

Relative likelihood for life as a function of cosmic time

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Relative likelihood for life as a function of cosmic time

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Received June 29, 2016

Accepted July 26, 2016

Published August 18, 2016

Abstract. Is life most likely to emerge at the present cosmic time near a star like the Sun? We address this question by calculating the relative formation probability per unit time of habitable Earth-like planets within a fixed comoving volume of the Universe, $dP(t)/dt$, starting from the first stars and continuing to the distant cosmic future. We conservatively restrict our attention to the context of “life as we know it” and the standard cosmological model, Λ CDM. We find that unless habitability around low mass stars is suppressed, life is most likely to exist near $\sim 0.1M_{\odot}$ stars ten trillion years from now. Spectroscopic searches for biosignatures in the atmospheres of transiting Earth-mass planets around low mass stars will determine whether present-day life is indeed premature or typical from a cosmic perspective.

Keywords: stars, star formation, first stars

ArXiv ePrint: [1606.08448](https://arxiv.org/abs/1606.08448)

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1 Introduction

The known forms of terrestrial life involve carbon-based chemistry in liquid water [1]. In the cosmological context, life could not have started earlier than 10 Myr after the Big Bang ($z \gtrsim 140$) since the entire Universe was bathed in a thermal radiation background above the boiling temperature of liquid water. Later on, however, the Universe cooled to a *habitable epoch* at a comfortable temperature of 273–373 K between 10–17 Myr after the Big Bang [2].

The phase diagram of water allows it to be liquid only under external pressure in an atmosphere which can be confined gravitationally on the surface of a planet. To keep the atmosphere bound against evaporation requires strong surface gravity of a rocky planet with a mass comparable to or above that of the Earth [3].

Life requires stars for two reasons. Stars are needed to produce the heavy elements (carbon, oxygen and so on, up to iron) out of which rocky planets and the molecules of life are made. Stars also provide a heat source for powering the chemistry of life on the surface of their planets. Each star is surrounded by a habitable zone where the surface temperature of a planet allows liquid water to exist. The approximate distance of the habitable zone, r_{HZ} , is obtained by equating the heating rate per unit area from the stellar luminosity, L , to the cooling rate per unit area at a surface temperature of $T_{\text{HZ}} \sim 300$ K, namely $(L/4\pi r_{\text{HZ}}^2) \sim \sigma T_{\text{HZ}}^4$, where σ is the Stefan-Boltzman constant [1].

According to the standard model of cosmology, the first stars in the observable Universe formed ~ 30 Myr after the Big Bang at a redshift, $z \sim 70$ [2, 4–6]. Within a few Myr, the first supernovae dispersed heavy elements into the surrounding gas, enriching the second generation stars with heavy elements. Remnants from the second generation of stars are found in the halo of the Milky Way galaxy, and may have planetary systems in the habitable zone around them [7]. The related planets are likely made of carbon, and water could have been delivered to their surface by icy comets, in a similar manner to the solar system. The formation of water is expected to consume most of the oxygen in the metal poor interstellar medium of the first galaxies [8].

Currently, we only know of life on Earth. The Sun formed ~ 4.6 Gyr ago and has a lifetime comparable to the current age of the Universe. But the lowest mass stars near the hydrogen burning threshold at $0.08M_{\odot}$ could live a thousand times longer, up to 10 trillion years [9, 10]. Given that habitable planets may have existed in the distant past and might exist in the distant future, it is natural to ask: *what is the relative probability for the emergence of life as a function of cosmic time?* In this paper, we answer this question conservatively by restricting our attention to the context of “life as we know it” and the standard cosmological model (Λ CDM).¹ Note that since the probability distribution is normalized to have a unit integral, it only compares the relative importance of different epochs for the emergence of life but does not calibrate the overall likelihood for life in the Universe. This feature makes our results robust to uncertainties in normalization constants associated with the likelihood for life on habitable planets.

In section 2 we express the relative likelihood for the appearance of life as a function of cosmic time in terms of the star formation history of the Universe, the stellar mass function, the lifetime of stars as a function of their mass, and the probability of Earth-mass planets in the habitable zone of these stars. We define this likelihood within a fixed comoving volume which contains a fixed number of baryons. In predicting the future, we rely on an extrapolation of star formation rate until the current gas reservoir of galaxies is depleted. Finally, we discuss our numerical results in section 3 and their implications in section 4.

2 Formalism

2.1 Master equation

We wish to calculate the probability $dP(t)/dt$ for life to form on habitable planets per unit time within a fixed comoving volume of the Universe. This probability distribution should span the time interval between the formation time of the first stars (~ 30 Myr after the Big Bang) and the maximum lifetime of all stars that were ever made (~ 10 Tyr).

The probability $dP(t)/dt$ involves a convolution of the star formation rate per comoving volume, $\dot{\rho}_*(t')$, with the temporal window function, $g(t-t', m)$, due to the finite lifetime of stars of different masses, m , and the likelihood, $\eta_{\text{Earth}}(m)$, of forming an Earth-mass rocky planet in the habitable zone (HZ) of stars of different masses, given the mass distribution of stars, $\xi(m)$, times the probability, $p(\text{life}|\text{HZ})$, of actually having life on a habitable planet. With all these ingredients, the relative probability per unit time for life within a fixed comoving volume can be written in terms of the double integral,

$$\frac{dP}{dt}(t) = \frac{1}{N} \int_0^t dt' \int_{m_{\min}}^{m_{\max}} dm' \xi(m') \dot{\rho}_*(t', m') \eta_{\text{Earth}}(m') p(\text{life}|\text{HZ}) g(t-t', m'), \quad (2.1)$$

where the pre-factor $1/N$ assures that the probability distribution is normalized to a unit integral over all times. The window function, $g(t-t', m)$, determines whether a habitable

¹We address this question from the perspective of an observer in a single comoving Hubble volume formed after the end of inflation. As such we do not consider issues of self-location in the multiverse, nor of the measure on eternally inflating regions of space-time. We note, however, that any observers in a post-inflationary bubble will by necessity of the eternal inflationary process, only be able to determine the age of their own bubble. We therefore restrict our attention to the question of the probability distribution of life in the history of our own inflationary bubble.

planet that formed at time t' is still within a habitable zone at time t . This function is non-zero within the lifetime $\tau_*(m)$ of each star, namely $g(t - t', m) = 1$ if $0 < (t - t') < \tau_*(m)$, and zero otherwise. The quantities m_{\min} and m_{\max} represent the minimum and maximum masses of viable host stars for habitable planets, respectively. Below we provide more details on each of the various components of the above master equation.

2.2 Stellar mass range

Life requires the existence of liquid water on the surface of Earth-mass planets during the main stage lifetime of their host star. These requirements place a lower bound on the lifetime of the host star and thus an upper bound on its mass.

There are several proxies for the minimum time needed for life to emerge. Certainly the star must live long enough for the planet to form, a process which took ~ 40 Myr for Earth [11]. Moreover, once the planet formed, sufficient cooling must follow to allow the condensation of water on the planet's surface. The recent discovery of the earliest crystals, Zircons, suggest that these were formed during the Archean era, as much as 160 Myr after the planet formed [12]. Thus, we arrive at a conservative minimum of 200 Myr before life could form - any star living less than this time could not host life on an Earth-like planet. At the other end of the scale, we find that the earliest evidence for life on Earth comes from around 800 Myr after the formation of the planet [11], yielding an upper bound on the minimum lifetime of the host star. For the relevant mass range of massive stars, the lifetime, τ_* , scales with stellar mass, m , roughly as $(\tau_*/\tau_\odot) = (m/M_\odot)^{-\alpha}$, where α depends on the stellar mass, as shown in equation (2.3). Thus, we find that the maximum mass of a star capable of hosting life (m_{\max}) is in the range $2.8\text{--}4.7M_\odot$. Due to their short lifetimes and low abundances, high mass stars do not provide a significant contribution to the probability distribution, $dP(t)/dt$, and so the exact choice of the upper mass cutoff in the above range is unimportant. The lowest mass stars above the hydrogen burning threshold have a mass $m = 0.08M_\odot$.

2.3 Time range

The first stars are predicted to have formed at a redshift of $z \sim 70$, about 30 Myr after the Big Bang [2, 4–6]. Their supernovae resulted in a second generation of stars — enriched by heavy elements, merely a few Myr later. The theoretical expectation that the second generation stars should have hosted planetary systems can be tested observationally by searching for planets around metal poor stars in the halo of the Milky Way galaxy [7].

Star formation is expected to exhaust the cold gas in galaxies as soon as the Universe will age by a factor of a few (based on the ratio between the current reservoir of cold gas in galaxies [13] and the current star formation rate), but low mass stars would survive long after that. The lowest mass stars near the hydrogen burning limit of $0.08M_\odot$, have a lifetime of order 10 trillion years [9]. The probability $dP(t)/dt$ is expected to vanish beyond that time.

2.4 Initial mass function

The initial mass function (IMF) of stars $\xi(m)$ is proportional to the probability that a star in the mass range between m and $m + dm$ is formed. We adopt the empirically-calibrated, Chabrier functional form [14], which follows a lognormal form for masses under a solar mass,

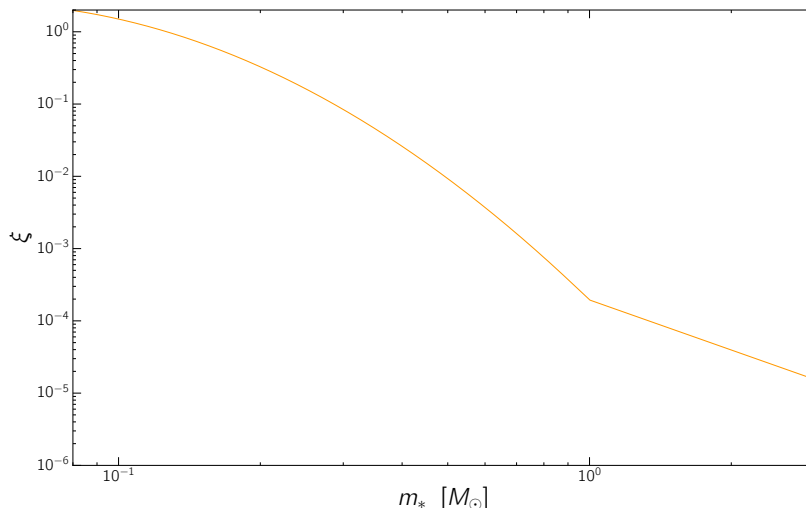


Figure 1. The Chabrier [14] mass function of stars, $\xi(m_*)$, plotted with a normalization integral of unity.

and a power law above a solar mass, as follows:

$$\xi(m) \propto \begin{cases} \left(\frac{m}{M_\odot}\right)^{-2.3} & m > 1 M_\odot \\ a \exp\left(-\frac{\ln(m/m_c)^2}{2\sigma^2}\right) \frac{M_\odot}{m} & m \leq 1 M_\odot \end{cases}, \quad (2.2)$$

where $a = 790$, $\sigma = 0.69$, and $m_c = 0.08M_\odot$. This IMF is plotted as a probability distribution normalized to a unit integral in figure 1.

For simplicity, we ignore the evolution of the IMF with cosmic time and its dependence on galactic environment (e.g., galaxy type or metallicity [15]), as well as the uncertain dependence of the likelihood for habitable planets around these stars on metallicity [7].

2.5 Stellar lifetime

The lifetime of stars, τ_* , as a function of their mass, m , can be modelled through a piecewise power-law form. For $m < 0.25M_\odot$, we follow ref. [9]. For $0.75M_\odot < m < 3M_\odot$, we adopt a scaling with an average power law index of -2.5 and the proper normalization for the Sun [16]. Finally, we interpolate in the range between 0.25 and $0.75 M_\odot$ by fitting a power-law form there and enforcing continuity. In summary, we adopt,

$$\tau_*(m) = \begin{cases} 1.0 \times 10^{10} \text{ yr} \left(\frac{m}{M_\odot}\right)^{-2.5} & 0.75M_\odot < m < 3M_\odot \\ 7.6 \times 10^9 \text{ yr} \left(\frac{m}{M_\odot}\right)^{-3.5} & 0.25M_\odot < m \leq 0.75M_\odot \\ 5.3 \times 10^{10} \text{ yr} \left(\frac{m}{M_\odot}\right)^{-2.1} & 0.08M_\odot \leq m \leq 0.25M_\odot \end{cases}. \quad (2.3)$$

This dependence is depicted in figure 2.

The metallicity of galaxies increases steadily as stars fuse hydrogen and helium into heavier elements. A metallicity of $Z \approx 0.04$, about twice the solar value, maximizes the

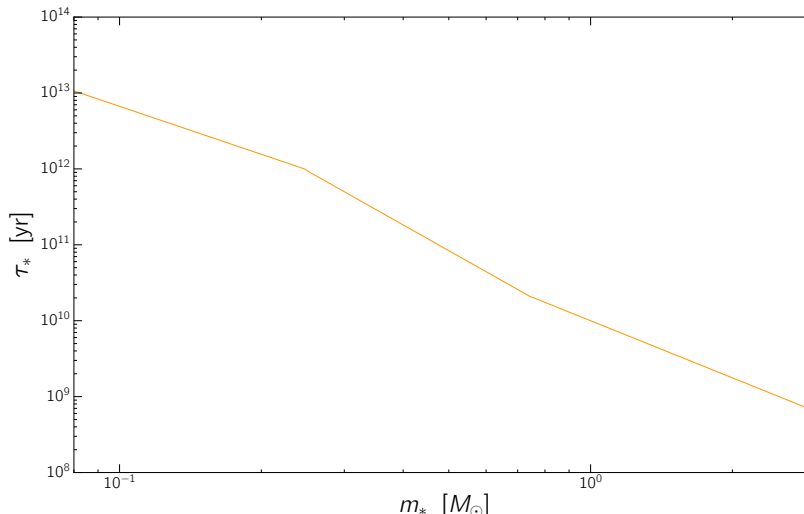


Figure 2. Stellar lifetime (τ_*) as a function of mass.

lifetime of stars [17]. We have incorporated the metallicity dependence of stellar lifetime into our calculations and found the resulting change in our results to be small compared to other uncertainties. For simplicity, we therefore ignore the metallicity evolution in our calculations.

2.6 Star formation rate

We adopt an empirical fit to the star formation rate per comoving volume as a function of redshift, z [18],

$$\dot{\rho}_*(z) = 0.015 \frac{(1+z)^{2.7}}{1 + [(1+z)/2.9]^{5.6}} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}, \quad (2.4)$$

and truncate the extrapolation to early times at the expected formation time of the first stars [2]. We extrapolate the cosmic star formation history to the future or equivalently negative redshifts $-1 \leq z < 0$ (see, e.g. ref. [19]) and find that the comoving star formation rate drops to less than 10^{-5} of the current rate at 56 Gyr into the future. We cut off the star formation at roughly the ratio between the current reservoir mass of cold gas in galaxies [13] and the current star formation rate per comoving volume.

To avoid an abrupt cutoff in the star formation rate, we assume a simple exponential form, $\exp\{-(t/t_1)\}$, with a characteristic timescale of $t_1 \sim 50$ Gyr that is dictated by the ratio between the present-day gas reservoir and star formation rate. This form is appropriate for a closed box model in which the consumption rate of gas in star formation is proportional to the gas mass available. The infall of fresh gas into galaxies is heavily suppressed in the cosmic future due to the accelerated cosmic expansion [20, 21]. Although galaxies continue to consume their gas reservoirs through star formation, some of this gas may be lost through supernova or quasar-driven winds. We therefore considered also a sharper exponential form, $\exp\{-(t/t_2)\}$ with $t_2 \sim 20$ Gyr, but found the final results to be indistinguishable within the overall uncertainties of the model.

The resulting star formation rate as a function of time and redshift is shown in figure 3.

2.7 Probability of life on a habitable planet

The probability for the existence of life around a star of a particular mass m can be expressed in terms of the product between the probability that there is an Earth-mass planet in the

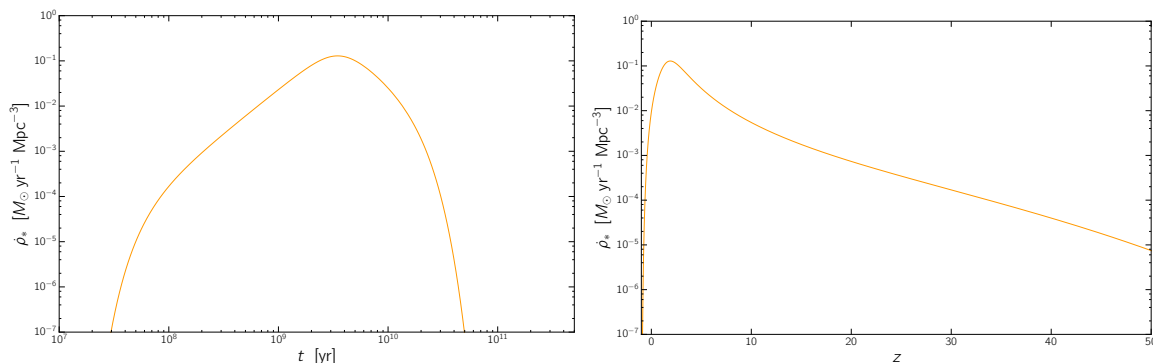


Figure 3. Star formation rate, $\dot{\rho}_*$, as a function of the cosmic time t (left panel) and redshift z (right panel), based on an extrapolation of a fitting function to existing data [18].

star’s habitable zone (HZ) and the probability that life emerges on such a planet: $P(\text{life}|m) = P(\text{HZ}|m)P(\text{life}|\text{HZ})$. The first factor, $P(\text{HZ}|m)$, is commonly labeled η_{Earth} in the exo-planet literature [22].

Data from the NASA Kepler mission implies η_{Earth} values in the range of $6.4_{-1.1}^{+3.4}\%$ for stars of approximately a solar mass [23–25] and $24_{-8}^{+18}\%$ for lower mass M-dwarf stars [26]. The result for solar mass stars is less robust due to lack of identified Earth-like planets at high stellar masses. Owing to the large measurement uncertainties, we assume a constant η_{Earth} within the range of stellar masses under consideration. The specific constant value of η_{Earth} drops out of the calculation due to the normalization factor N .

There is scope for considerable refinement in the choice of the second factor $p(\text{life}|\text{HZ})$. One could suppose that the probability of life evolving on a planet increases with the amount of time that the planet exists, or that increasing the surface area of the planet should increase the likelihood of life beginning. However, given our ignorance we will set this probability factor to a constant, an assumption which can be improved upon by statistical data from future searches for biosignatures in the molecular composition of the atmospheres of habitable planets [27–30]. In our simplified treatment, this constant value has no effect on $dP(t)/dt$ since its contribution is also cancelled by the normalization factor N .

3 Results

The top and bottom panels in figure 4 show the probability per log time interval $t dP(t)/dt = dP/d \ln t$ and the cumulative probability $P(< t) = \int_0^t [dP(t')/dt'] dt'$ based on equation (2.1), for different choices of the low mass cutoff in the distribution of host stars for life-hosting planets equally spaced in $\ln m$. The upper stellar mass cutoff has a negligible influence on $dP/d \ln t$, due to the short lifetime and low abundance of massive stars. In general, $dP/d \ln t$ cuts off roughly at the lifetime of the longest lived stars in each case, as indicated by the upper axis labels. For the full range of hydrogen-burning stars, $dP(t)/d \ln t$ peaks around the lifetime of the lowest mass stars $t \sim 10^{13}$ yr with a probability value that is a thousand times larger than for the Sun, implying that life around low mass stars in the distant future is much more likely than terrestrial life around the Sun today.

For mass ranges centered narrowly around a solar mass, we find that the current time indeed represents the peak of the probability distribution. However, as we allow lower mass stars to enter the distribution, the peak is shifted into the future due to the higher abundance

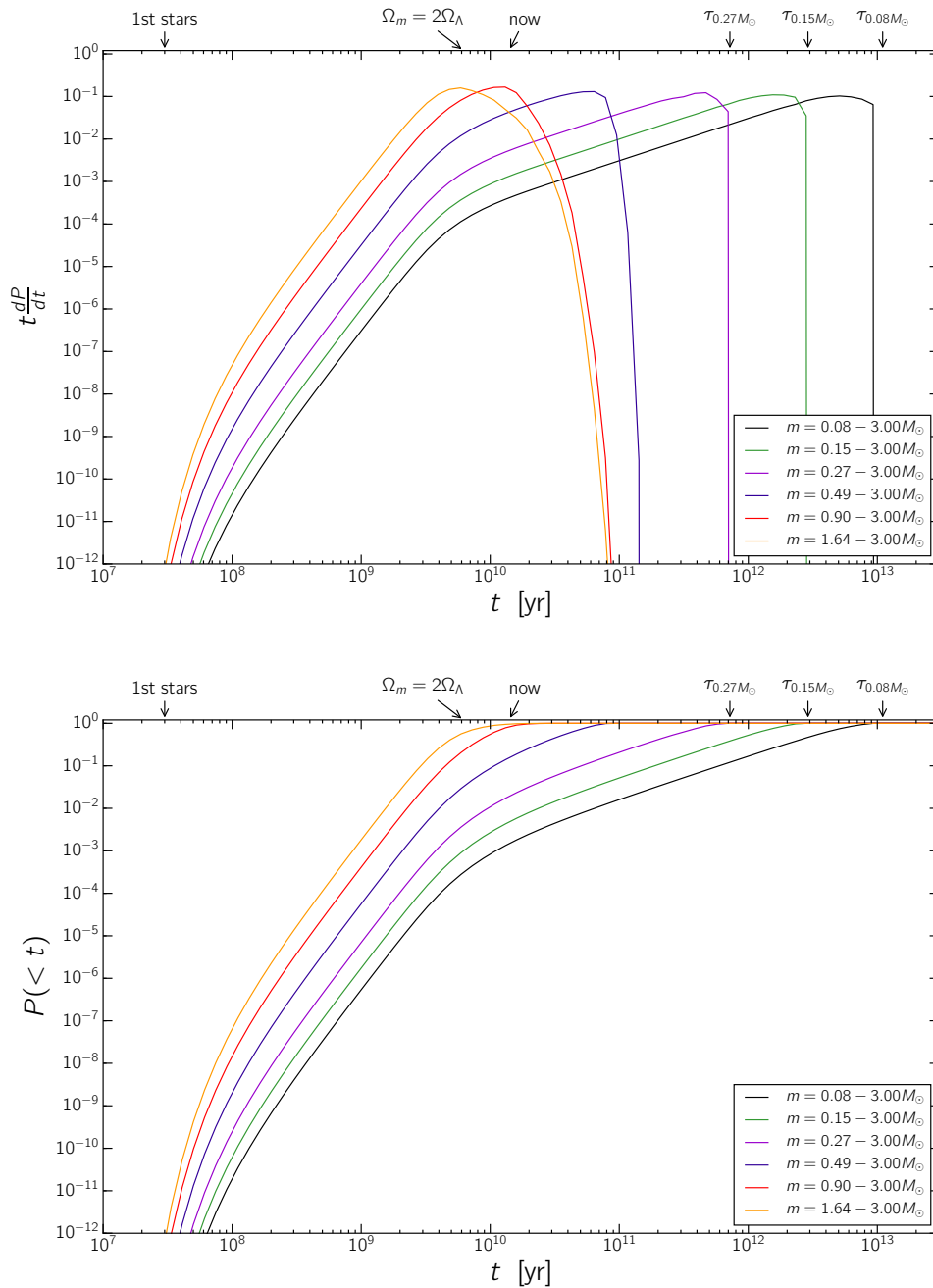


Figure 4. Probability distribution for the emergence of life within a fixed comoving volume of the Universe as a function of cosmic time. We show the probability per log time, $t dP/dt$ (top panel) as well as the cumulative probability up to a time t , $P(<t)$ (bottom panel), for different choices of the minimum stellar mass, equally spaced in $\log m$ between $0.08M_{\odot}$ and $3M_{\odot}$. The contribution of stars above $3M_{\odot}$ to $dP(t)/dt$ is ignored due to their short lifetimes and low abundances. The labels on the top axis indicate the formation time of the first stars, the time when the cosmic expansion started accelerating (i.e., when the density parameter of matter, Ω_m , was twice that of the vacuum, Ω_{Λ}), the present time (now) and the lifetimes of stars with masses of $0.08M_{\odot}$, $0.15M_{\odot}$ and $0.27M_{\odot}$.

of low mass stars and their extended lifetimes. It is interesting to note that a rather small extension of the mass range down to a quarter of a solar mass shifts the peak by two orders of magnitude in time into the future. Evidence of life around the nearest star, Proxima Centauri ($m = 0.12M_{\odot}$), for example, would indicate that our existence at or before the current cosmic time would be at the 0.1% level.

4 Discussion

Figure 4 implies that the probability for life per logarithm interval of cosmic time, $dP(t)/d\ln t$, has a broad distribution in $\ln t$ and is peaked in the future, as long as life is likely around low-mass stars. High mass stars are shorter lived and less abundant and hence make a relatively small contribution to the probability distribution.

Future searches for molecular biosignatures (such as O_2 combined with CH_4) in the atmospheres of planets around low mass stars [27, 29] could inform us whether life will exist at late cosmic times [31]. If we insist that life near the Sun is typical and not premature, i.e. require that the peak in $dP(t)/d\ln t$ would coincide with the lifetime of Sun-like stars at the present time, then we must conclude that the physical environments of low-mass stars are hazardous to life (see e.g. ref. [32]). This could result, for example, from the enhanced UV emission and flaring activity of young low-mass stars, which is capable of stripping rocky planets of their atmospheres [33].

Values of the cosmological constant below the observed one should not affect the probability distribution, as they would introduce only mild changes to the star formation history due to the modified formation history of galaxies [20, 21]. However, much larger values of the cosmological constant would suppress galaxy formation and reduce the total number of stars per comoving volume [34], hence limiting the overall likelihood for life altogether [35]. This is of course a crude estimate, as we are varying only one fundamental parameter out of a plethora of possible changes in cosmological parameters. A larger amplitude of density fluctuations could certainly allow for structure formation to continue; however, ref. [36], for example, argues that this is anthropically disfavoured as it would lead to increased instability in planetary orbits and the habitable zones would not be occupied long enough for life to emerge.

Our results provide a new perspective on the so-called ‘‘coincidence problem’’, *why do we observe $\Omega_m \sim \Omega_{\Lambda}$?* [37] The answer comes naturally if we consider the history of Sun-like star formation, as the number of habitable planets peaks around present time for $m \sim 1M_{\odot}$. We note that for the majority of stars, this coincidence will not exist as $dP(t)/dt$ peaks in the future where $\Omega_m \ll \Omega_{\Lambda}$ (cf. ref. [38, 39]). The question is then, why do we find ourselves orbiting a star like the Sun now rather than a lower mass star in the future?

One can certainly contend that our result presumes our existence, and we therefore have to exist at some time. Although our result puts the probability of finding ourselves at the current cosmic time within the 0.1% level, rare events do happen. In this context, we reiterate that our results are an order of magnitude estimate based on the most conservative set of assumptions within the standard Λ CDM model. If one were to take into account more refined models of the beginning of life and observers, this would likely push the peak even farther into the future, and make our current time less probable. As an example, one could consider that the beginning of life on a planet would not happen immediately after the planet becomes ‘habitable’. Since we do not know the circumstances that led to life on Earth, it would be more realistic to assume that some random event must have occurred to initiate

life, corresponding to a Poisson process. This would suppress early emergence and thus shift the peak probability to the future.

A similar effect would arise from refining our notion of a probability through re-weighting by the number observers on a planet. Although this may reach some theoretical peak, populations are at best exponentially suppressed to the past, and so a given *observer* (as opposed to inhabited planet) would be more likely to exist later on in a planet’s existence. There are several other such factors (stability of habitable zone, galactic mergers and reseeded, etc) all of which push the peak to the future. Our conclusion is therefore that the most conservative estimate put the probability of our existence before the current cosmic time at 0.1% at most. It is likely that with more refined models this number will be reduced, and so the above mentioned question becomes ever more pertinent.

We derived our numerical results based on a conservative set of assumptions and guided by the latest empirical data for the various components of equation (2.1). However, the emergence of life may be sensitive to additional factors that were not included in our formulation, such as the existence of a moon to stabilize the climate on an Earth-like planet [40], the existence of asteroid belts [41], the orbital structure of the host planetary system (e.g. the existence of nearby giant planets or orbital eccentricity), the effects of a binary star companion [42], the location of the planetary system within the host galaxy [43], and the detailed properties of the host galaxy (e.g. galaxy type [15] or metallicity [44]), including the environmental effects of quasars, γ -ray bursts [45] or the hot gas in clusters of galaxies. These additional factors are highly uncertain and complicated to model and were ignored for simplicity in our analysis.

The probability distribution $dP(t)/d\ln t$ is of particular importance for studies attempting to gauge the level of fine-tuning required for the cosmological or fundamental physics parameters that would allow life to emerge in our Universe.

Acknowledgments

AL thanks the “Consolidation of Fine-Tuning” project for inspiration that led to this work. RAB and DS thank Harvard’s Institute for Theory & Computation for its kind hospitality during the work on this paper. RAB and DS acknowledge the financial support of the John Templeton Foundation.

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