Is Life Most Likely Around Low-Mass Stars?

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The anthropic argument postulates the existence of other regions of space where the cosmological conditions are different, within the so-called multiverse that encompasses a volume far larger than our inflationary patch. Some of those regions would resemble ours except that they have matured to an older age. If such regions exist, we show that life is most likely to develop around low-mass stars, the so-called M-dwarfs, with a mass down to $\sim 0.1 M_\odot$. The lifetime of the lowest mass stars is longer by up to a factor of $\sim 10^3$ than that of the sun and their local abundance is a few times larger than stars more massive than the sun. The likelihood for life near M-dwarfs is therefore increased relative to sun-like stars by a factor of $\sim 3 \times 10^3 f$ over long timescales, where f is the efficiency of making rocky planets within the habitable zone of M-dwarfs relative to that of the sun. Upcoming observational program will be able to refine the observational estimate of f and provide a new test of the anthropic argument. An observed value of f well above a percent would imply that either the anthropic assumption about the diversity of regions within the multiverse is wrong, or else the environments around M-dwarfs lead to primitive life but not intelligent civilizations. In either case, primitive life will be most abundant in our universe in the future.

I. INTRODUCTION

Is life most likely to develop near stars like the sun? Over the past decade, more than 160 new planets outside the solar system were discovered [1]. Although most of the surveyed stars were sun-like, it is now becoming technologically feasible to search for planets near lower-mass (fainter) stars. On the one hand, the habitable zone around a star occupies a larger size if the star burns its nuclear fuel over a shorter time, but on the other hand the duty cycle decreases once the lifetime of the star gets to be shorter than the age of the Universe, t. The conditions for life are optimized when the star exhausts its nuclear fuel on a timescale comparable to t, as is the case for the sun. *Hence, in the future it would seem most favorable for life to develop near low-mass stars, the so-called M-dwarfs, with a lifetime longer than that of the sun.* If so, then in the context of the global history of our Universe, life around M-dwarfs would be much more common than life around sun-like stars. A global perspective of this type is achieved by viewing our observable universe in four (space+time) dimensions.

The above conclusion, although interesting, might seem asoteric to most astronomers since it applies to the long-term future of our Universe which will not be accessible any time soon. Nevertheless, here we show that it has far reaching consequences for one of the most fashionable ideas in string theory, namely the *anthropic argument*. Weinberg [2] and Linde [3] first suggested that the observed conditions in our Universe, such as the vacuum energy density, could arise in a theory that allows these conditions to be free parameters. On a scale much bigger than the observable Universe, one could then find regions in which the values of these parameters are different. However, if one selects those regions that give life to observers, then only a restricted range of parameter values would be allowed near the observed magnitudes. Vilenkin [4] showed that this so-called "anthropic argument" [5] can be used to calculate the probability distribution of vacuum densities with testable predictions. This notion [6–11] gained popularity when it was realized that string theory predicts the existence of an extremely large number [12–15], perhaps as large as $\sim 10^{100}$ to 10^{500} [16], of possible vacuum states. The resulting landscape of string vacua [17] in the "multiverse" encompassing a volume of space far greater than our own inflationary patch, made the anthropic argument appealing to particle physicists and cosmologists alike [11, 18, 19].

The anthropic argument postulates the existence of a *multiverse* that encompasses a volume far larger than our inflationary patch. Some of the regions within this volume might resemble ours except that they have matured to a much older age. The only way to quantify the likelihood for life would be in four-dimensions, as discussed above. The anthropic argument would suggest that intelligent life is not likely to develop around low-mass stars or else the solar system would represent a statistical fluke in the global four-dimensional cotext of the multiverse. The astronomical search for life near low-mass stars could provide an interesting test for the diversity of the multiverse which is postulated by the anthropic argument. This test is analogous to that offered by the descendents of high-redshift galaxies [20]. In §2 we quantify this novel test and in §3 we examine its implications.

II. QUANTITATIVE ANALYSIS

To illustrate our argument, let us first consider the fiducial example a star with a mass $M = 0.1 M_\odot$ (just above the hydrgen burning threshold of $0.08 M_\odot$). The luminosity of such a star on the main sequence is $L \approx$

$10^{-3}L_\odot$ and its radius $R \approx 10^{-0.9}R_\odot$ [21, 22]. Stars with $M \lesssim 0.3M_\odot$ are fully convective and burn most of their hydrogen into helium, compared to the sun which burns only $\sim 10\%$ of its hydrogen over its lifetime $t_\odot = 10^{10}$ years. Thus, the hydrogen burning lifetime of a $0.1M_\odot$ star is $\sim 10^{13}$ years, two orders of magnitude larger than the present age of the Universe.

Longer-lived environments for life may exist under special circumstances. For example, $0.3M_\odot$ is the lower mass limit for burning helium by the triple-alpha process, and so just around that mass range there will be stars which will burn all their hydrogen to helium and then, slowly all of their helium to carbon. Potentially, $0.3M_odot$ stars are the longest lived nuclear reactors. Below $0.3M_\odot$, a fully convective star never become a giant. The abrupt composition discontinuity that separates the evolution of the outer envelope from that of the core in giant star never develops. Hence, when such a star runs out of nuclear fuel, it simply gradually cools and shrinks to become a white dwarf [23]. Such stars might be more suitable long-term habitats for life since the gravitational binding energy of the white dwarf is available to life on a nearby planet in a rather gentle and benign way.

The latest data on the mass function of nearby stars at low masses [24] indicates that $\sim 75\%$ of all stars are M-dwarfs with masses in the range $0.08 < M < 0.6M_\odot$. If we restrict our attention to masses $0.08 < M < 0.2M_\odot$, the fraction is $\sim 40\%$.

We define the habitability radius to be the radius where the surface of the planet obtains the same temperature as the Earth. Assuming that the planet has the Earth's albedo and that the stellar spectrum is close to a black body, the habitability radius is

$$R_h = 1\mathrm{AU} \times \left(\frac{L}{L_\odot}\right)^{1/2}, \tag{1}$$

which for a $0.1M_\odot$ star gives

$$R_h = 4 \times 10^{11}\ \mathrm{cm}. \tag{2}$$

Simple estimates indicate that this radius is an order-of-magnitude smaller than the tidal-locking radius for an Earth-like planet, $R_t \sim 3 \times 10^{12}$cm [25]. Tidal locking might potentially lead to a freezing of the atmosphere, eliminating the prospects for life. However, the conditions in a synchronously-rotating planet atmospheres were modelled in detail with 3D climate codes [26], with the overall conclusion that a fairly modest atmosphere (e.g., $\sim 10\%$ of the Earth's) can provide sufficient heat transport to prevent freeze out of the atmosphere on the dark side. The existence of an atmosphere around planets near M-dwarfs can be in principle inferred from precise spectroscopy of transits[27], although this would be very challenging for faint stars and Earth-like planets.

The goal of an observing program (e.g. using a proposed far-IR instrument on Gemini ???) would be to calibrate the abundance of planets in the habitable zone around low-mass stars relative to that of solar-type stars. We denote this "planet-formation efficiency" factor as f. There is another factor involving the chance of having an intelligent civilization (IC) above some "intelligence threshold" in a habitable planet near an M-dwarf, which we denote as F. The value of F could only be inferred from Searches for Extraterrestrial Civilizations (SETI, see http://www.seti.org/), and is very difficult to calculate from first principles.

In summary, the likelihood of having intellogent life around a $0.1M_\odot$ star in the future is larger than that near the sun by an overall factor

$$P \sim 3 \times 10^3 \times f \times F. \tag{3}$$

Under the optimistic circumstances of $f \times F \sim 1$, it would be possible to rule-out the anthropic argument at a confidence level of 99.9% *as long as planets retain their atmospheres inside the tidal locking radius.*

FIG. 1: The dependence of the lifetime of low-mass stars on their mass. The upper panel shows the lifetime and the lower-panel shows the product of the lifetimes with the stellar mass.

The radial profile of the surface mass density $\Sigma(R)$ of proto-planetary disks is not well known. For a power-law dependence $\Sigma \propto R^{-2}$ which is favored by some data [28], the mass per logarithmic radius bin is independent of radius and therefore independent of the normalization of R_h[**?**]. The planet formation probability in the habitable zone would then scale as the total mass in the disk, M_d. The relation between M_d and M is not well known either. If $M_d \propto M$, then the coefficient $f \propto M$ would drop by an order of magnitude for $0.1 M_o dot$ stars relative to the sun, but arguments to the contrary were made in the literature [29]. Existing searches have so far failed to find close-in Jovian planets around M-dwarfs [30].

To gauge the sensitivity of $P(M)$ to different assumptions about f, we show in Fig. 1 two panels corresponding to $f = const$ and $f \propto M$. The upper panel shows the mass dependence of the lifetime of stars with $0.08 < M < 1 M_\odot$, while the lower panel shows the same for the product of the lifetime and M. The plots were calculated assuming that the hydrogen fuel makes the same fraction of M for all stars with $0.3 M_\odot < M < 1 M_\odot$ [21], and by adopting lifetimes in the range $0.08 M_\odot < M < 0.25 M_\odot$ from Ref. [23].
• Comment on the sensitivity of predictions to metallicity.

III. CONCLUSIONS

The lifetime of M-dwarfs with a mass of $\sim 0.1 M_\odot$ is longer by a factor of $\sim 10^3$ than that of the sun and their local abundance is a few times larger than stars more massive than the sun. The likelihood for life near them relative to sun-like stars is therefore increased by a factor of $\sim 3 \times 10^3 f$ over long timescales, where f is the efficiency of making planets within the habitable zone of M-dwarfs relative to that of the sun. Future observations will be able to refine the value of f and provide a new test of the anthropic argument. An observed value of f well above a percent would imply that either the basic anthropic assumption about diversity of the multiverse is wrong, or else an intelligent civilization as we know it - is a very rare form of life, and primitive life is much more abundant elsewehre in the multiverse.
• Because the majority of the known planets were detected through precise radial velocity measurements which require a large number of photons, most of the known extra-solar planets are jupiter like around nearby stars within tens of parsec from the sun. Habitable conditions for life may exist on moons around these giant planets or in other planetary systems that better resemble the solar system. Given the high detection rate of new planets, the question of whether intelligent life exists elsewhere in the Galaxy is very timely.
• At the end it might be some threshold factor that will do the selection, but getting to that conclusion is itself very important. At least one would conclude that the most likely site for primitive life in the future of our Universe is an M-dwarf. This is a non-trivial result. For example, it implies that the nearest star where primitive life might exist is closer than previously thought. Also, it allows our civilization to choose a more abundant relocation site once the sun will die. This could be of "practical" importance for future generations.
• In the paper by Segura et al. (astro-ph/0510224), there is relevant information about planets near M-dwarfs (see Introduction and Conclusion sections and references therein) that we should use here. Given this and the Tarter et al. paper, our novel addition to existing discussions is clearly the time domain and the connection to the anthropic argument.

Acknowledgments. We thank Bohdan Paczynski for useful discussions.

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[] For the maximum solar nebula, the power-law index of $\Sigma(R)$ is $-3/2$ and the reduction in the value of the f factor with decreasing mass is a bit milder although not too different from the case where the index is -2.