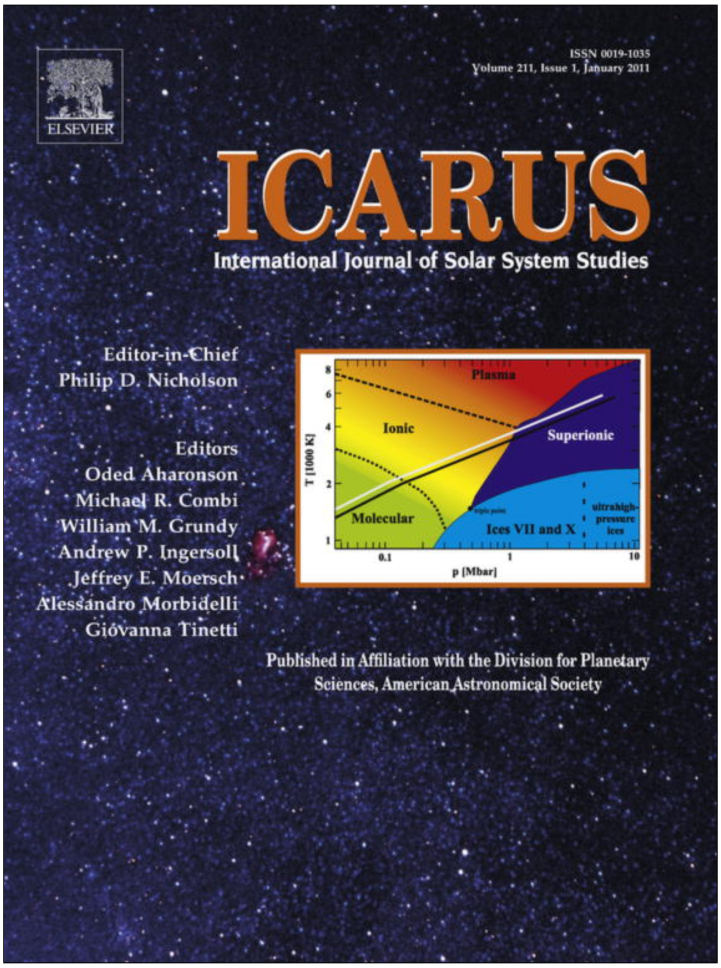
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Anthropic selection and the habitability of planets orbiting M and K dwarfs

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ABSTRACT

The Earth may have untypical characteristics which were necessary preconditions for the emergence of life and, ultimately, intelligent observers. This paper presents a rigorous procedure for quantifying such "anthropic selection" effects by comparing Earth's properties to those of exoplanets. The hypothesis that there is anthropic selection for stellar mass (i.e. planets orbiting stars with masses within a particular range are more favourable for the emergence of observers) is then tested. The results rule out the expected strong selection for low mass stars which would result, all else being equal, if the typical timescale for the emergence of intelligent observers is very long. This indicates that the habitable zone of small stars may be less hospitable for intelligent life than the habitable zone of solar-mass stars. Additional planetary properties can also be analyzed, using the approach introduced here, once relatively complete and unbiased statistics are made available by current and planned exoplanet characterization projects.

1. Introduction

The possibility that life-bearing planets may orbit low-mass (M and K dwarf) stars is currently of great interest since terrestrial-sized planets orbiting within the habitable zone (Kasting et al., 1993) of such stars are detectable using radial velocity (Mayor et al., 2011) and transit (Charbonneau et al., 2009; Borucki et al., 2011) methods. Furthermore, space-based telescopes which may be capable of determining the atmospheric chemistry of such planets are already being planned for launch within the next decade or so (e.g. the EChO mission, Tinetti et al., 2011). In contrast, detailed characterization of habitable planets orbiting solar-like G-dwarfs is likely to remain beyond our capabilities for a considerable time because of their smaller planet/star mass-ratios and radius-ratios.

However, the question of whether planets orbiting M and K dwarfs are suitable abodes for life is unresolved (see Scalo et al. (2007) and Lammer et al. (2009) for recent reviews). Some studies (e.g. Dole, 1964) have suggested that, since planets in the habitable zones of low mass stars will be tidally locked, there is a possibility that the atmosphere will freeze out on the nightside. However, more recent studies using Global Circulation Models (e.g. Joshi et al., 1997; Edson et al., 2011) have shown that atmospheric circulation should keep the nightside warm provided the atmosphere is sufficiently dense. Another potential problem is that such planets have greater exposure to XUV, γ-rays, cosmic rays and stellar winds since: low-mass stars are generally more active (Zendajas et al., 2010); tidally-locked planets may have smaller magnetic fields (Grießmeier et al., 2005); and planets are no longer screened from galactic cosmic rays by a small star's "astrosphere" if it passes through a dense interstellar cloud (Smith and Scalo, 2009). However, other studies have suggested that these effects are not as severe as feared (e.g. Christensen and Aubert, 2006; Khodachenko et al., 2007; Lammer et al., 2007; Tarter et al., 2007; Segura et al., 2010). Finally, some authors have suggested that Earth-mass planets may be uncommon around small stars (e.g. Whitmire and Matese, 2009) but, once again, these ideas are disputed by other studies (e.g. Montgomery and Laughlin, 2009).

A further relevant issue is the question of habitable lifetime. A planet is usually considered to be habitable if liquid water can exist on its surface. The Earth's habitable period therefore began >4 Gyr ago and will cease $\sim$1 Gyr into the future when the steadily increasing solar-luminosity reaches a threshold where a run-away greenhouse effect is initiated (Walker et al., 1981). However, planets orbiting lower-mass stars should be habitable for longer than this (Kasting et al., 1993) since smaller stars evolve more slowly. Hence, more time may be available for the emergence of life and, eventually, observers on planets orbiting M and K dwarfs. If life in general, or intelligence in particular, are rare then longer habitable lifetimes will favour their appearance.

Observers have actually arisen on Earth $\sim$80% of the way through the habitable timescale of $\sim$5 Gyr. This supports the idea that intelligent life may be rare for the following reason. The habitability timescale is determined by the nuclear physics of fusion in stars whereas the time taken for observers to evolve is governed by factors such as mutation rates, population sizes and generation-lengths. Thus, there is no obvious reason why stellar evolution and biological evolution should take place on similar timescales. A widely accepted explanation for this coincidence is that the

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characteristic timescale for the emergence of intelligence is actually much greater than 4 Gyr (Carter, 1983; Watson, 2008). On this interpretation, intelligent life will not arise on the great majority of habitable planets since there will be insufficient time. As a consequence, on the few rare worlds where intelligence does arise, it is likely to be a relatively late event. Thus, observers should be very rare but they should also be more probable on worlds with long habitability durations. This argument suggests that M and K dwarfs should be favoured as abodes for intelligent life compared to more massive stars such as the Sun.

Of course, our biosphere has been through many steps between the origin of life and the emergence of intelligence and it is far from clear which of these steps are rate-determining. The fact that intelligence has emerged at 80% of the habitable life-time has been used to argue that there are 4–5 improbable steps (Watson, 2008) but it is possible that the most difficult step is the origin of life itself (i.e. the first step) or that the critical step is much later. In the first case, the implication is that life is very rare whereas, in the second case, simple life could be quite common (and present around many star types) but with more complex biospheres being rare. This latter interpretation has been called the "Rare Earth hypothesis" (Ward and Brownlee, 2000).

Given all this background, it is far from clear whether M and K dwarfs should be regarded as promising or unpromising targets for harbouring life-bearing planets. This paper attempts to shed light on this problem by using the anthropic principle that "what we can expect to observe must be restricted by the conditions necessary for our presence as observers" (Carter, 1974). More specifically, this paper investigates whether any conclusions can be drawn about M/K-dwarf habitability from the fact that our Sun is not one of these very common star types.

The anthropic principle at the core of this paper remains controversial (Kasting, 2001; Larson, 2007). This partly arises from its apparent conflict with the, Copernican-inspired, "principle of mediocrity" (Barrow and Tipler, 1986) that we should not regard our position in time or space as in any way privileged. This very successful principle has, over four centuries, allowed us to realize that the Earth is one planet amongst many and that it orbits an undistinguished star in one of billions of galaxies. However, it may now be time to recognize the limitations of the principle of mediocrity. Perhaps the Earth is special in some ways and has unusual properties which were essential preconditions for the emergence of intelligent life. Importantly, the tension between these two ideas can be resolved by combining them into a principle that the Earth should be a typical inhabited world. This principle already underpins much astrobiological thinking (e.g. NASA's policy of "follow the water" (Des Marais et al., 2008)).

This paper therefore has two aims. Firstly, it develops the mathematical framework required for using observational data to test claims of anthropic selection effects. Secondly, since we do not yet have sufficient unbiased data on the properties of exoplanets themselves, it applies this methodology to the specific question of whether there has been anthropic selection for the Sun's mass. This second aim is relevant to the issue of whether M and K dwarfs are likely to be good targets for astrobiological investigations.

2. The second best of all possible worlds

The key to quantitative understanding of anthropic selection is Bayes' Theorem (Carter, 1983; Waltham, 2007, 2011) (Fig. 1) that

$$P(x/O) = P(O/x)P(x)/P(O) \quad (1)$$

where x is a planetary property (e.g. star-mass, planet-mass, water-fraction, semi-major axis, etc.), $P(x/O)$ is the probability density function (pdf) of x for planets with observers whilst $P(x)$ is the corresponding pdf for all planets. $P(O/x)$ is the likelihood function for observers (i.e. a function which is high for values of x which favour observers and smaller at values which discourage their appearance). Note that likelihood functions are not pdfs and do not have unit area. The final term, $P(O)$, is a constant giving the frequency of planets with observers (i.e. the total number of planets with observers divided by the total number of planets). $P(O)$ ensures that $P(x/O)$ is a pdf (i.e. has a total area of unity).

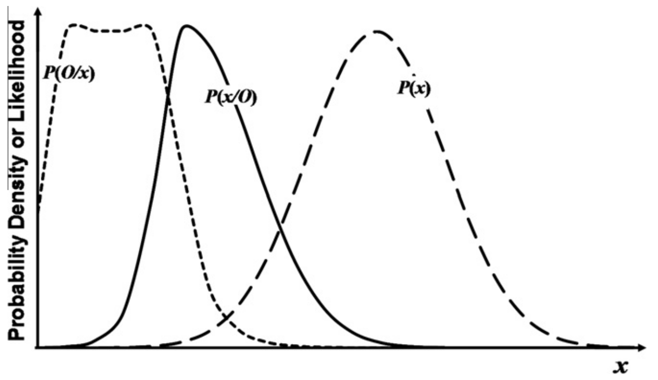

Fig. 1. Bayes theorem applied to anthropic selection. $P(x)$ is the probability density function (pdf) for a planetary property (e.g. water-fraction by mass). $P(x/O)$ is the equivalent pdf for planets which happen to have observers. These two pdfs differ in shape because $P(x/O) \propto P(x) \cdot P(O/x)$ where $P(O/x)$ is the likelihood of observers given that a planet has property x. Note that the most likely x on an inhabited planet (i.e. the peak of $P(x/O)$) is intermediate between the best value (i.e. the peak of $P(O/x)$) and the most common value (i.e. the peak of $P(x)$).

The effect of Eq. (1) is to shift the peak of $P(x/O)$ away from the peak in the habitability likelihood function ($P(O/x)$) so that observers typically appear on planets with properties intermediate between those which are common and those which are favourable. For example, if the Earth is a typical inhabited world we would expect it's mass to be intermediate between the most common value and the best value (in the sense of the value most likely to result in the evolution of observers). Anthropic selection therefore does not result in inhabited worlds having optimized values and this unavoidable consequence of Bayes' Theorem significantly complicates the problem of demonstrating anthropic effects. Nevertheless, the following section sets out how such a demonstration could be achieved.

3. Quantifying anthropic selection

In principle, observation of exoplanets allows the shape of $P(x)$ to be estimated for any measurable property, x. Furthermore, if x is known for the Earth and we assume that it is a typical inhabited world, then we have some (very incomplete) information about $P(x/O)$. Hence, Bayes theorem should allow us to say something about the shape of the habitability likelihood $P(O/x)$. In particular, as shown below, we can determine whether the information we have is consistent with an assumption that $P(O/x)$ is flat (i.e. that there is no anthropic selection effect for property x).

A convenient way to quantify the strength of anthropic selection is to define an anthropic index

$$A = \log [P(O/x > x_e)/P(O/x < x_e)] \quad (2)$$

where x_e is the value of x for the Earth, $P(O/x > x_e)$ is the probability of observers appearing on planets where $x > x_e$ and $P(O/x < x_e)$ is the probability of observers appearing on planets where $x < x_e$. This anthropic index encapsulates information about the shape of the habitability likelihood function, $P(O/x)$ since, if the likelihood is generally higher for $x < x_e$ than for $x > x_e$, A will be negative indicating that low values of x are more likely to produce inhabited worlds. Similarly, if large values of x are anthropically favoured, this will be indicated by a positive value for A. Clearly, there are many ways of characterizing the shape of $P(O/x)$ but the form chosen here has the advantage that, as will be shown below, the ratio of the probabilities given in Eq. (2) can be estimated given knowledge of x_e and $P(x)$. Furthermore, taking the logarithm of this ratio ensures that selection for large x or for small x are treated equally (e.g. if the typical habitability likelihood for $x > x_e$ is ten times bigger than for $x < x_e$, $A = 1$ whilst, if it is ten times smaller, $A = -1$). Using a logarithm also has the advantage that positive (negative) A indicates a broadly positive (negative) gradient for $P(O/x)$ in the vicinity of $x = x_e$.

The probabilities in Eq. (2) are by definition

$$P(O/x < x_e) = \int_{-\infty}^{x_e} P(x)P(O/x)\,dx \Big/ \int_{-\infty}^{x_e} P(x)\,dx = \int_{-\infty}^{x_e} P(x)P(O/x)\,dx \Big/ P(x < x_e) \quad (3)$$

and

$$P(O/x > x_e) = \int_{x_e}^{\infty} P(x)P(O/x)\,dx \Big/ P(x > x_e) \quad (4)$$

The integral in Eq. (3) can be determined by integrating Eq. (1) to give $P(x < x_e/O)$, the probability that, on planets with observers, the value for x will be less than its Earth value, x_e, i.e.

$$P(x < x_e/O) = \int_{-\infty}^{x_e} P(x/O)\,dx = \int_{-\infty}^{x_e} P(x)P(O/x)\,dx/P(O) \quad (5)$$

Similarly, the integral in Eq. (4) can be obtained from

$$P(x > x_e/O) = \int_{x_e}^{\infty} P(x/O)\,dx = \int_{x_e}^{\infty} P(x)P(O/x)\,dx/P(O) \quad (6)$$

Combining Eqs. (2)–(6) then gives

$$A = \log[P(x < x_e)/P(x > x_e)] + \log[P(x > x_e/O)/P(x < x_e/O)] = \log[P(x < x_e)/\{1 - P(x < x_e)\}] + \log[\{1 - P(x < x_e/O)\}/P(x < x_e/O)] \quad (7)$$

Note that $P(x < x_e)$ can be determined by observation of the general population of exoplanets whilst $P(x < x_e/O)$ can be assigned based upon the assumption that the Earth is a typical inhabited world, i.e. the best estimate is

$$P(x < x_e/O) = 0.5 \quad (8)$$

with a plausible range of

$$0.5\alpha < P(x < x_e/O) < (1 - 0.5\alpha) \quad (9)$$

where α is a chosen level of statistical significance. Hence, Eq. (7) can be rewritten as

$$A = A_{best} \pm \Delta A \quad (10)$$

with

$$A_{best} = \log[P(x < x_e)/\{1 - P(x < x_e)\}] \quad (11)$$

and

$$\Delta A = \log[\{1 - 0.5\alpha\}/0.5\alpha] \quad (12)$$

The null hypothesis that there is no anthropic selection effect would then be accepted if $|A_{best}| < \Delta A$ since the allowed range then includes $A = 0$. The significance level chosen for any statistical test is arbitrary but, in cases where the consequences of incorrectly rejecting the null-hypothesis are not too critical, a significance level of 5% is typically chosen (e.g. see Davis, 2002). This level of significance will be used in the remainder of this paper.

4. Stellar mass example

The mathematics in Section 3 has been developed to analyze statistical properties of the Earth compared to those of exoplanet populations. However, current data from exoplanet surveys is likely to be highly biased since both radial velocity and transit techniques are more sensitive to large planets in small orbits. Hence, the test cannot yet be usefully applied with confidence to any currently catalogued exoplanet properties (although this situation will hopefully change over the next few years and decades). Instead, the approach will be demonstrated here by comparing solar properties to those of the wider stellar population since solar properties may also be subject to anthropic selection effects.

In particular, the statistical test can determine whether there is significant anthropic selection for stellar mass, i.e. a tendency for observers to evolve on planets orbiting stars within a specific mass range. Fig. 2 shows a cumulative frequency plot for the masses of the nearest stars to the Sun (data from http://www.chara.gsu.edu/RECONS/TOP100.posted.htm). The 157 stars used here all lie within ~6 pc of the Sun as determined by the RECONS project (Henry et al., 2006). Nearby stars have been chosen to minimize underestimation of the frequency of low-luminosity stars. However, choosing nearby stars also means that the conclusions below only apply to planets orbiting stars similar to those in the solar neighbourhood (i.e. population I stars).

With this data, 94.9% of nearby stars are smaller than the Sun, i.e. $P(x < x_e) = 0.949$, where x is stellar mass. Combining this result with expressions (10)–(12) gives an anthropic index of $A = 1.27 \pm 1.59$ (assuming a significance level of $\alpha = 5\%$). Hence, the null hypothesis of no overall anthropic effect cannot be excluded.

5. Discussion

The development in this paper of the anthropic index, A, does not actually add much to testing of the null hypothesis, that there is no significant selection effect, since the requirement $A \neq 0$ is equivalent to the statement that the null hypothesis should be rejected if the Earth's value lies outside the 95% confidence zone of typical values (assuming $\alpha = 5\%$). The real importance of A is that it encodes information about the shape of the habitability likelihood function, $P(O/x)$. In particular, if the best estimate is accepted, the analysis above implies that the habitability likelihood for $M_\star > M_\odot$ is 18.6 times larger than for $M_\star < M_\odot$ (since $10^{1.27} = 18.6$). In practice, the shape of Fig. 2 implies that the integral in Eq. (3) will be dominated by the likelihood of observers orbiting low mass stars (roughly $M_\star < 0.2M_\odot$) whilst the integral in Eq. (4) will be dominated by the likelihood of observers orbiting solar mass stars. Hence, the

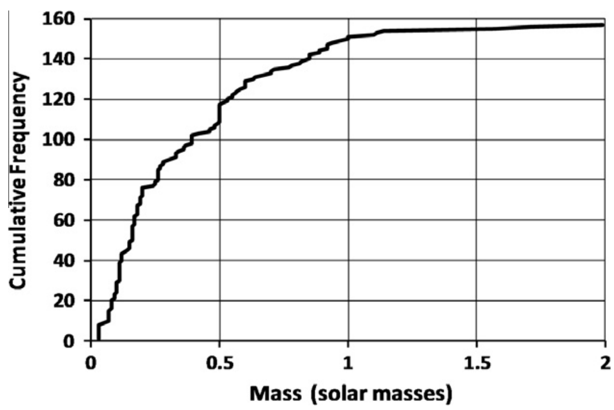

Fig. 2. Cumulative frequency plot, for stars in the solar neighbourhood, showing that 94.9% (149 out of 157) are smaller than the Sun (data from http://www.chara.gsu.edu/RECONS/TOP100.posted.htm).

above result together with Eq. (2) implies that observers are 18.6 times more likely around solar mass stars than they are around low mass stars.

On the other hand, if the minimum estimate of A is accepted (i.e. $A = 1.27 - 1.59 = -0.32$), the habitability likelihood for solar mass stars is 0.48 times larger than for low mass stars (since $10^{-0.32} = 0.48$), i.e. low mass stars can be no more than twice as habitable as solar mass stars.

This conclusion has major implications when combined with the coincidence, outline in Section 1, that the emergence of observers has occurred on Earth on a similar timescale to that of the habitability duration of our planet. These two observations can only be reconciled if the environment around low-mass stars is sufficiently unfavourable to outweigh the benefits of a longer habitability timescale. For example, a star with $M_\star = 0.2M_\odot$ will stay on the main sequence for approximately 500 billion years and, as shown by Kasting et al. (1993), the habitable zone will remain essentially static through nearly all of that period. Hence, a $0.2M_\odot$ star could be habitable for 100 times as long as the Earth. Furthermore, the Carter (1983) and Watson (2008) models imply that the probability of intelligent life is approximately constant with time and, hence, the overall implication is that a $0.2M_\odot$ star should have a habitability likelihood 100 times larger than that of a solar-mass star. Since this conclusion is incompatible with $A = 1.27 \pm 1.59$, the habitability of low-mass stars must be significantly reduced by other factors.

A final general point, which emerges from the developments in this paper, is that it is extremely hard to conclusively demonstrate an anthropic selection effect. For $\alpha = 5\%$, the analysis of Section 3 implies that the null hypothesis can only be rejected if $|A_{best}|$ is greater than 1.59, i.e. the typical habitability likelihood should change by a factor of at least 39 ($=10^{1.59}$) across $x = x_e$ before the case for anthropic selection can be considered to be statistically significant. This is a very severe test indeed which may make convincing demonstrations of anthropic selection effects almost impossible.

6. Conclusions

1. Anthropic selection can be characterized by an anthropic index
$$A = \log[P(x < x_e)/\{1 - P(x < x_e)\}] \qquad (14)$$
where $P(x < x_e)$ is the cumulative probability that $x < x_e$ for property x and where the Earth-value is x_e. This index can therefore be determined from the statistics of exoplanet surveys. The anthropic index indicates the strength and direction of possible selection effects.
2. The plausible range of the anthropic index is given by $A \pm 1.59$ (at the 5% significance level) and so the null hypothesis (no selection effect) cannot be ruled out unless $|A| > 1.59$.
3. Conclusion 2 implies that the habitability likelihood must change by a factor of $10^{1.59} = 39$ between $x < x_e$ and $x > x_e$. Hence, only very strong anthropic effects are conclusively detectable from a comparison of Earth properties to exoplanet properties.
4. Calculation of the anthropic index for stellar mass produces $A = 1.27$ implying an anthropic bias towards stars with $M_\star > M_\odot$. This supports previous studies showing that the environment around low-mass stars may be unfavourable for life. However the null hypothesis, that there is no anthropic selection for stellar mass, cannot be ruled out at the 5% significance level.

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