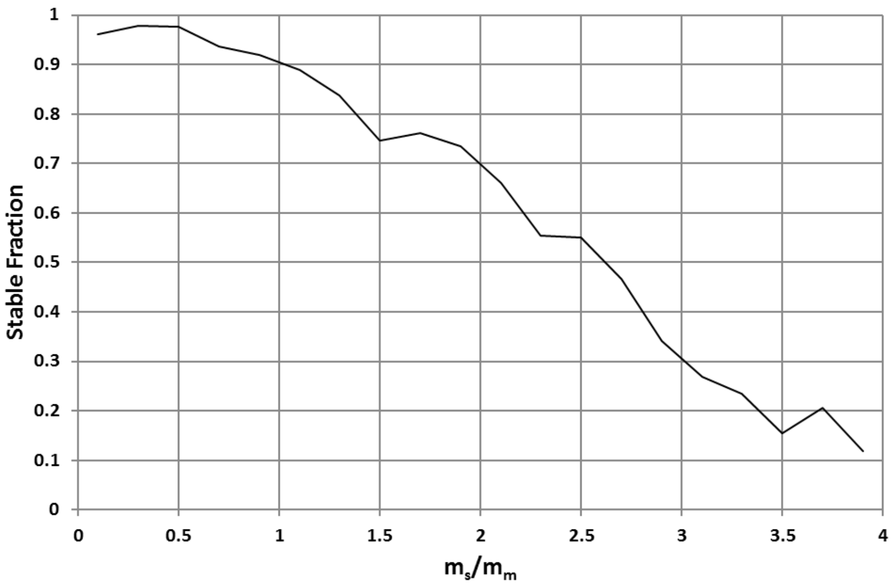

Figure 4. Fraction of moons (after 5000 Monte Carlo simulations) that retain axial-stability for at least 4.5 Gy. Most Earth-moon-like systems have stable obliquity but the fraction drops with increasing moon-mass.

This is not the last word on the topic. Moon-forming collisions sufficiently energetic to explain the almost identical chemistry of Moon and Earth, produce systems with too much angular momentum (Ćuk and Stewart, 2012; Canup, 2012). Hence, to reconcile models of moon formation with geochemical constraints, there must be a mechanism that removes angular momentum (or enhances mixing). Ćuk and Stewart (2012) proposed that angular-momentum loss is a consequence of “evection resonance”—a process that allows angular momentum to be tidally extracted by the Moon from Earth’s rotation and, indirectly, added into the angular momentum of Earth’s orbit around the Sun. This process ceases when Earth’s rotation slows to the point where it is approximately synchronous with the orbital rotation of the Moon (at perigee) since tidal bulges then become stationary, with respect to Earth’s surface, and angular-momentum is no longer extracted from Earth’s rotation. This evection-escape mechanism accurately predicts the observed angular-momentum of the Earth-Moon system (Ćuk and Stewart, 2012). When applied to systems with other moon masses, the approach predicts post-evection angular momentum shown by the black line in Figure 3 (assuming identical parameters to those Ćuk and Stewart used to reproduce the Earth-Moon system). If these evection resonance ideas are correct, systems lying above the black line will lose angular momentum, over ~100 My, until they lie on the line. Note that this predicts that all systems above the line will have their stability-lifetime reduced and that, for moons much larger than a lunar-mass, the resulting lifetimes are short. However, the evection-resonance mechanism is sensitive to its controlling parameters and, hence, the black-line on Figure 3 should only be taken as indicating that evection-resonance reduces the longevity of axial stability and that, for Earth-like planets with moons significantly larger than our own, this tends to result in stability-lifetimes shorter than the present age of the Earth.

In summary, long-term axial stability is more likely in a system with a small moon than in a system with a large one. This effect is enhanced if young planet-moon systems generally loose angular momentum through the evection-resonance mechanism. The proposal that our large moon has been anthropically selected to provide axial stability is therefore not supported by a convincing mechanism.

However, the Moon may have other benefits beyond conferring obliquity-stability. It's formation may, for example, play a role in allowing Earth to have a strong, long-lived magnetic field (Jacobson et al., 2017). Earth's core formed through multistage accretion in which lighter elements became more easily incorporated into core-forming materials as temperatures and pressures increased with planet growth. In addition, variable impactor compositions superimposed fluctuations onto this general trend of increasing light-element abundance. Hence, the core should have formed with a mixture of stable and unstable density stratification but with a preponderance of stable stratification. Relaxation of the rarer unstable regions then led to a core made of concentric shells (containing smoothly decreasing density with radius) separated by sharp drops in density. Such a density structure is highly stable and does not easily allow the large scale convection required to explain Earth's magnetic field. However, in Earth's case, core-stratification may have been disrupted by the late, large impact that formed our Moon. A strong, long-lived magnetic field could, in turn, be necessary for habitability (see section 6). Furthermore, it's possible that the Moon also plays an on-going role in generating our magnetic field (see section 6).

The moon-forming collision would also have disrupted the density stratification of Earth's mantle. Without this mixing, convection of the mantle might also have been supressed, leading to an absence of plate tectonics—a process likely to be important for Earth habitability (see section 7).

Finally, the Moon-forming collision must have affected the thermal and volatile-expulsion history of our planet and these will have had important consequences, e.g. through altered atmospheric composition, water volume and volcanism. It is not unreasonable to suggest that, without these changes, Earth would have been a very different planet and, possibly, one where complex life was less likely.

Given all these consequences of the moon-forming collision on our core, mantle and volatile budget, the idea that it conferred habitability benefits--other than axial-stability--is plausible. This possibility will be important later in this section.

3.2 Frequency

Earth is the only terrestrial planet in the Solar Systems with a large moon. However, four such planets is too small a sample to demonstrate that large moons are rare. The binomial distribution shows that the probability of a large moon must exceed 33% before the chances of seeing one planet, out of four, with a moon is less likely than that of seeing multiple planets with moons. The probability has to exceed 85% before it becomes unlikely (at 1% significance) that only one planet with a moon would be seen. Thus, the only inference that can be drawn, from the fact that Earth is the only terrestrial planet in the Solar System with a large moon, is that large moons probably orbit less than 85% of such worlds; this is hardly strong evidence for rarity.

Furthermore, moons can be lost by outward tidal-evolution beyond the gravitational influence of their planet or by inward tidal-evolution followed by collision (Barnes and O'Brien, 2002; Sasaki et al., 2012). It is therefore possible that Mercury and Venus, in particular, had moons when young which are now lost (Ward et al., 1973; Rawal, 1986). Thus, even within the Solar System, terrestrial planets with large moons may have initially been more common than they now appear. It is also notable that three of the four brightest Kuiper Belt objects (KBOs) are binary (Brown et al., 2006) and that these may have formed through collision (Canup, 2005). This implies that the mechanism that probably produced our Moon is commonplace; a conclusion reinforced by numerical models of young planetary systems which indicate that 2-25% of terrestrial planets should have moons at least half the mass of our own (Elser et al., 2011).

Hence, at present, there is no convincing evidence that terrestrial planets with large moons are rare enough to imply, on its own, an anthropic-selection explanation for Earth's large moon.

3.3 Fine tuning

If, for sake of argument, we accept that a large moon is good for something (without specifying what), then Fig 3 does show evidence for fine tuning. As already noted, the evection line crosses the stability line at ~1.1 lunar masses and, hence, our Moon is nearly as large as it could possibly be without causing unstable obliquity. The simulation used to generate Figure 3 shows that ~2% of simulated moons come even closer to this evection mass-limit without exceeding it. This is suggestive but not quite rare enough to provide convincing evidence, on its own, of anthropic selection for a large moon, i.e. we seem to have the maximum possible benefit (e.g. maximum core-mixing if that is important) consistent with obliquity stability.

3.4 Lifetime

The stability lines shown in Fig 3 migrate upward through time so that, as already discussed, the Earth's obliquity will become unstable in the distant future. Hence, if it is accepted that this instability will result in a climate varying too rapidly for complex life, there is a habitability lifetime associated with our Moon. Ward (1982) estimated the time until instability as 1.5 Gy, a figure confirmed by the more detailed calculations of Néron De Surgy and Laskar (1997), although this later paper also considered the effects of uncertainty in the long-term tidal dissipation rate and concluded that the time to instability could be as long as 4.5 Gy. Hence, Earth has a Moon-related, habitable lifetime of 7.5±1.5 Gy after formation.

3.5 Future evidence

The Brasser et al. (2013) model used for the Monte-Carlo simulation in Figure 3 was based upon scaling relations derived from “smooth particle hydrodynamic” simulations of moon-forming collisions (Cameron, 2000; Kokubo et al., 2000; Williams and Pollard, 2000; Canup and Asphaug, 2001; Canup, 2012). It would therefore be sensible to directly use these primary models themselves, in a similar analysis, rather than the derived scaling laws. Unfortunately, published results from these models are largely confined to “successful” results which approximately reproduce the Earth-Moon system. Hence, a very simple step forward would be for all results from such simulations to be released.

Another area for further research would be in comparative studies of binary-asteroids and binary-KBOs to investigate their mass/angular-momentum distributions and whether processes such as Ćuk and Stewart's (2012) evection-resonance mechanism are ubiquitous.

However, even more relevant observational constraints of moon-forming collisions would be produced if it was possible to discover Earth-Moon-like systems around other stars. Proposals for spotting exomoons have been made (e.g. Sartoretti and Schneider, 1999; Szabó et al., 2006; Kipping, 2009; Kipping et al., 2012) and searches undertaken (Kipping et al., 2013b, 2013a, 2014, 2015; Teachey et al., 2017). Recently, Teachey and Kipping (2018) have announced the discovery of a possible exomoon candidate orbiting the exoplanet Kepler 1625b. Their observations are compatible with a Jupiter-sized planet orbited by a

Neptune-sized moon but their data could conceivably be reproduced by additional exoplanets in the system or by chance fluctuations in the data. Thus, to make this discovery firm, it will be necessary to observe more transits. Plans to undertake additional observations using the Hubble Space Telescope are under consideration at the time of writing and, if they go ahead, will occur in May 2019. Interestingly, the proposed Kepler 1625b system is in some senses a scaled up version of the Earth-Moon system (i.e. the planet radius, moon radius and planet-moon separation are all of order 10-times larger) and so it is conceivable that it could shed light on the formation and tidal evolution of the Earth and Moon. Current models for the origin of giant-planet moons involve condensation of a circum-planetary disk (Mosqueira and Estrada, 2003) or capture (Nesvorný et al., 2007) and these do not easily account for the proposed properties of the Kepler 1625b system. An intriguing possibility, suggested in Teachey and Kipping (2018), is that it formed by collision between two giant planets i.e. by an analogous process to that proposed for the Earth-Moon system.

4 Solar System architecture

This section considers the masses and locations of the other planets in our Solar System. Planets influence the Earth in two major ways; they affect her impact history and they perturb her orbit and spin-axis.

4.1 Possible benefits

Mass extinction events have been linked with large impacts (Alvarez and Muller, 1984; Hut et al., 1987; Schulte et al., 2010) although this remains controversial with other explanations such as flood-volcanism also being implicated (see Wignall, 2001 and Bond and Grasby, 2017 for reviews). Nevertheless, it is undeniable that sufficiently large impacts would cause catastrophes. Furthermore, the fossil record indicates that it takes around 10 My for biodiversity to recover from mass-extinctions (Kirchner and Weil, 2000; Sahney and Benton, 2008). Hence, if Earth had typically suffered major bombardments more often than once every 10 My, her biodiversity would probably have been severely reduced which, in turn, would have made the eventual emergence of intelligent observers unlikely.

On the other hand, challenging conditions may help to encourage evolutionary innovation. This idea is supported by paleontological evidence such as the emergence of *Homo sapiens* during the climatically unstable Neogene (Calvin, 1991, 2002; Stanley, 1998) and the emergence of metazoans around the time of the late Neoproterozoic glaciations (Breyer et al., 1995; Wray et al., 1996; McNamara, 1996; Fedonkin and Waggoner, 1997).

There is, therefore, no simple relationship between impact frequency and the likelihood of observers but it remains plausible that very frequent impacts would be deleterious. Given this, it is often stated that Jupiter acts as a “shield” that collects stray bodies in the Solar System that might, otherwise, have collided with Earth. This suggestion became particularly popular following the collision of comet P/Shoemaker-Levy 9 with Jupiter in 1993 (Weaver et al., 1994). However, modelling studies (Laakso et al., 2006; Horner and Jones, 2008, 2009; Horner et al., 2010; Grazier, 2016) show that, whilst giant planets do indeed sweep-up many comets and asteroids, they are also responsible for deflecting those bodies out of stable orbits in the first place. On balance, these papers suggest that the shielding effects of the giant planets are roughly cancelled by their perturbation effects and so there is no strong net-benefit. A further complication is that, for some giant planet configurations, deflections are so strong that the population of potential colliders become rapidly depleted and the long-term impact flux is actually reduced (Horner and Jones, 2012). In summary, it is hard to demonstrate conclusively that Jupiter has had the overall effect of reducing the incidence of mass-extinction-level impacts.

A distinct issue is that impacts had constructive influences on the early Earth. The young Solar System had a very different architecture to that seen today, because the major planets initially migrated considerable distances as the planets interacted with each other and with the disk from which they formed (Gomes et al., 2005; Tsiganis et al., 2005; Walsh et al., 2012). This shuffling of the planets perturbed potential impactors into the inner Solar Systems and produced, for example, the "Late Heavy Bombardment" (Wetherill, 1975) responsible for the major impact structures still visible on our Moon (but note that the concept of a late heavy bombardment has been challenged recently (Boehnke and Harrison, 2016; Nesvorný et al., 2018). This period of high impact flux must have affected Earth too and may have frustrated the origin of life for a considerable period of time (Maher and Stevenson, 1988). However, even more importantly, these impacts were probably responsible for delivering water to the young Earth. Jupiter, in particular, may also have influenced the early Earth by limiting the supply of ice-grains in the inner solar system (Morbidelli et al., 2016). This resulted in the inner planets being relatively small and dry. A larger, wetter Earth would experience much higher pressures at the ocean floor leading to the formation of ice-VII (or possibly ice-VI) that would have cut the ocean off from the nutrient rich crust (Noack et al., 2016). Note that Earth's oceans are discussed, in more detail, in section 5.

In terms of present-day effects; the architecture of a planetary system controls the speed at which eccentricities and orientations of orbits change with time (Spiegel et al., 2010). These "secular frequencies" can be calculated, to first order, using a simple linear approximation developed by Laplace and Lagrange 200 years ago (Murray and Dermott, 1999) but more accurate estimates are now produced through numerical integrations (e.g. Laskar et al., 2011). Combinations of these frequencies, and the precession frequency of Earth's spin axis, give rise to the Milankovitch climate cycles (see Hinnov, 2000) for a review) and these may directly influence habitability. However, more critically, resonant interaction between these secular frequencies and planetary precession can produce chaotic obliquity (Laskar and Robutel, 1993). In Earth's case, as discussed in the section on lunar mass, our precession frequency is significantly faster than any secular frequencies and obliquity is stable but, in a planetary system with high mass planets or planets which are closer together, the secular frequencies would be faster and an Earth-like system would have unstable obliquity. Thus, there may be anthropic selection for the Solar System to be unusually light or widely spaced (Waltham, 2006).

One final aspect of the Solar System needs to be considered—orbital eccentricities. The low eccentricity of most planets may help to stabilize the solar system since it prevents planets from making close approaches to one-another (Laskar, 1996). In addition, the generally low eccentricities help prevent Earth from being perturbed into a high-eccentricity orbit and this may, in-turn, be necessary for avoiding extreme seasonality (Dressing et al., 2010). For example, Pilat-Lohinger (2009) shows that any small planet orbiting in the HZ, of the star HD143361, would have a chaotic orbit if the eccentricity of its known, 3-Jupiter-mass planet is greater than about 0.3. Similarly, numerical modelling by Horner et al. (2015)

demonstrate that increasing Jupiter's eccentricity to 0.2 has the effect of perturbing Earth's orbit into eccentricities as high as 0.25.

In summary, the masses and locations of the other planets (particularly Jupiter) have profound consequences for the impact and climate history of Earth but the details are highly complex and no simple picture emerges. Tentative predictions are that planetary systems are more habitable if they have low-mass planets in widely-spaced, low-eccentricity orbits.

4.2 Frequency

In principle, thanks to the recent discovery of thousands of exoplanets, the predictions from above can be directly compared to observations, i.e. we can compare the Solar System to other planetary systems to see if it does indeed look unusually light, big and circular.

Unfortunately, exoplanet detection methods are highly biased and this must be allowed for. The two most successful techniques—the radial velocity (Mayor and Queloz, 1995) and transit (Henry et al., 2000) methods—are much more sensitive to large, close-in planets than to smaller worlds further from their stars. Gravitational microlensing (Bond et al., 2004), on the other hand, is most sensitive to planets orbiting at Jupiter-like separations. Hence, the raw data from any given survey is not suitable for comparing to the Solar System and attempts must be made to correct for the inherent biases.

I will start with eccentricity since there are no strong biases associated with that parameter (Butler et al. 2006; Shen and Turner, 2008). The only correction required is that very close-in planets must be excluded from the analysis because their orbits are circularized by tidal interactions. The results of Butler et al. (2006) were based upon 168 nearby exoplanets and show that, for planets further from their star than 0.1 AU, eccentricities range between 0.0 and 0.8. More recent studies (Wang and Ford, 2011; Kipping, 2013) indicate that a uniform distribution does not fit the data as well as probability distributions that reduce at higher eccentricities although, even then, the distribution is wide compared to the eccentricities seen in the Solar System.

A complication is that a number of studies now strongly suggest that there is a dichotomy in eccentricity distribution with single-planet systems tending to have relatively high eccentricities whilst multi-planet systems have eccentricities comparable to those of the solar system (Wright et al., 2009; Winn and Fabrycky, 2015; Xie et al., 2016). Xie et al. (2016) also shows that the mutual inclinations of the orbits in the Solar System are similar to those of other multi-planet systems. However, this dichotomy is probably the result of an observational bias; we will only see multiple transiting planets in systems where the mutual inclinations are relatively small and low-inclination systems are also likely to exhibit smaller eccentricities (Izidoro et al., 2017).

In summary, Solar System eccentricities are significantly smaller than those seen in exoplanet systems with only one, known planet but we cannot yet be sure that this is also true for multiple-planet systems.

The next property that can be looked at is the size (i.e. mass and/or radius) distribution of the Solar System's planets. Here, I will concentrate on radius rather than mass because that allows us to include the Kepler dataset which accounts for a large fraction of all currently known exoplanets. The size distributions for exoplanets have been looked at most recently by Youdin (2011), Dong and Zhu (2013), Batalha (2014), Morton and Swift (2014), Malhotra (2015) and Suzuki et al. (2016) using a variety of different detection methods and a range of statistical techniques to remove biases. The first bias that needs to be accounted for is that transits of small planets are more likely to be hidden by noise than the transits of larger planets. However, as discussed by Youdin (2011) and Morton and Swift (2014), the Kepler mission probably captured the majority of transits for planets larger than 2 earth-radii. This leads to a more subtle bias; it is possible that the majority of planetary systems have a largest planet that is too small for Kepler to see and so we may be comparing the Solar System to a biased sample of planetary systems self-selected to have unusually large planets. Thus, any indication that the Solar Systems planets look unusually small must be treated with caution. Another issue is that, as discussed by Dong and Zhu (2013), short period planets (period <10 days) of size 4-8 earth radii are relatively rare but this feature disappears for longer periods.

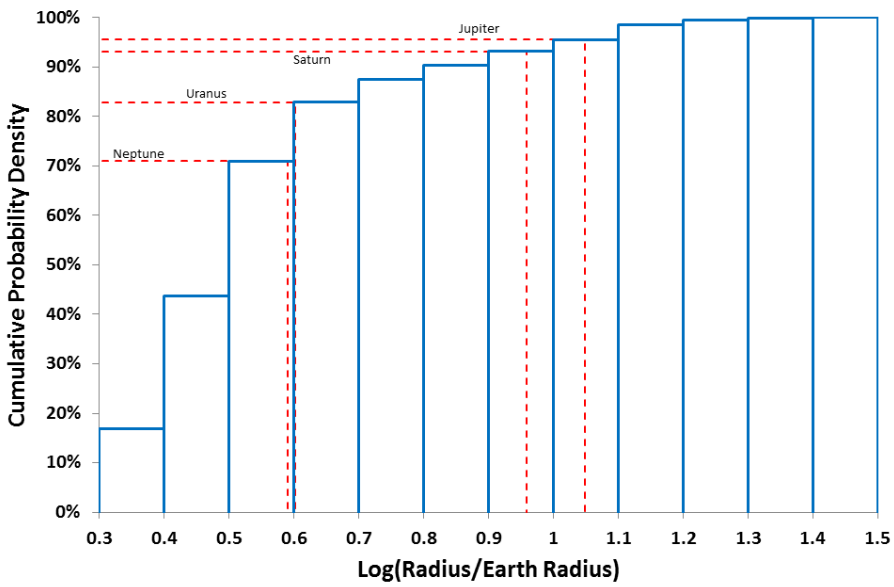

Figure 5. The cumulative probability of exoplanet radii (larger than twice Earth-size) along with the radii of the giant planets in the Solar System (data from exoplanet.eu on June 12th 2018). There is little evidence that our giant planets are either unusually small or large.

Given these biases, Figure 5 shows the cumulative probability of exoplanets larger than 2 Earth-radii and with periods greater than 10 days. This was estimated using 1350 confirmed-planets in the exoplanet.eu on-line catalogue of June 12th 2018. Figure 5 also shows the radii of the Solar System's giants. Jupiter is larger than 96% of all planets included here and so the bias of Kepler data towards planetary systems with large components is not an issue since, even with this possible bias, Jupiter does not look small. Neither is Jupiter sufficiently large to provide strong evidence that there has been selection for large (rather than small) planets although this cannot be ruled out; 4% of the planets considered here are bigger than Jupiter, a fraction small enough to be interesting but not small enough to be convincing evidence of anthropic selection effects. This may change with more sensitive surveys in the future since they may allow us to include a more representative sample of planetary systems. However, for now, the conclusion is that the giant planets of the Solar System are not unusually small but it remains possible that they are moderately large.

Finally, we should consider the frequency of planetary systems having large planets at comparable distances from their star as Jupiter, Saturn, Uranus and Neptune in the Solar System. This cannot easily be done using radial-velocity or transit surveys since these are heavily biased towards close-in planets. However, gravitational micro-lensing approaches are sensitive to planets at the appropriate distances (Griest and Safizadeh, 1998). Thus far, 77 exoplanets have been detected using this approach (exoplanet.eu catalogue on June 12th 2018) with distances from their star ranging from 0.05 AU to 40 AU. Statistical analysis of the subset of "high-magnification" microlensing events of non-binary stars suggests that, if all non-binary stars had planetary systems similar to the Solar System, then 18 planets should have been found from the 13 observed high-magnification events (Gould et al., 2010). In fact, just six planets were found. This suggests that one planetary system in three has large planets in wide orbits. More recently, Suzuki et al. (2018) reported 2 planets orbiting the star OGLE-2014-BLG-1722 using a low-magnitude microlensing event and, based upon this, they propose that 6±2% of stars host two cold (i.e. distant) giant planets. Thus, on the present rather thin evidence it looks as if planetary systems, with giant planets as widely spaced as the Solar System's, are mildly unusual at roughly the 10% level.

4.3 Fine tuning

Waltham (2011) attempted to demonstrate that the particular configuration of planets in the Solar System produces unusually slowly varying orbits and, hence, a relatively stable climate for Earth. An interesting conclusion was that Jupiter's orbital size is within 0.8% of the optimum value for minimizing the secular frequencies of the Solar System. However, this study used the 200 year-old linear approximations of Laplace and Lagrange rather than modern numerical simulations. More recent work (Horner et al., 2015) using the MERCURY simulation package (Chambers, 1999) undermined the Waltham (2011) result by showing, instead, a monotonic tendency for orbits to be better behaved as Jupiter is moved closer to the Sun.

An alternate approach to the problem is to consider the dynamic evolution of exoplanetary systems to see if the Solar System appears to be unusually stable. Studies have also been undertaken to see if an Earth-like planet in the HZ of known exoplanetary systems would be able to maintain low eccentricity (e.g. see Dvorak et al., 2003). These studies generally support the contention that a Solar-System-like level of stability is not difficult provided planets have moderately low eccentricity, avoid commensurable orbits (i.e. orbits whose period-ratios are simple fractions) and are not too closely packed. In addition, any systems where these conditions are not met will tend to evolve rapidly until they hit configurations where the conditions do hold (e.g. by expelling planets that are too close to one another (Laskar, 1996) although this tends to push remaining planets onto eccentric orbits).

In summary, current evidence does not strongly support fine-tuning of the Solar System's architecture to produce slowly-varying, or unusually stable, orbits.

4.4 Lifetime

The timescale over which the Solar System's architecture remains stable is not easy to determine. As a result of the chaotic nature of planetary evolution, position uncertainties of a few centimetres grow to planetary-orbit size within 10s of My and, hence, it is not possible to predict the positions of the planets further into the future than this (Laskar, 1989; Laskar, 1996; Varadi et al., 2003; Laskar et al., 2004). However, by modelling ensembles of Solar Systems in which the initial setups are varied very slightly (e.g. changes in eccentricity of 10^{-9} as used in Laskar, 1996) it is possible to investigate, statistically, how probable it is that the orbits of each of the planets will change dramatically (leading, possibly, to escape or collision) over billions of years.

The resulting numerical models indicate that Mercury's orbit can become highly eccentric on time scales of 5 Gy but only in around 1% of simulations (Laskar, 1996; Ito and Tanikawa, 2002; Laskar, 2008; Laskar and Gastineau, 2009). Even more dramatically, in one simulation out of 2501, Laskar and Gastineau (2009) found that Mercury's high eccentricity induced instability in the orbits of all the terrestrial planets leading to the possibility that Mercury, Mars or Venus could collide with Earth. However, these were the most extreme cases; in most of the simulations Mercury's eccentricity remained smaller than 0.4 and no dramatic consequences unfolded. The eccentricities and inclinations of all other planets remain small on these timescales and one recent study (Zeebe, 2015) indicates that even the long-term instability of Mercury's orbit may be significantly less severe than previously thought. Hence, the Solar System appears to be stable for at least another 5 Gy.

Unfortunately, as a consequence of the computational intensity of these simulations, it has not yet been possible to extend full-simulations more than 5 Gy into the future. However, Ito and Tanikawa (2002) did investigate the stability of the outer planets (Jupiter to Pluto) over the next 50 Gy and no serious instabilities were discovered. Given that such long-term modelling has not yet been attempted with the inner planets included, all that can be stated is that the orbital-stability lifetime of Earth is, at least, of the order of 10 Gy and, possibly, much greater than this.

4.5 Future evidence

The most important future evidence is likely to come from exoplanet studies. As our instruments become more sensitive, as we concentrate on closer, brighter stars through missions such as TESS (Ricker et al., 2014), or PLATO (Rauer et al., 2016), and as we increase our total observing time (hence spotting planets with longer orbital periods) our catalogue of planetary systems will become more complete and less biased. In addition, space telescope concepts currently under development will, if they go forward, allow direct imaging and spectroscopy of exoplanets (e.g. LUVOIR (Aloezos et al., 2017) and HabEx (Mennesson et al., 2016)). This will allow many of the analyses discussed above to be revisited. Incremental improvements in computational power will also be useful as they will allow investigation of Solar System stability over increasing timescales.

5 Oceans

This review now moves onto a relatively uncontentious example of anthropic selection—the fact that Earth has the right composition, and orbits at the right distance from the Sun, to allow liquid water on her surface. This section assumes that observers are carbon-based life-forms whose key biochemical reactions take place in water-based solvents. It is likely that most, if not all, life elsewhere in the Universe is based on these principles since the chemistry of life is the chemistry of the cosmos (see review by Ehrenfreund and Charnley (2000)), i.e. water is probably the most common fluid and carbon-chemistry is ubiquitous in inter-stellar clouds, meteorites and in the atmospheres of many worlds. However, in the unlikely event that Earth is peculiar in this regard, she must still have properties compatible with our own existence and so an environment suitable for water/carbon-based lifeforms remains the relevant starting-point for discussion of Earth's peculiar attributes.

It is much less clear how important it is that the liquid water is on the surface rather than beneath it. A number of icy-moons (e.g. Enceladus and Europa) have oceans in their subsurface (Cassen et al., 1979; Squyres et al., 1983; Hansen et al., 2006) and there are no incontrovertible reasons why such an environment should not be capable of producing life and, ultimately, intelligent observers (but see discussion in Stern, 2016). Nevertheless, as with the discussion of carbon/water-based life, we must see conditions compatible with our own existence and Earth's observers do live on her surface. Hence, there may be an anthropic bias towards properties that allow surface liquid water.

Given this background, there are a number of separate conditions that must be satisfied to produce a wet, rocky world. Firstly, there must be a mechanism to deliver water to the planet, after it has largely formed, since terrestrial planets accrete inside the "snow-line", i.e. too close to their stars to allow condensation of volatiles such as water and carbon dioxide (see Righter and O'Brien, 2011 and Morbidelli et al., 2012 for reviews of terrestrial planet formation). Secondly, the planet must be at the right distance from its star to allow surface temperatures compatible with liquid water, i.e. the planet must be within the habitable zone (Huang, 1959; Kasting et al., 1993). Note, however, that the exact location of the HZ is affected by factors such as atmosphere composition, planet mass and spin-rate (Pierrehumbert and Gaidos, 2011; Yang et al., 2013; Abe et al., 2011; Kopparapu et al., 2014). Finally the planet must have all properties that allow long-term retention of an atmosphere such as sufficient mass and, possibly, attributes such as plate-tectonics and magnetism (discussed in sections 6 and 7 below).

5.1 Possible benefits

Any chemistry-based life is likely to require a solvent as a medium for its chemical reactions as well as a fluid for transport of nutrients and removal of waste products. Water has many advantages in these roles. Firstly, it is an extremely common compound in the Universe since it is composed of the most abundant element (hydrogen) and the third most abundant (oxygen). Hence, water is likely to be one of the most common molecules. This expectation is fully justified by detections of H_2O in meteorites (Mason, 1972), on the planets/moons of the solar system from Mercury (Slade et al., 1992) to Pluto (Grundy et al., 2016), in interstellar clouds (Herbst, 1995) and in the atmospheres of exoplanets (Tinetti et al., 2012).

Furthermore water's polar nature makes it an extremely effective solvent of ionic compounds but a relatively poor solvent of organic molecules (Schulze-Makuch and Irwin, 2008); these properties are vital for allowing many of the key reactions of life (e.g. photosynthesis, the Krebs cycle and DNA replication) within a cell that is not dissolved by its own contents. Furthermore, water can be found in the liquid state across an unusually wide range of temperature and pressure conditions (Schulze-Makuch and Irwin, 2008) and this property has allowed Earth-life to colonize our planet in environments ranging from the low-pressure, low-temperature tops of mountains through to high temperature, high pressure deep-sea thermal vents; in fact, we find life nearly everywhere there is liquid water (Rothschild and Mancinelli, 2001) with the only known limits to this being associated with very high salinity (Grant, 2004).

Water may also play a role in climate stabilization. The high thermal capacity and latent heats for water mean that relatively large amounts of heat loss (or gain) produce relatively small changes in temperature (Schulze-Makuch and Irwin, 2008). However it should also be noted that, through ice-albedo positive-feedback, water contributes to the sharp glacial-interglacial climate swings of the Quaternary (Sellers 1969; Budyko, 1969) and may have been responsible for even more dramatic climate jumps during Neoproterozoic glaciations (Hoffman et al., 1998). Water-vapour feedback may also be positive (e.g. see Dessler et al., 2008) although the role of clouds remains unclear (Bony et al., 2015; Tan et al., 2016). On longer timescales, water is central to the silicate-weathering cycle which may be the key factor in enabling climate stability on multi-million-year scales (Walker et al., 1981; Berner et al., 1983; Berner and Berner, 1997). Finally, water dissolved in Earth's mantle may be a key ingredient in enabling plate tectonics. This issue will be considered in section 7 below.

In summary, the suggestion that liquid water was a necessary precondition for the emergence of observers is strongly supported by diverse lines of argument.

5.2 Frequency

Water is found in every body of the Solar System except the Sun. Mercury has water-ice in the shadowed parts of its polar craters (Slade et al., 1992), Venus has water in its clouds (Cottini et al., 2012), Mars has water at its poles and in the subsurface (Head et al., 2003) whilst the gas giants contain water in their atmospheres (Bergin et al., 2000). Comets contain a significant fraction of water (Mumma et al., 1986) as do many of the Solar Systems moons (Cassen et al., 1979; Squyres et al., 1983; Hansen et al., 2006). Even the rocks of our own Moon—one of the driest bodies in the Solar System—have been found to contain a little water (Hui et al., 2013) and surface-ice has recently been confirmed within the permanent shadows of her polar craters (Li et al., 2018). Beyond the Solar System, the newly emerging field of exoplanet spectroscopy has already found water in the atmospheres of, for example, HD189733b (Swain et al., 2009b), HD209458b (Swain et al., 2009a), two planets orbiting HR8799 (Konopacky et al., 2013), WASP-43b (Kreidberg et al., 2014) and HAT-P-11b (Fraine et al., 2014).

Earth is therefore not unusual in having water. But, she may be unusual in retaining significant amounts of liquid water on her surface over several billion years. There is clear evidence that Mars had flowing surface water in the distant past (Jakosky and Phillips, 2001) and, even today, has occasional, small, briny, ephemeral flows (McEwen et al., 2014) but, nevertheless, any seas, rivers or lakes that Mars once had, disappeared at least 3 billion years ago. Venus, too, seems to have had significantly more water when young–as demonstrated by her high D/H ratio (Donahue et al., 1982)—but surface conditions are now far too warm and her atmosphere has been desiccated by photo-dissociation of the water molecules and subsequent loss to space of the hydrogen.

The reasons Earth has always maintained a climate suitable for liquid water remain the subject of active discussion. It is possible that negative climate feedback processes (e.g. Walker et al., 1981) are sufficiently strong to completely explain this. It is also possible that biospheres necessarily stabilize their climates (i.e. the Gaia hypothesis (Lovelock and Margulis, 1974)) but, while progress has been made in finding a theoretical basis for the Gaia hypothesis (e.g. see Lenton et al., 2018), it remains highly contentious (e.g. see Tyrrell, 2013). It has recently been argued that the evolution of siliceous organisms destabilized the Phanerozoic climate (Isson and Planavsky, 2018) and, if true, this would present a concrete example of an anti-Gaia process. It is also possible that long-term climate stability is an anthropically selected property that happened on Earth purely by chance (Waltham, 2014).

Regardless of these on-going debates, it is widely accepted that biological and geological processes have changed Earth's atmosphere and reflectivity, hence keeping the climate cool despite gradually increasing solar insolation (e.g. Lovelock and Margulis, 1974; Walker et al., 1981; Berner et al., 1983; Berner and Berner, 1997; Schwartzman, 2002; Lenton and Watson, 2011; Isson and Planavsky, 2018).

Another question is whether delivery of volatiles (such as water) to the rocky, inner planets of a planetary system is a common process or an unusual property of our own system. It is believed that rocky planets form too close to their stars for them to contain any primary water and that this is, therefore, delivered later in their history as a result of collisions with asteroids and comets sourced from further out (Morbidelli et al., 2000; Raymond et al., 2004). In early studies it proved difficult to model an evolutionary history for the Solar System which simultaneously reproduced planetary masses (especially Mars), planetary locations, asteroid-belt structure and the water content of Earth (Raymond et al., 2009). A major step forward was the realization that Jupiter and the other giant planets probably migrated (as a result of gas-drag in the protoplanetary disk) until Jupiter reached about 1.5 AU at which point resonant-interaction with Saturn caused a change to an outward migration (Morbidelli and Crida, 2007) in what has come to be called the "Grand Tack". This scenario has the effect of concentrating protoplanetary disk material into the region within 1 AU of the Sun which, in turn, reproduces the observed low Mars-mass and many of the features of the Asteroid belt (Walsh et al., 2011). The migrating giant planets also perturbed small bodies, formed across the Solar System, into the inner regions and, hence, delivered water to the terrestrial planets (O'Brien et al., 2014; Raymond and Izidoro, 2017). The Grand-Tack therefore simultaneously explains many important features of our Solar System. Other successful planetary-formation models are now coming forward such as Levison et al.'s (2015) terrestrial-planet model and the "pebble-accretion" model for the giant-planets (see review by Johansen and Lambrechts, 2017) but these models, too, invoke planetary migration and involve scattering of outer Solar-System bodies into the near-Sun region.

In addition, further scattering may have taken place a little later in the Solar System's history. For example, at around 700 My (or perhaps as early as 100 My (Nesvorný et al., 2018)) after Solar System formation, the orbits of Uranus and Neptune destabilized and this instigated a new phase of giant-planet migration known as the Nice Model (Tsiganis et al., 2005). This event, too, sent water-rich planetesimals into the inner Solar System (Gomes et al., 2005).

Hence, there are many processes which are likely to have caused scattering of grain-sized to asteroid-sized icy-bodies into the inner Solar System during its first few hundred million years. Moreover, such processes are believed to be ubiquitous in young planetary systems suggesting that "whenever a giant planet forms it invariably pollutes its inner planetary systems with water-rich bodies" (Raymond and Izidoro, 2017; O'Brien et al., 2014). The implication is that water is probably common on rocky planets although, as discussed in section 4, there is a potential habitability problem when planets have too much water (Noack et al., 2016), an outcome that is likely to occur on many worlds.

In summary, rocky planets that are wet when young are probably common but it is not yet clear whether Earth is unusual in retaining her liquid water across billions of years and unusual in having only partial coverage by water.

5.3 Fine tuning

The volume of surface water on the Earth ensures that our planet is neither dominated by land nor sea but, instead, has reasonably large fractions of both. More remarkably, the height of sea level compared to the continents has been maintained to within a few hundred metres through much of Earth's history (Wise, 1974). This "constant freeboard" has occurred despite factors that should have substantially altered sea levels such as growth of the continents, decreasing geothermal gradients, outgassing of the mantle and subduction of hydrated-slabs (Eriksson et al., 2006; Korenaga et al., 2017). Earth's mantle is thought to contain 0.25-4 times as much water as the surface oceans (Hirschmann, 2006; Nakagawa and Spiegelman, 2017) and subduction adds to this at the rate of one ocean-volume every few billion years (Ito et al., 1983). Hence, mantle outgassing must have balanced the subduction-losses quite closely otherwise substantial changes in ocean volume would have occurred over Earth's history. For example, modelling by Rüpke et al. (2004)—in which outgassing and subduction rates are controlled by evolving mantle heat production—predicts imbalances between sources and sinks of surface water giving changes in sea level of up to a kilometre within just the last 600 My.

Hence, there are two distinct ways in which fine-tuning may be necessary to explain Earth's long history of maintaining both land and ocean at her surface: (i) Earth may have needed just the right amount of water and (ii) the outgassing rate should have always been close to the rate of subduction losses.

But is the maintenance of both land and ocean important for habitability? A reasonably large fraction of both land and ocean may be necessary to allow the silicate-weathering cycle to operate and, hence, for Earth to maintain a stable climate (Walker et al., 1981; Berner et al., 1983). More generally, greater water depths reduce the area of continent available for weathering whilst a drier planet reduces the amount of water available to mediate formation of carbonate. However, the few studies undertaken on the effect of water-coverage on climate indicate either that habitability is monotonically enhanced as ocean-area increases (Franck et al., 2003) or—in direct contradiction—that it monotonically falls as ocean-area increases (Abe et al., 2011). Abbot et al. (2012), on the other hand, conclude that the effect is minimal unless there is no land at all. Thus there is neither consensus on the effect of ocean-coverage nor any indication that Earth's ocean-coverage is optimal.

Alternatively, a planet with only partial coverage by oceans may be important because it allows nutrients to be weathered from the land and washed into the ocean (Maruyama et al., 2013). This not only makes a greater range of nutrients available but also provides mechanisms for concentrating them. Nutrient availability, in turn, would have been essential for the origin of life (however it happened) and also to allow its spread across the planet.

However, it may not be necessary to find an anthropic explanation for the amount of water in our oceans. Kasting and Holm (1992) suggested that ocean volume is controlled by the depth to which subducting plates are hydrated and that this, in turn is controlled by the efficiency of ridge hydrothermal circulation. When water depths are shallow, outgassing of mantle water exceeds subduction-losses and ocean volume expands until water depth above ridges is deep enough to substantially enhance hydrothermal circulation (convection becomes more rigorous as pressures within the ridge approach the critical point of seawater). The necessary water depth of 2.5-3.0 km above typical ridges would then fix sea level as being close to the continental shelves. These conclusions have been supported by the more recent study of Cowan and Abbot (2014) which also showed that this mechanism would operate to produce a partially flooded planet for a wide range of planet masses and initial water-inventories. Furthermore, Kasting et al. (2006) proposed that this model, along with slightly shallower water depths in the distant past, accounts for the anomalously low Oxygen-18 levels of ancient sediments and cherts. The fact that an otherwise puzzling change in the $\delta^{18}O$ of ancient sediments is accounted for by the Kasting and Holm (1992) hypothesis is additional circumstantial evidence in its favour.

In summary whilst it is possible that Earth has been fine-tuned to have a long history of land plus ocean, the evidence to support this contention is currently weak.

Another way in which there could be fine-tuning for liquid-water is in the position of Earth's orbit within the HZ (defined for this purpose as the locations where liquid water is possible at some point during the Sun's main-sequence lifetime; note that this differs from the normal definitions that concentrate either on the present-day locations or on the "continuously habitable" locations). Locations relatively close to the Sun lose habitability quickly as the Sun becomes more luminous whereas locations further out may only become habitable for a brief period at the end of the Sun's main-sequence lifetime. Thus, the habitable lifetime increases from zero at the HZ inner-edge to maximum near the centre of the HZ and then back to zero again at the HZ outer-edge. Fig 2 shows this effect. Note that Earth does not appear to be particularly close to the peak of this distribution; planets further out may actually be habitable for longer.

5.4 Lifetime

If the rough balance between water-subduction and water-outgassing is not an anthropic selection effect but the result of stabilizing feedback processes, then the lifetime of Earth's oceans will be controlled by climate. Earth's oceans will eventually evaporate as a consequence of solar warming and the ocean-related habitable-lifetime will be identical to the Sun-related habitable-lifetime estimated in section 2.4.

If, on the other hand, the subduction losses exceed the outgassing gains then the oceans will disappear on a time-scale dictated by the difference in rates. This is the case in the Rüpke et al. (2004) model which predicts that recycling into the mantle will remove all surface water on a timescale of approximately 10 Gy. Similarly, Korenaga et al. (2017) required a net water influx into the mantle of 3 x 10^{14} g yr^{-1} to maintain constant freeboard and this rate will deplete Earth's ocean in another 4.5 Gy, i.e. implying a total ocean-lifetime of 9 Gy.

5.5 Future evidence

The announcement in March 2018 that the European Space Agency (ESA) will launch the ARIEL (Atmospheric Remote-sensing Exoplanet Large-survey) mission in 2028 represents a major step forward in the characterization of exoplanet atmospheres. Previous spectroscopic results have been obtained using general purpose telescopes (such as the Hubble Space Telescope), on which there is limited observing time, and this has restricted results to just a handful of targets. The ARIEL mission (Tinetti et al., 2016, 2018) will provide spectra for more than 500 planets from gas-giants to super-Earths. This mission will concentrate on hot to warm (>500 K) planets and the atmospheres of such worlds should allow determination of bulk composition and chemistry (Venot et al., 2018; Tinetti et al., 2018). As a direct consequence, we should be able to estimate the frequency with which larger rocky worlds have Earth-like mass-fractions of water. However, determining bulk-composition from atmospheric composition will depend upon models of atmospheres and of interiors. Getting the best possible information from ARIEL will therefore also require development of new generations of such models.

The ARIEL mission will also allow searches for "glint", i.e. specular reflection off water bodies that can lead to a sharp increase in the planetary contribution to the star+planet total-brightness just before transit (Williams and Gaidos, 2008; Robinson et al., 2010; Zugger et al., 2010). However false positives are possible (Cowan et al., 2012) and so discovery of such a signature will need careful analysis.

6 Magnetic field

Earth's magnetism is reasonably well reproduced by a small dipole magnet near the Earth's centre. Such a magnetic field cannot be due to permanent magnetism, given the high temperatures within the Earth, and must therefore be generated by the dynamo action of a moving conductor. Geophysical and geochemical evidence indicates a dense core composed largely of iron which is at least partially molten (Jeffreys, 1926). More recent work indicates an iron-rich solid inner core surrounded by a liquid outer core containing significant quantities of lighter elements (e.g. see Poirier, 1994). Hence Earth's magnetism is due to the flow of molten metal in her outer core. This motion is assumed to consist of convection currents driven by cooling of the inner-core and by compositional buoyancy produced as light-elements are expelled from freezing iron at the surface of the solid inner core (see review by Buffett, 2000). A similar geodynamo must have existed since at least 3.4 Ga as shown by remnant magnetism in inclusions of that age which indicate a field strength at least 50% of the modern value (Tarduno et al., 2010). Furthermore, a strong (but fluctuating) magnetic field seems to have been maintained ever since as shown by remnant magnetism through the Archean and Proterozoic (Hale, 1987) and into the Phanerozoic (Perrin and Shcherbakov, 1997).

6.1 Possible benefits

It is often stated that a strong magnetic field aids habitability (e.g. Lammer et al., 2009; Horner and Jones, 2010; Vidotto et al., 2011; Tachinami et al., 2011; Seager, 2013; Le Bars, 2016; Kaltenegger, 2017) although McKay (2014) has argued that this may not be necessary. The claim that magnetism is important arises because the field deflects charged particles that would, otherwise, hit Earth. Two arguments are then made concerning how this deflection aids habitability: firstly it reduces atmospheric erosion by the solar wind; secondly it reduces cosmic ray flux.

Mechanisms causing atmospheric loss can be broadly divided into thermal and non-thermal processes (see Shizgal and Arkos, 1996 and Tian, 2015 for reviews). Thermal escape occurs when upper-atmosphere temperatures are high enough to cause a significant fraction of gas molecules to move faster than escape velocity. For a planet of Earth mass and temperature, only H_2 and He would be expected to be removed over geological timescales by this mechanism (Jeans, 1916). Hence, for Earth-like planets, non-thermal escape mechanisms are more important. Many of these mechanisms are the consequence of ionization produced by UV radiation or, in the absence of a magnetic field, by direct collision of the solar wind with the atmosphere. The presence of ions in the upper atmosphere then leads to charge-exchange and recombination reactions that generate sufficient energy to accelerate particles to escape velocity. Furthermore, in the absence of a magnetic field, these ions can be caught up in the solar magnetic field and dragged away (a process called ion pickup). Thus, a planet without a magnetic field suffers from both an increase in upper-atmosphere ionization and more rapid loss of those ions. It is possible that a magnetism-free Earth would have had a thin atmosphere and/or a very dry atmosphere since the absence of a magnetic field played a role in these outcomes on Mars (Lundin et al., 2007). However, it has not yet been thoroughly demonstrated that a magnetism-free Earth would have suffered this fate since, to the best of this author’s knowledge, no quantitative study has been undertaken to specifically assess how Earth’s atmosphere would have been altered had our planet lacked a magnetic field. For example, the existence of a cold-trap on Earth keeps water out of our upper-stratosphere (Kasting, 1988) and, perhaps, that would allow even a magnetic-field-free Earth to retain much of its moisture.

When it comes to the effect of Earth's magnetic field on cosmic ray flux, modelling by Grießmeier et al. (2009) shows a reduction in high energy galactic cosmic rays by 1-2 orders of magnitude for Earth compared to an otherwise identical planet without a magnetic field. However, only the very highest energy cosmic rays are able to penetrate Earth's atmosphere (Kampert and Watson, 2012) and so the main effects will be changes in upper-atmosphere chemistry such as enhanced ozone depletion (Lu, 2009).

Thus, a magnetic field may help to prevent loss of important constituents of an atmosphere and may also offer protection against cosmic rays. To provide these benefits, Earth's magnetic field must have existed for most of Earth's history and must have been of sufficient strength to keep the magnetopause (the boundary between the Earth's field and the solar wind) substantially above the atmosphere.

6.2 Frequency

A long-lived magnetic field is not guaranteed—as shown by the fact that Mars has lost its early global field (Acuña et al., 1998)—but the continuing presence of intrinsic magnetic fields for Mercury (Anderson et al., 2011) and Ganymede (Schubert et al., 1996) suggests that longevity is not particularly rare for solid worlds either. High strength is a different matter. Mercury's field is only ~1% the strength of Earth's (412±98 nT at Mercury's surface (Winslow et al., 2014) compared to 45000±20000 nT (Finlay et al., 2010) for Earth) and, partially as a consequence of this, Mercury's magnetopause can be pushed down to her surface during extreme solar wind events (Zhong et al., 2015). Ganymede's field is also significantly less than Earth's (~750 nT (Showman and Malhotra, 1999)) and no other solid planets or moons have any detectable intrinsic field at all. However, as already discussed for the case of the Moon, the sample size within the Solar System is too small to provide strong evidence of rarity for any Earth attribute.

Nevertheless, maintaining a strong magnetic field for billions of years may be sufficiently difficult to make it unusual. The main issue is that of providing an energy source with enough total energy. Within Earth's geodynamo, energy is dissipated largely as a consequence of electrical resistance. Estimates of these ohmic losses are in the range 0.1-3.5 TW (Christensen and Tilgner, 2004) implying total losses over 3.5-4.5 Gy of 1-50 x 10^{28} J. Furthermore, if outer-core flow was primarily driven by thermal convection, the unavoidable thermodynamic inefficiency of this heat-engine implies thermal losses from the core that were a factor of 5-10 times higher (Buffett, 2000); hence the core must have lost 5-500 x 10^{28} J of heat. As supporting evidence for this estimate of the core's energy consumption, direct estimates of the present-day heat-output at the core-mantle boundary (CMB) derived from a number of arguments suggests a range of 5-15 TW (Lay et al., 2008) implying a total heat loss over Earth's history of 55-830 x 10^{28} J.

These estimates of energy consumption can be compared to the total amount of energy available from cooling, latent heat of fusion (as the inner core freezes) and gravitation (as the freezing core differentiates and loses lighter elements). Labrosse et al. (2001) estimate this as 10-26 x10^{28} J, i.e. a sufficient power supply only if the true power requirements are at the lower end of the ranges given above. Furthermore a core-cooling rate of 5-15 TW implies formation of the solid inner-core as recently as 1 Ga (Labrosse et al., 2001) so that latent heat and compositional buoyancy were not available earlier than this. This alleviates the energy balance problem for recent times but only at the expense of making it hard to understand how a strong field could have existed during the first 3 Gy of life's existence. It therefore appears that additional energy sources might be needed such as radioactive heating by potassium (Lewis, 1971), high magnesium in the core to enhance compositional buoyancy (O'Rourke and Stevenson, 2016), or tidal/precession effects which directly convert Earth's rotational energy into outer-core flow (Le Bars, 2016).

The presence of such additional energy sources may imply that Earth is unusual because, for example, radioactive heating may require a geochemically unlikely core-composition (Lassiter, 2006; Corgne et al., 2007) whilst the magnitude and frequency of tidal/precession effects is altered by Earth's possession of a large Moon. However, it is premature to conclude that a long-lived, strong magnetic field is rare. Christensen and Tilgner (2004) provide evidence that the ohmic losses really do lie at the lower end of estimates. In addition, several geodynamo models (e.g. Aubert et al., 2009) function adequately prior to the appearance of an inner core even without the presence of additional energy sources. It is also not yet clear whether the proposed composition-related energy sources (e.g. radioactive ^{40}K or additional Mg) will turn out to be ubiquitous or peculiar within terrestrial-planet cores. Furthermore, additional work is needed concerning the pumping of outer-core flows by tides and precession; the coupling of these gravitational effects to the inertial waves responsible for extracting the energy of rotation is non-linear (Le Bars, 2016) and it is not clear that the presence of a large Moon necessarily helps the process. In conclusion, whilst it is possible that strong, long-lived magnetic fields are unusual for Earth-like planets, it also remains plausible that such fields are ubiquitous.

6.3 Fine tuning

Stevenson (2003) has suggested that there is a narrow range of electrical conductivities over which a geodynamo could operate. At low conductivity, ohmic losses become large and a dynamo is hard to sustain. At high electrical conductivities, the thermal conductivity is also high (these properties are strongly correlated in a metal) and this supresses thermal convection. Using estimates for the present day Earth geodynamo properties (Table 1), Stevenson's (2003) analysis implies that the thermal conductivity should lie between a lower limit of 0.9-11 W m^{-1} K^{-1} and an upper limit of 46-150 W m^{-1} K^{-1}. For comparison, recent measurements of the thermal conductivity of iron, at high temperature and pressure, are 80-160 W m^{-1} K^{-1} (Davies et al., 2015) suggesting that any iron-rich core is likely to satisfy these conductivity requirements.

	Min	**Max**	**Comments or Reference**
Magnetic Reynold's Number	10	100	Stevenson, 2003
Flow speed (m/s)	4.00×10^{-4}	4.00×10^{-4}	Finlay and Amit, 2011
Length scale (m)	1.54×10^{6}	1.54×10^{6}	Outer core thickness
μ_0	$4\pi \times 10^{-7}$	$4\pi \times 10^{-7}$	Permeability of free space
σ low ($\Omega^{-1}m^{-1}$)	1.30×10^{4}	1.30×10^{5}	Equations in Stevenson, 2003
k low (W m^{-1} K^{-1})	0.86	11.1	Equations in Stevenson, 2003

CMB flux (mW m^{-2})	39	98	Lassiter, 2006
Heat capacity (J K^{-1})	700	700	Gubbins, 2001
Lorenz number, L'	2 x 10^{-8}	2 x 10^{-8}	Poirier, 2000
Expansion coefficient	1.30 x 10^{-5}	1.30 x 10^{-5}	Gubbins, 2001
Temperature (K)	4300	3300	Lay et al., 2008
g (ms^{-2}) at CMB	10.7	10.7	Klotz, 2015
σ high ($\Omega^{-1}m^{-1}$)	5.35 x 10^{5}	2.27 x 10^{6}	Equations in Stevenson, 2003
***k* high (W m^{-1} K^{-1})**	46.0	150	Equations in Stevenson, 2003

Table 1. Physical properties of Earth's outer-core and resulting bounds on electrical (σ) and thermal (k) conductivity (following Stevenson, 2003).

A rather different area of fine-tuning concerns the mass of the Earth. Some geomagnetism models fail to produce a strong, long-lived magnetic field if the mass is much lower (or higher) than that of the Earth. For example, Stevenson et al. (1983) modelled a Venus-mass planet which was, otherwise, identical to Earth and found that the resulting marginal decrease in core pressure delayed formation of a solid inner-core. Using a similar model, Tachinami et al. (2011) confirmed that smaller planets have problems sustaining long-lived magnetic fields but, in addition, found that larger-mass planets also had a problem; the increased pressure in their mantles produced high viscosity which inhibited mantle convection and, hence, heat loss from the core. Remarkably, in the Tachinami et al. (2011) model, the magnetic-field lifetime peaks sharply at around 1 Earth-mass. Less dramatically, the model of Gaidos et al. (2010) demonstrated a different problem for planets larger than 2 Earth-masses since, in these cases, the core-solidifies inwards from the outside thus removing core-freezing as a source of compositional or thermal convection.

Hence, there is some evidence from modelling that there has been fine-tuning of the Earth's mass to allow a magnetic field but, given that we do not yet have a wholly satisfactory model of energy-balance within the Earth's core, these conclusions must be taken as highly provisional.

6.4 Lifetime

Maintenance of a magnetic field requires the magnetic Reynolds number to exceed about 10-100 (Stevenson, 2003; Gaidos et al., 2010) but, given the typical fluid velocity and electrical conductivity of the outer core (Table 1), this implies the fluid layer of the core could shrink to a thickness of only a few hundred km before the dynamo stalls. Earth's magnetic field might therefore be sustained until the inner core grows to 95-99% of the total core radius.

On the other hand, as the outer core freezes and expels lighter elements, their concentration in the remaining liquid core increases and approaches a eutectic composition. Once this occurs, the lighter elements are no longer expelled during freezing and compositional buoyancy disappears. This may be sufficient to shut down the dynamo (Dehant et al., 2007). Oxygen would be the most effective element for driving compositional convection (Alfè et al., 2002; Ozawa et al., 2008) and could have a present-day outer core concentration as high as 5 wt% (Siebert et al., 2013). The eutectic concentration for oxygen has been estimated as 11 wt% (Morard et al., 2017) and this composition will be reached when the inner core radius has grown to 90% of the total core radius.

Thus, magnetism could be maintained until the inner-core has grown to 90-99% of the outer-core radius. The time scale for this can be estimated by assuming that the inner-core radius, *r*, grows at some power, *p*, of the time-elapsed since inner-core formation, *t*, i.e.

$$t = t_0 \left(r / r_0 \right)^{1/p} \qquad (1)$$

where t_0 is the present-day value of *t* and r_0 is the present-day inner-core radius. Stevenson et al. (1983) suggest p=1/4 whilst, if we assume that constant power is required to maintain core convection and that the power largely comes from core-freezing, the implication is that the inner-core should grow at a constant mass-rate (i.e. p=1/3). Alternatively, there is evidence that Earth's mantle has been cooling since 2.5 Ga (Ruiz, 2017) and that, therefore, the rate of heat extraction from the core has been increasing. To first-order we can assume the cooling rate increases linearly and this implies p=2/3. Labrosse et al. (2001) propose a likely age for Earth's inner core of 1.0±0.5 Ga with an upper limit of 2.5 Ga whilst Lassiter (2006) suggests a plausible range of 0.2-2.5 Ga. Combining all these factors gives a total magnetic-field lifetime, after Earth formation, of 5-27 Gy.

For comparison, Tachinami et al.'s (2011) simulations of Earth-like dynamos for super-Earths (rocky planets ~2-10 times Earth mass) gave a lifetime of 10 Gy for their Earth-mass base-case. Similarly, the models of van Summeren et al. (2013) give a magnetic-field lifetime of 8.2 Gy for their "nominal Earth-like scenario" whilst the core-growth model of Buffett et al. (1992) implies a lifetime ≥10 Gy. Clearly, the lifetime of the Earth's magnetic field is not currently well constrained but a value of the order of 10 Gy is indicated by the few studies which have attempted to model its future evolution and by assessment of plausible rates of inner-core growth.

6.5 Future evidence

From the above discussion it is clear that further work is needed to demonstrate or refute the hypothesis that our long-lived and strong magnetic field has been anthropically selected. Modelling of both mantle and core dynamics is required to better constrain the heat evolution of the Earth and the energy balances involved in outer-core flow. Experimental and computational work is required to improve our understanding of physical and chemical properties under core conditions. Together, improved models and better constrained properties may be able to show whether unusual conditions—or fine-tuning of parameters—is needed to produce a strong, long-lived magnetic field. Improved models will also allow much better estimates of the future lifetime of our field. Finally on the numerical modelling aspects, it would be valuable to explicitly model the atmospheric evolution of Earth in the absence of a magnetic field.

A different way to show whether long, strong geomagnetism is peculiar, would be to investigate whether such fields are common (or rare) for Earth-like exoplanets. This requires remote detection of their magnetospheres and three possible ways to do this have been proposed.

Firstly, magnetospheres (or components thereof, such as bow-shocks) may be opaque to certain electromagnetic frequencies; as a consequence, transits of exoplanets in front of their stars may last longer at some wavelengths than at others. Vidotto et al. (2010) proposed this as an explanation for the early UV ingress of transits for the planet WASP-12b. Further work by the same authors (Vidotto et al., 2011) proposed 12 other exoplanets where similar effects could be looked for. Subsequent modelling by Turner et al. (2016) indicated that magnetosphere absorption will be too small to detect at any wavelengths between radio and X-Ray. Furthermore, the same authors investigated 15 candidates (including some of those proposed by Vidotto et al., 2011) and failed to detect transit anomalies. On the other hand, Cauley et al. (2015) detect fairly convincing absorption at Hydrogen-α wavelengths prior to the optical transit of HD189733b; an outcome previously predicted by Llama et al. (2013). Hence, the evidence remains equivocal and it is not yet clear whether looking for transit anomalies is a viable technique for detecting remote magnetospheres.

In principle, it might be possible to make transit observations at unusually low radio-frequencies of a few GHz—frequencies substantially lower than those normally employed in radio-astronomy (i.e. 100s of GHz)—since magnetospheres are highly opaque at these very long wavelengths. Unfortunately, Earth’s own ionosphere is also opaque to such low-frequency signals and, furthermore, stellar radiation is probably too faint at these frequencies to be detectable.

The second technique to look for exoplanetary magnetism is to look for radio-signals from the planets themselves, i.e. we could search for the cyclotron emissions which results from stellar-wind electrons spiralling around the magnetic-field lines of a planet (Zarka, 2007; Jardine and Cameron, 2008; Hess and Zarka, 2011; Driscoll and Olson, 2011). Modelling of a number of nearby super-Earths and hypothetical Earth-like planets around nearby stars indicates that the frequency of these emissions fall below the ionosphere cut-off at 10Mhz and also fall below the detectability limits of proposed low-frequency radio-telescopes (Driscoll and Olson, 2011). This last issue is a problem even for radio telescopes placed in space (as proposed in Zarka et al., 2012, Budianu et al., 2015, Rajan et al., 2016 and Gemmer et al., 2017) and can probably only be overcome by an extremely large radio telescope on the far side of the Moon (Zarka et al., 2012). Even then it will be difficult to detect fields as small as that of Earth.

The final way whereby exoplanet magnetic fields may be detectable is to look for their influence on radio-emissions of parent stars (Ip et al., 2004; Jardine and Cameron, 2008; Hess and Zarka, 2011). These interaction can lead to a radio-bright spot on the star, immediately below the planet, but this form of interaction is only relevant to a planet orbiting very close to the star. It is therefore not relevant to the investigation of magnetic fields on Earth-like worlds and will not be discussed further here.

7. Plate tectonics

Plate tectonics is the unifying principle of Geology; it is essential for understanding nearly everything we see at the surface of Earth and in her interior. It may be equally central to understanding her habitability. Plate tectonics is the surface expression of mantle convection. Mid-ocean ridges (and hot-spots) represent upwelling and subduction represents down-welling. This behaviour contrasts that seen on Mercury, Venus, Mars and the Moon which have mantle convection but with a stagnant lid at the surface, i.e. cooling occurs largely by conduction through an immobile crust (Solomatov and Moresi, 1996). In particular, with a stagnant lid, there is no mantle-cooling due to subduction of cold lithospheric slabs. Hence, heat loss from Earth's interior is more efficient than it would be in the absence of plate tectonics; Driscoll and Bercovici (2014) predict that there has been 600 K of cooling of Earth's mantle over the last 4.5 Gy compared to the 700 K of heating there would have been in the absence of plate tectonics.

Subduction also enables recycling of volatiles between the surface and the mantle e.g. carbon and water are exchanged via the carbon and water-cycles. These cycles prevent complete mantle de-volatization and also prevent excessive build-up of water and carbon in the near-surface and atmosphere.

7.1 Possible benefits

Foley and Driscoll (2016) have provided an excellent review of the coupling between climate, mantle and core and the central role that plate-tectonics plays in this. This coupling is important because Earth's habitability is directly impacted by both the behaviour of the core and by climate. Starting with the core, increased cooling by plate-tectonics may be essential for heat loss sufficiently fast to drive our magnetic field. On the climate side, plate-tectonics drives the silicate-weathering cycle by providing fresh rocks for weathering, high topography to allow erosion and ocean basins where carbonate can accumulate.

Even if the silicate-weathering cycle is not a significant contributor to climate stability, subduction coupled with mantle cooling produces a decreasing atmospheric concentration of CO_2 over Earth's history (see recent modelling by Krissansen-Totton et al., 2018 and Isson and Planavsky, 2018). This has, at least partially, compensated for the enhanced warming from solar evolution. Thus, plate-tectonics may be important for resolving the faint young Sun paradox—i.e. the issue that the relatively low luminosity of the young Sun should have resulted in an early Earth that was well below freezing whilst geological evidence indicates plentiful liquid water (Donn et al., 1965; Sagan and Mullen, 1972; Walker, 1982; Jenkins, 1993; Kienert et al., 2012; Feulner, 2012; Charnay et al., 2013). Plate tectonics may therefore have been vital in maintaining Earth's multi-Gy habitability.

It has also been suggested that plate-tectonics may have provided the habitats where life originated. Hydrothermal vents, in particular, are now a popular candidate location for life's origins (Corliss et al., 1981; Baross and Hoffman, 1985; Russell et al., 1993; Martin and Russell, 2007; Martin et al., 2014; Sojo et al., 2016). Alkaline hydrothermal vents are especially favoured for biogenesis and modern examples of such vents are associated with serpentinization at locations off-axis of spreading centres (e.g. the Lost City Hydrothermal Field 15 km from the Mid-Atlantic Ridge (Kelley et al., 2005)). Archean serpentinites are common and may indicate the presence of alkaline, hydrothermal systems on the early Earth although they have also been interpreted as associated with mud-volcanoes rather than mid-ocean hydrothermal systems. However, mud-volcanoes are also related to plate-tectonics (they're associated with subduction) and, furthermore, they are another favourable location for the origin of life (Pons et al., 2011).

If plate-tectonics provided the location for life's origins then this obviously implies that plate-tectonics came before biogenesis. Plate-tectonics may have emerged at around 3.8 Ga (Dilek and Polat, 2008) or even earlier (de Wit, 1998) but some researchers place it as recently as 2.5 Ga (Bédard, 2018). On the other hand, proposals for the origin of life go back as far as 3.85 Ga but these dates are debated and life is only incontrovertibly present by 1.9 Ga (see Moorbath, 2005 for a review). Hence, for now, an origin for life in a plate-tectonically generated environment remains plausible but further work could push the origin of life back to before the origin of plate tectonics.

Finally, Stern (2016) makes the interesting point that plate-tectonics provides a more diverse planetary surface and that this may have played a role in encouraging evolutionary innovation—thus making the emergence of intelligent observers more likely.

In summary, there are good reasons for suggesting that plate-tectonics played a major role in the continuing habitability of Earth and plausible proposals for ways in which it may have contributed to the origin of life and the evolution of complex organisms.

7.2 Frequency

As with the other properties discussed so far in this paper, the small sample of rocky worlds in the Solar System makes it impossible to draw any conclusions about the frequency of plate-tectonics from the observation that only Earth exhibits this property. However, although Earth is the only planet with unambiguous plate-tectonics, Venus may have processes that are intermediate between plate tectonics and a truly stagnant lid, i.e. surface features indicating plate-tectonic deformation immediately below a deforming (but not subducting) crust (Ghail, 2015). If this interpretation is correct, it would suggest that plate-tectonics is common on rocky worlds (i.e. we see one full example and one partial example within the Solar System).

Furthermore, there is significant evidence that Jupiter's icy-moon, Europa, exhibits plate-tectonic-like behaviour in the ice-shell that lies above its subsurface ocean. Features have been noted that resemble spreading ridges (Prockter et al., 2002), strike-slip faults (Hoyer, Kattenhorn, and Watkeys, 2014) and subduction zones (Kattenhorn and Prockter, 2014). One major issue with these interpretations is that it is not immediately obvious that cold icy plates are dense enough to sink into the warmer ice below but it is possible that the required extra density is supplied by deposition of exogenic salts onto Europa's surface (Johnson et al., 2017).

If Europan-tectonics really does resemble Earth-tectonics, this is not direct evidence that plate-tectonics is common on rocky worlds. However, it is evidence that plate-tectonics is reasonably common on icy worlds—since there are no anthropic selection effects to worry about—and hence indicates that the conditions necessary for plate-tectonics are not particularly hard to satisfy. Thus, it is indirect, weak evidence in favour of the contention that plate-tectonics may be common for rocky worlds too.

The other approach that can be taken to investigating the frequency of plate-tectonics is via mathematical and numerical modelling. Sensitivity analysis of such models allows the factors controlling the presence or absence of plate-tectonics to be investigated and, hence, an assessment made of whether mobile-surfaces are likely to be ubiquitous or rare on rocky planets.

Mathematically, a necessary (but not sufficient) condition for plate tectonics is that the effective strength of the lithosphere should be smaller than the convective stress driving plate motion, i.e. the forces present should be sufficient to break the surface into distinct plates. In Earth's case, this requires mechanisms that weaken the lithosphere such as damage zones (Toth and Gurnis, 1998; Gurnis et al., 2000; Bercovici and Ricard, 2012), serpentinization of faults and subduction zones (Escartín et al., 2001; Hilairet et al., 2007; Guillot et al., 2015), phyllosilicates in faults (Amiguet et al., 2012), partial melting and associated crust production (Rolf and Tackley, 2011; Lourenço et al., 2016) and hydration of the mid-lithosphere (Korenaga, 2007). The presence of water is central to the formation of both serpentine and phyllosilicates and may also assist plate-tectonics by allowing formation of a low-viscosity-zone in the upper mantle (Richards et al., 2001). Hence, many of the proposed mechanisms that allow driving forces to exceed lithospheric yield-stress only operate because Earth is wet. Surface temperature may also be important since cold lithospheric slabs are easier to subduct. The presence of plate tectonics may therefore be strongly dependent on climate factors (Weller et al., 2015; Foley and Driscoll, 2016).

The presence of plate-tectonics is also likely to be affected by planet mass. However, there is no consensus on the details of this. In many studies (Valencia et al., 2007; Valencia and O'Connell, 2009; van Heck and Tackley, 2011; Foley et al., 2012) plate tectonics is predicted to be more likely for larger planets but other models predict the opposite (O'Neill and Lenardic, 2007; Stamenković and Breuer, 2014; Noack and Breuer, 2014). It has also been claimed that size is relatively unimportant compared to other issues such as the presence or absence of water (Korenaga, 2010). These disparate conclusions occur because of different assumptions concerning mantle-rheology, lithosphere-weakening, internal temperatures and plate-initiation. Stamenković and Breuer (2014) concluded that the key factor was whether these different assumptions led to plate-yielding that was more likely, or less likely, for planets with warmer interiors. In contrast, Weller and Lenardic (2016) argued that the key difference concerned whether the mantle was primarily warmed from below or by internal radioactivity.

With this theoretical background, Venus is an interesting test case. Does it lack full plate-tectonics because it is slightly smaller than Earth, because it has higher surface temperatures or because it lacks liquid water? Perhaps all three factors are important but, at present, there is no consensus and the unavoidable conclusion is that we simply do not know whether plate-tectonics is a common property of Earth-sized rocky planets.

7.3 Fine tuning

The models discussed above imply either that Earth has close to the minimum mass for plate-tectonics (e.g. Foley et al., 2012) or imply that Earth is close to the optimum mass for plate-tectonics (e.g. Noack and Breuer, 2014). However, given that there is little consensus about the effect of mass, it would be unwise to read very much into these observations.

7.4 Lifetime

As discussed earlier, heat-flow from Earth's core makes an important contribution to the total heat-flow driving mantle convection. Hence, it is possible that plate-tectonics will stall at the point in Earth's future when outer-core convection ceases (i.e. at ~10 Gy after Earth formation, see section 6.4). In addition, some authors have attempted numerical modelling of plate tectonics into the distant future. O'Neill et al. (2016) use numerical models to suggest that a stagnant-lid regime of tectonics is likely to (re)emerge 10-15 Gy after the initiation of plate-tectonics whilst Cheng (2018) extrapolates past cooling trends to suggest that plate-tectonics has around 1.45 Gy left (i.e. a total lifetime of ~6 Gy).

An interesting point, in the context of plate-tectonic lifetime, is made by Weller et al. (2015) in that future warming of Earth's surface (as discussed in section 2) could bring plate-tectonics to a premature end as it would weaken the temperature gradient driving convection. This effect would be greatly enhanced by the associated loss of liquid water, when surface temperatures become high, as this would strengthen the lithosphere. Plate-tectonic habitable lifetime would then be linked to surface-temperature habitable lifetime.

The plate-tectonic lifetime is therefore of the order of 10 Gy but it is closely linked to other habitability lifetimes (i.e. magnetism or climate).

7.5 Future evidence

Our understanding of plate-tectonic likelihood and plate-tectonic benefits would be enhanced if we had more than one example to study and that requires development of methods for spotting plate-tectonics on exoplanets. A tall order; but perhaps not impossible.

One approach would be to spot atmospheric-signatures of plate tectonics since, as already discussed, the technology to analyse exoplanet atmospheres is now becoming available. In general, plate tectonics can affect the atmospheric abundance of any chemical species that permanently precipitate from an atmosphere. In Earth's case, carbon dioxide is such a species since it precipitates (via a complex path) as carbonate on Earth's surface. In the absence of subduction, any such species will be permanently locked-up on the planetary surface and, hence, will become rare (or even absent) in the atmosphere over geological time. However, if the precipitate is subducted, there is a return-path allowing the atmosphere to be replenished and, as a consequence, the atmosphere concentration will be controlled by a dynamic equilibrium.

An alternative for producing atmospheric signatures could be associated with chemical reactions, in the mantle, which would not occur in the absence of volatile subduction. In Earth's case, for example, subduction of water results in relatively oxidising conditions in mantle-wedges which may be important for liberating free nitrogen and, hence, allowing N_2 degassing into the atmosphere (Mikhail and Sverjensky, 2014). Earth's more efficient degassing of N_2 may, in turn, explain her high N_2/Noble-gas ratios compared to Venus and Mars (Fig. 6).

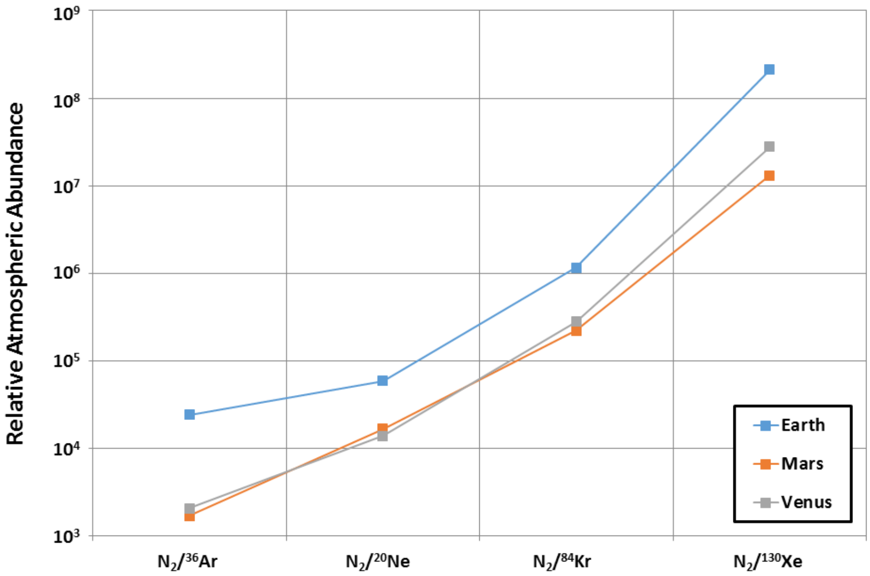

Figure 6. The Nitrogen to Noble-Gas ratios for the atmospheres of Venus, Earth and Mars (after Mikhail and Sverjensky, 2014). Note that Earth has significantly higher ratios than Venus or Mars implying more efficient outgassing of Nitrogen. This may be a direct consequence of plate-tectonics.

The carbon dioxide and nitrogen concentrations of Earth's atmosphere may therefore be indirect signatures of plate-tectonics and similar signatures may be present, and interpretable, on other planets. However, much work is needed to turn this idea into a practical and robust tool.

A rather different approach to detecting plate tectonics would be to look for evidence of continents and oceans; a combination that may only be possible on planets with plate-tectonics (Kasting, pers comm). Note that techniques are under development that may enable such detection (Cowan et al., 2009).

8. Discussion and conclusions

The analyses from the foregoing six sections are summarized in Table 2. Numbers in this table correspond to estimates of significance, i.e. the probability that the observed phenomenon could occur by chance. As is usual in statistics, the most convincing cases are the ones where the significance is small (i.e. the observation is unlikely to happen by chance). Where there is no quantitative estimate of significance, I have substituted the words “strong” (when the case is strong, i.e. the significance is low), “moderate” (where a case can be made) or “weak” (cases where there is either no supporting data or the data suggests that the significance-level is high).

	Benefits case	**Frequency significance**	**Fine-tuning significance**	**Associated Habitable Lifetime (Gy)**
Solar Mass	moderate	14%	weak	6.5±1.0 Gy
Moon Mass	weak	2%-25%	2%	7.5±1.5 Gy
Orbital Eccentricity	strong	weak	weak	>>10 Gy
Giant planet masses	weak	4%	weak	NA
Giant planet locations	weak	~10%	moderate	>50 Gy
Oceans	strong	weak	weak	~9 Gy or 6.5±1.0 Gy
Magnetism	moderate	unknown	unknown	~10 Gy
Plate-tectonics	strong	unknown	unknown	~10 Gy

Table 2. Summary of conclusions. Percentage figures are the significance-level, i.e. estimates of the probability of chance-occurrence. Weak, moderate or strong are used in the absence of a quantitative estimate.

None of the individual items show a convincing enough pattern across the table to lead to a strong statement that any one of them is likely to have been anthropically selected. The properties where there is a strong case for benefits (eccentricity, oceans and plate-tectonics) also correspond to features which are either likely to be common for rocky worlds or for which the frequency is unknown. Furthermore, there is little evidence that any of these properties require fine-tuning of controlling parameters.

The only individual feature worth discussing further is our Moon. The case for the benefits of a large moon is much weaker than has generally been assumed; its widely accepted role in stabilizing Earth's axis does not stand up to detailed scrutiny. Nevertheless, the Moon's properties do show evidence for significant fine tuning. In particular, the moon-mass is close to the upper limit beyond which obliquity-instability sets in, with only 2% of axially-stable, moon-forming collision resulting in an even larger moon. But it must be noted that this conclusion is only valid if evection-resonance removes angular momentum from Earth-Moon-like systems when they are young.

Moving now to the "Habitable Lifetime" column of Table 2, there are some indications here that anthropic selection affects our planet's properties. As discussed earlier, one possible signature of anthropic selection would be a set of habitable-lifetimes that are controlled by very different physical factors but which, none-the-less, have the same order of magnitude. This appears to be the case for lifetimes associated with the Solar-mass (i.e. the lifetime for liquid water), the Moon's mass (i.e. the lifetime for Earth's axial stability) and Earth's mass (i.e. the lifetime for magnetism and plate-tectonics)—all three timescales are ~10 Gy. The timescale associated with loss of oceans is also of similar magnitude although this is associated with solar warming (if it is climate controlled) or the cooling history of the Earth (if it is controlled by subduction into the mantle) and so is not independent of the others.

Further work will hopefully show whether these time-scales are, in fact, even closer than Table 2 suggests. Further work is also needed to demonstrate that these lifetimes are unusually long since, otherwise, the anthropic selection mechanism driving them towards similarity cannot operate.

The introduction asked whether Earth is a typical rocky-planet or, alternatively, one of the oddest planets in the Universe; the foregoing analysis makes it clear that we still do not know. Without a clear answer to this fundamental question, our knowledge of Earth remains superficial. In a very real sense, we have a deeper understanding of Mars and Venus than we do of our own home-world.

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Appendix A: Stellar mass to give a moon-free HZ planet with same tidal torque as Earth

The main-sequence luminosity of a star depends upon its mass according to the approximate relation (Le Blanc, 2010)

$$L/L_\odot = (M/M_\odot)^{3.5} \qquad \text{(A1)}$$

where L is luminosity, M is mass and ⊙ indicates Solar System values. In addition, for a planet orbiting a star of luminosity L to obtain the same illumination as the Earth, the inverse square law gives

$$a/a_\odot = (L/L_\odot)^{0.5} \qquad \text{(A2)}$$

where a is distance of the planet from the star. Finally tidal torque, F, from the star on the planet increases with stellar mass and decreases with the cube of the separation (Berger et al, 1992) and, hence,

$$F/F_\odot = M a_\odot^{3}/M_\odot\, a^3. \qquad \text{(A3)}$$

Combining these expressions gives

$$F/F_\odot = (M/M_\odot)^{-4.25}. \qquad \text{(A4)}$$

Setting $F/F_\odot = 3$ (to give the same total tidal torque as that provided by the Sun and Moon together) gives $M/M_\odot$=0.77. Thus, a moon-free planet orbiting in the HZ of a ~0.8 $M_\odot$ star experiences the same total, tidal forces as Earth.

Appendix B: Moon-mass, angular-momentum and axial-stability

The theory of lunar recession was developed by Darwin (1880) and modern treatments can be found in Goldreich (1966), Murray and Dermott (1999), Atobe and Ida (2007) and Laskar et al. (2004). For small obliquity and a circular lunar-orbit, the theory simplifies to

$$\mathrm{d}a/\mathrm{d}t = f\,a^{-5.5}, \qquad \text{(B1)}$$

with

$$f = 3(k_2/Q)(m/M)R^5\mu^{0.5} \qquad \text{(B2)}$$

(Lambeck, 1980; Murray and Dermott, 1999; Bills and Ray, 1999) where a is Earth-Moon separation, t is time, k_2 is Earth's Love-number (a measure of rigidity), Q the tidal quality factor (a measure of the rate of energy dissipation into heat), m and M the masses of the Moon and Earth respectively, R the radius of the Earth and $\mu = G(M+m)$. The approximation of (B1) and (B2) is used here, in preference to a numerical treatment of the full system of equations, because it has the analytical solution

$$a^{6.5} = a_o^{6.5} + 6.5\bar{f}t \qquad \text{(B3)}$$

where a_o is the initial Earth-Moon separation and $\bar{f}$ is the time-averaged f. This simple model is surprisingly accurate and has an rms deviation of only 0.015% from the more complete, numerical model of Laskar et al. (2004) (see Waltham, 2015). Note also that $a^{6.5}$ is typically >10^6 times larger than $a_o^{6.5}$ and so uncertainty in its value is unimportant (indeed, it can be set to zero without producing a significant error except for very early times).

The next element of the model is the Earth-Moon system angular momentum perpendicular to the ecliptic. Ignoring the small contribution from lunar rotation, the angular momentum is the sum of that from the lunar-orbit plus that from Earth's spin, i.e.

$$L = a^{0.5}\mu^{0.5}\,m' + C\Omega X \qquad \text{(B4)}$$

where m' is the reduced lunar mass ($= mM/(m+M)$), C is Earth's moment of inertia, Ω Earth's rotation rate, X=cos(obliquity) and Kepler's 3rd law ($\omega^2 a^3=\mu$) has been used in the orbital term. The lunar orbit is assumed to be coplanar with the ecliptic (the error from this is small as the inclination is only 5° and the nodal precession period is only 18.6 years). The final element of the model is Earth-axis precession. Following Berger et al. (1992) — but, as before, assuming a circular, coplanar lunar-orbit—the axial precession frequency is

$$k = A\,\Omega X\,[\,(m/a^3) + (m_\odot/a_\odot^{\,3})\,] \qquad \text{(B5)}$$

where A is a constant (chosen to make present day k=50.476 "/y (Laskar et al., 2004)), and $\odot$ indicates solar values. Combining equations (B4) and (B5) then yields the final result that

$$L = a^{0.5}\mu^{0.5}\,m' + Ck\,/\,\{\,A\,[\,(m/a^3) + (m_\odot/a_\odot^{\,3})\,]\,\}. \qquad \text{(B6)}$$

Equations (B3) and (B6) give the angular momentum required to produce a specified precession rate for a specified moon-mass and age. In the case of the red lines in Figure 3, the precession rate has been set to the minimum value for axial stability (i.e. 26"/y) with L then being calculated for a range of moon-masses and system-ages.

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