Formulation and resolutions of the red sky paradox

David Kipping

*Department of Astronomy, Columbia University, New York, NY 10027

Edited by Neta A. Bahcall, Princeton University, Princeton, NJ, and approved April 19, 2021 (received for review December 30, 2020)

Most stars in the Universe are red dwarfs. They outnumber stars like our Sun by a factor of 5 and outlive them by another factor of 20 (population-weighted mean). When combined with recent observations uncovering an abundance of temperate, rocky planets around these diminutive stars, we are faced with an apparent logical contradiction—Why do we not see a red dwarf in our sky? To address this "red sky paradox," we formulate a Bayesian probability function concerning the odds of finding oneself around an F/G/K-spectral type (Sun-like) star. If the development of intelligent life from prebiotic chemistry is a universally rapid and ensured process, the temporal advantage of red dwarfs dissolves, softening the red sky paradox, but exacerbating the classic Fermi paradox. Otherwise, we find that humanity appears to be a 1-in-100 outlier. While this could be random chance (resolution I), we outline three other nonmutually exclusive resolutions (II to IV) that broadly act as filters to attenuate the suitability of red dwarfs for complex life. Future observations may be able to provide support for some of these. Notably, if surveys reveal a paucity of temperate rocky planets around the smallest (and most numerous) red dwarfs, then this would support resolution II. As another example, if future characterization efforts were to find that red dwarf worlds have limited windows for complex life due to stellar evolution, this would support resolution III. Solving this paradox would reveal guidance for the targeting of future remote life sensing experiments and the limits of life in the cosmos.

Significance

Red dwarf stars are the most numerous and long-lived stars in the cosmos, and recent exoplanet discoveries indicate an abundance of rocky, temperate planets around them. This presents an apparent paradox as to why we do not see a red dwarf in our sky. This "red sky paradox" could plausibly be random chance at the 1-in-100 level but would then come into tension with the Copernican principle. Three additional resolutions to the paradox are outlined, which broadly inhibit the opportunities for complex life to develop around such stars: attenuated emergence rates, truncated evolutionary windows, and/or a paucity of suitable habitats. All three appear viable given our present limited knowledge but the potential for future observational tests is explored.

A basic observable concerning our existence is the star around which we find ourselves. Although many early thinkers reasoned as much prior to modern astronomy, it was not until the parallax measurement of 61 Cygni by Friedrich Bessel in 1838 (1) that the Sun’s banality as being merely another star within the cosmos was firmly established.” Yet despite this, the Sun is in many ways atypical of the ensemble.

The mass of our Sun (≡ 1 M☉), arguably its most fundamental property, is an order of magnitude greater than the minimum mass (∼0.08 M☉) necessary to generate the internal conditions required for hydrogen fusion (2–7), but two orders of magnitude less than the most massive stars observed (e.g., BI 253) (8). Although the Sun could thus be reasonably described as “middleweight,” it is hardly typical. Much like pebbles on the beach, there are far more small stars than massive ones, as revealed by studies of the stellar initial mass function (9–12). Indeed, approximately three-quarters of all stars are classified as M dwarfs, a range spanning ∼0.1 to 0.5 M☉. Due to their lower masses, the internal conditions are less intense than that of the Sun and so these stars have far lower luminosities, up to three orders of magnitude less, leading to cooler surface temperatures. Thus, inhabitants of these stars would see a pale orange/red disk in their sky, rather than the brilliant yellow disk we see in ours.1

The candle that burns twice as bright burns half as long, as so it is for stars too. Indeed, the Universe is not yet old enough for any red dwarfs (a.k.a. M dwarfs) to have yet exhausted their fuel supply of hydrogen; they are expected to live for ∼100 billion y for a 0.5-M☉ star and a staggering ∼10 trillion y for the smallest stars (13). In contrast, stars greater than 1.6 M☉, which are denoted as spectral types A, B, and O types, pass through their main sequence lifetimes in less than 2 billion y (14), compared to the Sun’s 10-billion-y stint. This severely truncates the opportunities for biology to evolve from simple chemical systems to complex, self-aware intelligent beings (15). It is thus perhaps no surprise that we do not find ourselves living around an O/B/A-type star: Not only are they intrinsically rare (comprising less than 1% of the stellar population) but also they simply do not persist for long enough to foster complex biology (16).

However, applying this same argument to M dwarfs, one encounters an apparent logical contradiction. All things being equal, one should expect that the far longer temporal window of stable luminosity that M dwarfs enjoy should yield a greater chance of complexity and intelligence eventually evolving (17, 18). This is compounded by the fact that M dwarfs are an order of magnitude more abundant than sun-like stars. In the same spirit as the Fermi paradox, we thus find ourselves facing another apparent logical contradiction dubbed here as the “red sky paradox”—If M dwarfs are so common and long lived, why don’t we find ourselves around one?

In the modern era of exoplanet hunting, one might immediately ask whether M dwarfs rarely harbor small rocky planets in their habitable zones, and so perhaps this offers an immediate remedy. Although we discuss this possibility in much more depth later, we highlight that current population statistics find that temperate, rocky planets are apparently common around both M dwarfs (19) and sun-like stars (20), and so no immediate observational resolution exists.

The outlined paradox has been previously noted in earlier work (21). In that work, the authors formulate the number

1Email: d.kipping@columbia.edu.
of habitable worlds associated with each star as the product of the number of such stars and the relative widths of their habitable zones. It is argued here that this formulation is problematic, since the abundance of planets around each star type does not appear to be uniform (22, 23), and indeed their properties that may affect habitability (such as composition, satellite system, impact rate, etc.) cannot be reasonably assumed to be uniform either (24). Further, when discussing the longer lives of M dwarfs, the authors weight the relative probability of a star being inhabited by the main-sequence lifetime directly, which is generally incorrect (17, 18). To see why, consider that the probability of a hypothetical Earth around an FGK star becoming inhabited equals 5%. If M dwarfs live 100 times longer, then by this reasoning the probability of an Earth around one of these stars becoming inhabited would be 500%—In other words, the probability exceeds unity and is improper. In reality, one should expect the probability to asymptotically approach unity (17, 18).

On this basis, it is worthwhile to revisit this paradox and in this work we formulate a Bayesian framework to understand the problem, which reveals four possible resolutions.

A Bayesian Framework

The outlined paradox concerns the probability of intelligent observers emerging on a habitable world around an FGK- versus an M-dwarf star. If these probabilities are approximately equal, or even favor FGKs, then no paradox exists. Although we have qualitatively outlined an argument as to why neither of these is likely true, we will here analytically do so.

Let us denote the probability of intelligent observers emerging on a habitable world, given that the world is bound to an FGK-type star, as \(P_r(I|G)\), where “I” denotes intelligence and “G” is shorthand for FGK. The specific conditions defining “habitable” are not well known and so our definition is operative—They are worlds with the necessary conditions to yield life and intelligence in infinite time under stable irradiance. Strictly, we truly do not mean “infinite” here, but rather a timescale that greatly exceeds the lifetime of the stars in question, to guard against the more exotic scenario of Boltzmann brains (25).

Following earlier work (17, 18, 26–28), we describe the emergence of life and intelligence as a uniform rate (i.e., Poisson process) defined by a rate parameter \(\lambda_G\). The justification, appropriateness, and weaknesses of this assumption are described in detail in the referenced works and we direct the reader to these for that discussion.

Unlike ref. 18, abiogenesis and intelligence are not treated as separate and causally dependent processes but rather as a single compound process that describes the entire process of nonliving chemicals developing into intelligent beings. This essentially absorbs all of the details into the \(\lambda_G\) term since the numbers of steps and their relationship to each other are unimportant to the question we seek to address in this work. The emergence of intelligence has a finite time window within which to occur (\(T_G\)), after which the FGK host star leaves the main sequence, leading to the likely terminal extinction of complex life (29). Accordingly, one may show that the probability of at least one successful emergence within this time frame equals (17)

\[
P_r(I|G) = 1 - \exp(-\lambda_G T_G).
\]  

Note that the above avoids the pitfalls of producing probabilities greater than one. In the limit of \(T_G \to 0\) one finds \(P_r(I|G) \to 0\), whereas \(T_G \to \infty\) yields \(P_r(I|G) \to 1\), as expected. Similarly, for M dwarfs we have

\[
P_r(I|M) = 1 - \exp(-\lambda_M T_M).
\]  

One may now flip this around and consider the probability of finding oneself around an FGK- or M-dwarf star, given that intelligence emerged. This can be accomplished through the use of Bayes’ theorem, with which one may show that

\[
P_r(G|I) = P_r(I|G)P_r(G)/P_r(I),
\]

where \(P_r(G)\) and \(P_r(M)\) represent the prior probabilities of choosing an FGK dwarf and an M dwarf or in other words the intrinsic abundance of these stars in the cosmos, \(n_G\) and \(n_M\).

Using a piecewise function, we can now incorporate these two possibilities as

\[
P_r(I) = \frac{1}{\text{Pr}(I)} \times \begin{cases} n_G(1 - e^{-\lambda_G T_G}), & \text{for } * = G \setminus M \setminus M \setminus G \setminus I, \text{ for } * = M. \end{cases}
\]  

Note that we have cast the paradox as a dichotomous problem; intelligence resides around either an FGK dwarf or an M dwarf. Other seats for life have certainly been speculated about in the literature, such as brown dwarfs (30), premain-sequence stars (31), evolved stars (32), stellar remnants (33) and rogue planets (34). However, including these objects, for which we have much greater uncertainty about their habitable windows and feasibility, serves only to exacerbate the red sky paradox. We thus take the conservative approach of neglecting these for the remainder of this study.

The as yet undefined \(P_r(I)\) term may be simply thought of as a normalization constant, which can be evaluated through summation over all possibilities defined to equal unity probability. In doing so, one finds

\[
P_r(I) = n_G(1 - e^{-\lambda_G T_G}) + n_M(1 - e^{-\lambda_M T_M}).
\]  

Equipped with a Bayesian formulation of the relevant probabilities, one can clearly see the various parameters affecting the analysis. Using this, we describe four possible resolutions to the red sky paradox.

Resolution I: An Unusual Outcome

Equipped with Eq. 4, one may now evaluate the likelihood of finding ourselves around an FGK dwarf. Just how surprising is it? Indeed, one possible resolution—dubbed resolution I—is that nothing is intrinsically different about the emergence of intelligence between FGK and M dwarfs; we are simply an unusual member by finding ourselves around a yellow dwarf.

All of the terms on the right-hand side of Eq. 4 can be reasonably estimated with the exception of \(\lambda_G\) and \(\lambda_M\)—the rate at which intelligent life emerges on habitable worlds around FGK dwarfs. Although we might consider that these rates are different between the two star types (as we will do explicitly in the next section), the simplest assumption is that they are approximately equal. Thus, we have just one unknown that can be explored through parameter variation.

For \(n_G\) and \(n_M\), one can simply assign these as the number of stars of each type. This implicitly assumes that the probability of finding a habitable world around each type of star is approximately equal. As discussed earlier, this is broadly consistent with current constraints from Kepler (19, 20), although very large uncertainties are in play. The possibility of this difference being significant is explored in the distinct resolution, resolution IV, later. With the initial mass function of ref. 35, the ratio \(n_G/n_M\) is evaluated to be 4.97 using the boundaries [0.08, 0.55] \(M_\odot\) for M dwarfs (M9 to M0 spectral types) (36) and [0.55, 1.6] \(M_\odot\) for FGK dwarfs (K9 to F0 spectral) (36).

Assigning singular values for \(T_G\) and \(T_M\) is challenged by the fact that subtypes within each category have very different lifetimes. One can calculate the weighted mean time across the
Formulation and resolutions of the red sky paradox

Kipping

∼ speaking then, M dwarfs are ratio of these values that is of greatest import here. Broadly only for some fraction of the total (29). Nevertheless, the habitable windows can be reasonably assumed to scale with the main-sequence lifetimes and thus we emphasize that it is the ratio of these values that is of greatest import here. Broadly speaking then, M dwarfs are ∼5 times more abundant and ∼20 times longer lived than FGK dwarfs. Together then, this quantifies that the red sky paradox concerns an imbalance of two orders of magnitude.

Using these numbers, we evaluate the likelihood of finding ourselves around an FGK star using Eq. 36 as a function of the one unknown parameter, λ, in Fig. 1. From this, two asymptotes are revealed in the slow (λ → 0) and fast (λ → ∞) emergence rate limits. In the limit of fast intelligence emergence, corresponding to a cosmos teaming with sentience, the red sky paradox is largely dissolved, which we dub as resolution I-f (f for “fast”), since

\[
\lim_{\lambda \to \infty} \Pr(G|I) = \frac{n_G}{n_G + n_M} \sim \frac{1}{6}. \tag{6}
\]

In contrast, in the rare intelligence limit, humanity would need to be a far more unusual example (which we dub resolution I-s, “slow”), with

\[
\lim_{\lambda \to 0} \Pr(G|I) = \frac{n_G T_G}{n_G T_G + n_M T_M} \sim 10^{-2}. \tag{7}
\]

On the face of it, resolution I-f might seem the most straightforward solution then. However, assuming such a fast emergence rate comes into tension with one hard observable and another softer one. The first hard limit is the timing of our own arrival in Earth’s evolutionary record (26). Although the 99% upper limit permits faster rates, this inference ignores any biological constraints on the rate of emergence and thus may be unrealistically expedient. Further, the softer constraint is that fast λ values exacerbate the classic Fermi paradox, since it leads to a cosmos teaming with intelligence that eludes detection. On this basis, there are good reasons to be skeptical that a fast emergence rate naturally explains the red sky paradox via resolution I-f.

Turning back to resolution I-s, then, this is also hardly satisfying by simply stating we are a 1-in-100 outlier. While it is indeed technically possible, it comes into tension with the Copernican principle that posits that our place in the Universe is typical and is indeed often treated as a basic assumption in our studies of the cosmos (37). We thus consider other resolutions in what follows.

Resolution II: Inhibited Life under a Red Sky

The paradox can be resolved if \( \Pr(G|I) \gtrsim \Pr(M|I) \). While one can be more specific than this and assign various confidence intervals (e.g., 95%), the simplicity of our model and approach does not warrant such an analysis, in our view. Applying this condition to Eq. 4, and rearranging to make \( \lambda_M \) the subject, one finds

\[
\lambda_M \lesssim T_M^{-1} \log \left( 1 - (n_G/n_M)(1 - e^{-3C}T_G) \right). \tag{8}
\]

Although \( \lambda_G \) is broadly unknown (although see ref. 18), one can evaluate Eq. 8 as a function of this unknown as done earlier. Since we are primarily interested in the relative capability of each star type producing intelligent life, the ratio \( \lambda_M/\lambda_G \) is of particular interest. This function is shown in Fig. 2, where one can see that for small \( \lambda_G \) values (a rare intelligence universe), \( \lambda_M/\lambda_G \) plateaus at around 1%. A turnover begins at around \( \lambda_G = 10^{-1.5} \) Gy^{-1}, which corresponds to even odds of each habitable planet around an FGK dwarf spawning intelligence. Beyond this point, one requires \( \lambda_M \ll \lambda_G \), which is because at high \( \lambda_G \), even the shorter-lived FGK stars become widely inhabited and thus \( \lambda_M \) has to dive down rapidly to prevent the more numerous, longer-lived M dwarfs dominating. One can thus see that this resolution may be analytically expressed as requiring

\[
\frac{\lambda_M}{\lambda_G} \lesssim \frac{T_G}{T_M} \frac{n_G}{n_M} \sim 10^{-2}. \tag{9}
\]

In other words, the probability of intelligent life emerging on M dwarfs would need to be at least two orders of magnitude less than that of emerging on FGK dwarfs. Certainly, much theoretical work has questioned the plausibility of complex life on M dwarfs (24), with concerns raised regarding tidal locking and atmospheric collapse (38–40), increased exposure to the effects of stellar activity (41–43), extended premain-sequence phases (3, 44), and the paucity of potentially beneficial Jupiter-sized companions (45–47). On this basis, there is good theoretical reasoning to support resolution II, although we emphasize that it remains observationally unverified.

Resolution III: A Truncated Window for Complex Life

Another way to inhibit life on M dwarfs is not to attenuate \( \lambda_M \), but instead truncate the time window available, \( T_M \). Terrestrial worlds forming in the main-sequence habitable zones of M dwarfs will be subject to an initial phase of high irradiance during the ∼Gy premain-sequence phase (44), potentially pushing them into a runaway greenhouse state (48) that persists thereafter (49). Although one might discount such worlds, their more distant orbiting siblings may enjoy a brief episode of habitability during this initial ∼Gy phase (31).
Fig. 2. Resolution II to the red sky paradox, where the emergence rate of intelligent life, $\lambda$, is much slower on M dwarfs than on FGK dwarfs. The hatched region shows the zone necessary to resolve the paradox such that $\Pr(G|I) \gtrsim \Pr(M|I)$, which is at least two orders of magnitude below the line of parity.

As before, we proceed by setting $\Pr(G|I) \gtrsim \Pr(M|I)$ but now instead solve for $T_M$. Under this resolution, which is distinct from resolution I, there is no significant difference between $\lambda_M$ and $\lambda_G$ and thus both are set to a universal value of $\lambda$, to give

$$T_M \lesssim -\lambda^{-1} \log \left( 1 - (n_G/n_M)(1 - e^{-\lambda T_G}) \right). \tag{10}$$

Eq. 10 displays similar functional behavior to Eq. 8, as can be seen in Fig. 3. Here, we find the plateau occurs at approximately one-fifth of $T_G$ when using our canonical values, or expressing actively we have

$$\frac{T_M}{T_G} \lesssim \frac{n_G}{n_M} \sim \frac{1}{5}. \tag{11}$$

Thus, resolution III requires that the habitable window of M dwarfs is $\lesssim 5$ times less than that of FGK dwarfs. Such a value aligns with the pre-main-sequence lifetimes ranging from 200 My (M1) to 2.5 Gy (M8), which is indeed $\lesssim 5$ times the main-sequence lifetimes of FGK stars, and thus we consider this a viable explanation.

Resolution IV: A Paucity of Pale Red Dots

The final way one can manipulate Eq. 4 to resolve the paradox is via the number of seats for life. Thus far, we have tacitly assumed that the occurrence rate of habitable worlds around FGK dwarfs is approximately the same as that around M dwarfs. Recall that our definition of a habitable world is one that will eventually culminate in complex, intelligent life in infinite time under stable irradiance. This is not an observable property, but modern astronomy is able to probe the occurrence rate of approximately Earth-sized planets in the temperate regions around stars where liquid water could be stable on their surfaces.

Statistical analysis of the Kepler exoplanet population reveals that $16^{+7}_{-2} \%$ of the observed M dwarfs host Earth-sized planets in a conservatively defined temperate zone (19), with other studies finding compatible values (23, 50). The situation for Kepler’s FGK stars is less clear with significant disagreement between different studies. For example, values of $2.8_{-1.9}^{+1.9}$, $1.9_{-0.8}^{+1.9}$, and $1.3_{-0.6}^{+0.6}$% have been reported (51–53), but so too have values as high as $103^{+14}_{-10}$ and $124^{+14}_{-12}$% (54, 55). The most recent analysis lands somewhere in the middle at $37^{+48}_{-21} \%$ (20). At the present time then, there is no clear evidence that the occurrence rate of temperate, Earth-sized planets is distinct between these stars.

However, there are crucial ways in which this could be wrong. First, the smallest M dwarfs hardly feature in the Kepler catalog despite comprising the majority of M dwarfs. This is due to Malmquist bias (56)—The smallest stars produce insufficient luminosities to be detected in such surveys in large numbers. It is deeply unclear whether the exoplanet population of M0 to M2 dwarfs is representative of the entire M-dwarf sample and thus it is possible that this could either resolve or exacerbate the red sky paradox. Second, the occurrence rate of temperate, Earth-sized planets is often presumed to be a proxy for the occurrence rate of habitable worlds, but this too could be challenged. Moons are completely ignored in this calculus, as are the subtle effects of internal composition, atmospheric composition, obliquity, rotation, and circumstellar environment. For example, the detected population of Earth-sized planets around M dwarfs could be dominated by photoevaporated cores of sub-Neptunes (57). Accordingly, it is quite plausible that there are substantial differences in the frequency of habitable abodes between the two categories.

To account for this, let us modify $n_G \rightarrow \epsilon G n_G$ and $n_M \rightarrow \epsilon_M n_M$ in Eq. 4, where $\epsilon$ represents the fraction of stars with one or more habitable worlds around them. Following this through and setting $\Pr(G|I) \gtrsim \Pr(M|I)$ as before, we can solve for $\epsilon_M/\epsilon_G$ to be

$$\frac{\epsilon_M}{\epsilon_G} \lesssim \frac{n_G}{n_M} \left( 1 - e^{-\lambda T_G} \right). \tag{12}$$

where we have again assumed that the emergence rate is approximately the same for habitable worlds bound to M dwarfs and FGK dwarfs. The functional form of Eq. 12 is plotted in Fig. 4, where the existence of two asymptotes becomes apparent. As with the previous resolutions, we again find a rare-life asymptote as $\lambda \to 0$, which tends to

$$\lim_{\lambda \to 0} \frac{\epsilon_M}{\epsilon_G} \lesssim \frac{n_G}{n_M} \frac{T_G}{T_M} \sim 10^{-2}. \tag{13}$$

In this case, intelligent life is rare among the cosmos and spawns universally between M and FGK dwarfs, but habitable worlds are at least two orders of magnitude less common around M dwarfs than around FGKs. Let us denote that as resolution IV-s. Two orders of magnitude is a considerable difference, making this a particularly interesting explanation. This would require that the vast majority of many known Earth-sized, temperate
Formulation and resolutions of the red sky paradox

The abundance of M dwarfs versus FGKs. However, this solution ingness” of our yellow host star is modest, given by the ratio of advantage that M dwarfs enjoy is dissolved and thus the “surprise of the distribution. Dubbed resolution I in this work, we with the logical argument only because we are a tail-end mem-

anywhere? In many ways, the paradox much longer lives. If M dwarfs are so numerous (in space and smaller M-dwarf stars dominate the stellar population and live

Conclusions
In this work, it has been argued that our emergence around an FGK-dwarf star is ostensibly in tension with the fact that smaller M-dwarf stars dominate the stellar population and live much longer lives. If M dwarfs are so numerous (in space and time), why don’t we live around one? In many ways, the paradox is conceptually analogous to the Fermi paradox—If life is presumed to be common, why don’t we see evidence for alien life anywhere?

Like the Fermi paradox, a straightforward solution is that we are simply outliers and our observation appears in tension with the logical argument only because we are a tail-end member of the distribution. Dubbed resolution I in this work, we find that if intelligent life emerges rapidly, the large temporal advantage that M dwarfs enjoy is dissolved and thus the “surprisingness” of our yellow host star is modest, given by the ratio of the abundance of M dwarfs versus FGKs. However, this solution exacerbates the related Fermi paradox and even starts to come into tension with the evolutionary record observed on Earth (18).

In the rare-intelligence scenario, tension on the Fermi paradox is relaxed but tension on the red sky paradox exacerbates, making our existence a ~1% outlier. Although we could simply accept our existence as unusual, this is inconsistent with the Copernican principle and is hardly a satisfying resolution.

Three other resolutions are proposed, by altering the various terms governing the likelihood function. Equipped only with our present and limited constraints on these terms, all of them are ostensibly viable. If resolution I is rejected, then one or more of these three must hold true: (I) The emergence rate of intelligence is slower for M dwarfs, (II) the available time for intelligence emergence is truncated for M dwarfs, and/or (IV) M dwarfs have fewer habitable worlds.

It is possible that resolution IV could find observational support in the near term. The occurrence rate of Earth-sized, temperate planets around late-type M dwarfs is not well known, but if it could be established to be much smaller than that around early Ms and FGKs, this would provide support for resolution IV. In such a case, this may actually be good news for astrobiologists, because it permits the emergence of intelligence on the early M-dwarfs subset. Since we know of a population of such worlds already (19), one could maintain justified optimism concerning future efforts to remotely detect life on these worlds.

If Earths are found to be common around late M dwarfs, it will not be possible to further test resolution IV until we can assess whether planets are truly capable of harboring complex life from remote observations. In this scenario, it is still possible that resolution IV operates, but in a more nuanced manner than the simple prevalence of planets. For example, such worlds may have less stable climates/atmospheres as a result of tidal locking (38–40). If not, resolutions II and III become increasingly favorable.

Resolution III could gain observational support if Earth-sized planets in the habitable zone of M dwarfs are consistently demonstrated to be runaway greenhouses, something potentially testable with James Webb Space Telescope (58) and hypothesized by ref. 49. Although reasoned speculation can be considered regarding resolution II, as a direct statement about exolife’s evolutionary development it would likely be untestable with any conceived missions and may perhaps only gain through support by deductive elimination of the stated alternatives. Ultimately, resolving the red sky paradox is of central interest to astrobiology and Search for Extra-Terrestrial Intelligence, with implications as to which stars to dedicate our resources to, as well as asking a fundamental question about the nature and limits of life in the cosmos.

Data Availability. All study data are included in this article and/or SI Appendix.

ACKNOWLEDGMENTS. I thank Tom Widdowson, Mark Sloan, Douglas Daughday, Andrew Jones, Jason Allen, Marc Lijoi, Elena West, Tristan Zajonc, Chuck Wolfred, Lasse Skov, Martin Kroebel, Geoff Suter, Max Wallistab, Methven Forbes, Stephen Lee, Zachary Danielson, Vasilen Alexandrov, Chad Souter, Marcus Gillette, and Tina Jeftcoast.

1. F. W. Bessel, Bestimmung der entfernung des 61sten sterns des schwans. Astron. Nachr. 16, 65 (1828).
2. A. Burrows et al., A nongray theory of extrasolar giant planets and Brown dwarfs. Astrophys. J. 491, 856–875 (1997).
3. I. Baraffe, G. Chabrier, F. Allard, P. H. Hauschildt, Evolutionary models for solar metal-licity low-mass stars: Mass-magnitude relationships and color-magnitude diagrams. Astronom. Astrophys. 337, 403–412 (1998).
4. G. Chabrier, I. Baraffe, F. Allard, P. Hauschildt, Evolutionary models for very low-mass stars and Brown dwarfs with dusty atmospheres. Astrophys. J. 542, 464–472 (2000).
5. I. Baraffe, G. Chabrier, T. S. Barman, F. Allard, P. H. Hauschildt. Evolutionary models for cool brown dwarfs and extragalactic giant planets. The case of HD 209458. Astron. Astrophys. 402, 701–712 (2003).
6. S. B. Dieterich et al., The solar neighborhood. XXXII. The hydrogen burning limit. Astrophys. J. 147, 94 (2014).
7. J. Chen, D. Kipping, Probabilistic forecasting of the masses and radii of other worlds. Astrophys. J. 834, 17 (2017).
8. J. M. Bestenlehner et al., The VLT-FLAMES Tarantula Survey. XVII. Physical and wind properties of massive stars at the top of the main sequence. Astronom. Astrophys. 570, A38 (2014).
9. E. E. Salpeter, The luminosity function and stellar evolution. Astrophys. J. 121, 161 (1955).
10. G. E. Miller, J. M. Scalo, The initial mass function and stellar birthrate in the solar neighborhood. Astrophys. J. Supp. Ser. 41, 513 (1979).
11. J. M. Scalo, The stellar initial mass function. Fundam. Cosmic Phys. 11, 1–278 (1986).
12. G. Chabrier, Galactic stellar and substellar initial mass function. PASP 115, 763–795 (2003).
13. F. C. Adams, G. Laughlin, A dying universe: The long-term fate and evolution of astrophysical objects. Rev. Mod. Phys. 69, 337–372 (1997).
14. C. J. Hansen, S. D. Kawaler, V. Trimble, Stellar Interiors: Physical Principles, Structure, and Evolution (Springer, 2004).

15. J. T. O’Malley-James, J. S. Greaves, J. A. Raven, C. S. Cockell, Svansong biospheres: Refuges for life and novel microbial biospheres on terrestrial planets near the end of their habitable lifetimes. Int. J. Astrobiol. 12, 99–112 (2013).

16. S. Tato, M. Countz, C. M. Guerra Olivera, D. Jack, K. P. Schröder, Habitability around F-type stars. Int. J. Astrobiol. 13, 244–258 (2014).

17. D. S. Spiegel, E. L. Bayesian analysis of the astrobiological implications of life’s early emergence on Earth. Proc. Natl. Acad. Sci. U.S.A. 109, 395–400 (2012).

18. D. Kipping, An objective Bayesian analysis of life’s early start and our late arrival. Proc. Natl. Acad. Sci. U.S.A. 117, 11995–12003 (2020).

19. C. D. Dressing, D. Charbonneau, The occurrence of potentially habitable planets orbiting M dwarfs estimated from the full Kepler dataset and an empirical measurement of the detection sensitivity. Astrophys. J. 807, 45 (2015).

20. S. Bryson et al., The occurrence of rocky habitable zone planets around solar-like stars from Kepler data. arXiv:2010.14812 (28 October 2020).

21. J. Haqq-Misra, R. K. Kopparapu, E. T. Wolf, Why do we find ourselves around a yellow star instead of a red star? Int. J. Astrobiol. 17, 77–86 (2018).

22. G. D. Mulders, I. Pascucci, D. Apai, A stellar-mass-dependent drop in planet occurrence rates. Astrophys. J. 798, 112 (2015).

23. K. K. Hardegree-Ullman, M. C. Cushing, P. S. Muirhead, J. L. Christiansen, Kepler planet occurrence rates for mid-type M dwarfs as a function of spectral type. Astronom. J. 158, 75 (2019).

24. A. L. Shields, S. Ballard, J. A. Johnson, The habitability of planets orbiting M-dwarf stars. Phys. Rep. 663, 1 (2016).

25. A. Linde, Sinks in the landscape, Boltzmann brains and the cosmological constant problem. J. Cosmol. Astropart. Phys. 2007, 022 (2007).

26. B. Carter, Five- or six-step scenario for evolution? Int. J. Astrobiol. 7, 177–182 (2008).

27. C. Scharf, L. Cronin, Quantifying the origins of life on a planetary scale. Proc. Natl. Acad. Sci. U.S.A. 113, 8127–8132 (2016).

28. J. Chen, D. Kipping, On the rate of abiogenesis from a Bayesian informatics perspective. Astrobiology 18, 1574–1584 (2018).

29. K. Caldeira, J. F. Kasting, The life span of the biosphere revisited. Nature 360, 721–723 (1992).

30. M. Lingam, I. Ginsburg, A. Loeb, Prospects for life on temperate planets around Brown dwarfs. Astrophys. J. 888, 102 (2020).

31. R. M. Ramirez, L. Kaltenegger, The habitable zones of pre-main-sequence stars. Astrophys. J. 797, L25 (2014).

32. R. M. Ramirez, L. Kaltenegger, Habitable zones of post-main-sequence stars. Astrophys. J. 823, 6 (2016).

33. E. Agol, Transit surveys for Earths in the habitable zones of white dwarfs. Astrophys. J. 731, L31 (2011).

34. D. S. Abbot, E. R. Switzer, The Steppenwolf: A proposal for a habitable planet in interstellar space. Astrophys. J. 735, L27 (2011).

35. P. Koumar, On the variation of the initial mass function. Mon. Not. R. Astron. Soc. 322, 231–246 (2001).

36. M. J. Pecaut, E. E. Mamajek, Intrinsic colors, temperatures, and bolometric corrections of pre-main-sequence stars. Astrophys. J. 208, 9 (2013).

37. C. Clarkson, B. Bassett, T. H. C. Lu, A general test of the Copernican principle. Phys. Rev. Lett. 101, 011101 (2008).

38. M. M. Joshi, R. M. Haberle, R. T. Reynolds, Simulations of the atmospheres of synchronously rotating terrestrial planets orbiting M dwarfs: Conditions for atmospheric collapse and the implications for habitability. Icarus 129, 450–465 (1997).

39. R. Wordsworth, Atmospheric heat redistribution and collapse on tidally locked rocky planets. Astrophys. J. 806, 180 (2015).

40. P. Audra-Destotrou, K. Heng, Atmospheric stability and collapse on tidally locked rocky planets. Astronom. Astrophys. 638, A77 (2020).

41. A. Segura, L. M. Walkowitz, V. Meadows, K. James, S. Hawley, The effect of a strong stellar flare on the atmospheric chemistry of an earth-like planet orbiting an M dwarf. Astrobiology 10, 751–771 (2010).

42. S. Rugheimer, L. Kaltenegger, D. Sasselov, UV surface environment of earth-like planets orbiting FGKM stars through geological evolution. Astrophys. J. 806, 137 (2015).

43. S. Rugheimer, L. Kaltenegger, A. Segura, J. Linsky, S. Mohanty, Effect of UV radiation on the spectral fingerprints of earth-like planets orbiting M stars. Astrophys. J. 809, 57 (2013).

44. I. Baraffe, D. Homeier, F. Allard, G. Chabrier, New evolutionary models for pre-main sequence and main sequence low-mass stars down to the hydrogen-burning limit. Astronom. Astrophys. 577, A42 (2015).

45. J. Horner, B. W. Jones, Jupiter - friend or foe? I: The asteroids. Int. J. Astrobiol. 7, 251–261 (2008).

46. J. Horner, B. W. Jones, Jupiter - friend or foe? II: The centaurs. Int. J. Astrobiol. 8, 75–80 (2009).

47. J. A. Johnson et al., Characterizing the cool KOIs. II. The M dwarf KOI-254 and its hot Jupiter. AJ 143, 111 (2012).

48. J. F. Kasting, Runaway and moist greenhouse atmospheres and the evolution of Earth and Venus. Icarus 74, 472–494 (1988).

49. R. Luger, R. Barnes, Extreme water loss and abiotic O2 buildup on planets throughout the habitable zones of M dwarfs. Astrobiology 15, 119–143 (2015).

50. M. Tuomi et al., Frequency of planets orbiting M dwarfs in the solar neighborhood. arXiv [Preprint] (2019). https://arxiv.org/abs/1906.04644 (Accessed 11 June 2019).

51. J. Catanzarite, M. Shao, The occurrence rate of Earth analog planets orbiting sun-like stars. Astrophys. J. 738, 151 (2011).

52. D. Foreman-Mackey, D. W. Hogg, T. D. Morton, Exoplanet population inference and the abundance of Earth analogs from noisy, incomplete catalogs. Astrophys. J. 795, 64 (2014).

53. S. Bryson et al., A probabilistic approach to Kepler completeness and reliability for exoplanet occurrence rates. Astronom. J. 159, 279 (2020).

54. W. A. Traub, Terrestrial, habitable-zone exoplanet frequency from Kepler. Astrophys. J. 745, 20 (2012).

55. D. Garrett, D. Savransky, R. Belikov, Planet occurrence rate density models including stellar effective temperature. Pub. Astron. Soc. Pac. 130, 114403 (2018).

56. K. G. Malmquist, On some relations in stellar statistics. Meddelanden fran Lunds Astronomiska Observatorium Serie I 100, 1–52 (1922).

57. D. Carrera et al., Identifying inflated super-earths and photo-evaporated cores. Astrophys. J. 866, 104 (2018).

58. J. K. Bartosz, S. Aigrain, P. G. J. Irwin, S. Kendrew, L. N. Fletcher, Telling twins apart: exo-Earths and Venuses with transit spectroscopy. Mon. Not. R. Astron. Soc. 458, 2657–2666 (2016).