Minimal Conditions for Survival of Technological Civilizations in the Face of Stellar Evolution

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Abstract

The ease of interstellar rocket travel is an issue with implications for the long-term fate of our own and other civilizations and for the much-debated number of technological civilizations in the Galaxy. We show that the physical barrier to interstellar travel can be greatly reduced if voyagers are patient, and wait for the close passage of another star. For a representative time of ∼1 Gyr, characteristic of the remaining time that Earth will remain habitable, one anticipates a passage of another star within ∼1500 au. This lowers the travel time for interstellar migration by ∼two orders of magnitude compared with calculated travel times based on distances comparable to average interstellar separations (i.e., ∼1 pc) in the solar vicinity. We consider the implications for how long-lived civilizations may respond to stellar evolution, including the case of stars in wide binaries, and the difficulties of identifying systems currently undergoing a relevant close encounter. Assuming that life originates only around G-type stars, but migrates primarily to lower mass hosts when the original system becomes uninhabitable, the fraction of extraterrestrial technological civilizations that exist as diaspora can be comparable to the fraction that still orbit their original host stars.

Unified Astronomy Thesaurus concepts: Astrobiology (74); Stellar evolution (1599); White dwarf stars (1799); Astrometric binary stars (79); Visual binary stars (1777); Solar neighborhood (1509); Space vehicles (1549)

1. Introduction

Serious discussion of the existence and prevalence of technological life around other stars dates back, at the least, to 1966 with the appearance of the classic book of Shklovskii & Sagan (1966) titled “Intelligent Life in the Universe.” Consideration of these issues naturally leads into the question of whether technological civilizations can migrate from one stellar system to another (Shklovskii & Sagan 1966; Dyson 1968; Oliver & Billingham 1971; Rood & Trefil 1981; Breuer 1982; Zuckerman & Hart 1995; Webb 2002; Crawford 2018). The majority of the discussions on this theme focus on the diffusion of settlements away from the origin point under various assumptions regarding the speed at which vessels might travel, and the interval required to launch additional steps. This frequently leaves a model Milky Way teeming with inhabited planets. In this paper we wish to examine the opposite limit—what is the minimum requirement that long-term survival of entire civilizations places on interstellar migration? Under this assumption there is no wave of expansion because civilizations would not expand beyond the range needed for survival. We anticipate that this will substantially weaken constraints on the abundance of interstellar civilizations based on the current lack of observed signatures.

Over the past 25 years a variety of observational techniques have enabled rapid advances in the search for, and study of, extrasolar planets. These studies have demonstrated that planetary systems are common around main-sequence stars (Howard et al. 2010; Mayor et al. 2011; Clanton & Gaudi 2014; Burke et al. 2015; Dressing & Charbonneau 2015; Zuckerman & Young 2018; Hsu et al. 2019, 2020). Given the selection effects involved, the vast majority of these planets receive far too much incident radiation to realistically reproduce the kinds of conditions we know to be amenable to life on Earth, but potentially habitable systems have been discovered at the limits of current technologies (e.g., Borucki et al. 2013) and correction for the selection effects suggests that potentially habitable planets are quite common (Petigura 2013; Dressing & Charbonneau 2015; Silburt et al. 2015; Hsu et al. 2019; Zink & Hansen 2019).

These discoveries breathe new life into the discussion of the frequency of extraterrestrial technological civilizations. If life-bearing planets are common in the Galaxy, and migration between star systems is physically possible, then technological civilizations could spread rapidly (relative to cosmological timescales) and one would expect their presence to be ubiquitous, including in the solar system (Hart 1975). Yet there is no evidence to suggest they are present.

A commonly suggested solution to this absence of evidence for interstellar migration is to assume that interstellar travel may simply be too difficult or too expensive, and that any civilization that forms on a planet is bound to remain in orbit about that star alone. However, there are some well-understood physical principles that we know must come into play eventually. We know that stars evolve and that Sun-like stars will get larger and more luminous before eventually shrinking and fading away as white dwarfs. Thus, the level of irradiation that a life-bearing planet will experience undergoes substantial changes in the latter stages of a star’s life and we cannot expect a specific planet to remain habitable forever. Courses of action are then to either adopt a strategy of mitigation by moving outward then inward while remaining within the gravitational sphere of influence of the host star (e.g., Gertz 2019) or make the attempt—however difficult—to migrate to another star (Zuckerman 1985). We focus on the latter option here because the mitigation approach requires multiple adjustments to
correct for the inescapable evolutionary changes that result in the later stages of the life of the star.

Thus, if we want to understand the minimum amount of interstellar migration necessary for the long-term survival of a civilization, we must understand how one can minimize the energy expenditure necessary to move from one star to another. In the case of relocation from Earth, the closest star to the Sun, presently, is Proxima Cen, at 4.22 light years distance. The precise thresholds of feasibility of traveling from Earth to Proxima Cen—in terms the vehicle speed that can be achieved and the trip duration that can be tolerated—are still a matter of speculation. Perhaps the only precise statement that can be made on this question is that such a trip is, at present, well beyond our technological and biological capabilities (e.g., Ashworth 2012). However, this estimate of the time it would take to migrate to the nearest star is based on an instantaneous snapshot of the relative positions of stars in the solar neighborhood. Stellar evolution, although inexorable, is also a slow process and impending doom due to evolution away from the main sequence will be readily apparent for a long time beforehand. The key component of our argument is therefore that a civilization under threat will have the opportunity to monitor the positions of nearby stars and choose the optimal time—when a star passes close by—to attempt a transfer to a different habitat.

In the following sections, we will estimate the spread of interstellar civilizations under the assumption that they make only enough jumps between stars to satisfy the requirement of long-term survival. We will also assume that civilizations only arise in conditions similar to our own, i.e., around G stars. Thus, our model assumes that some fraction of G stars produce civilizations capable of sufficient migration to guarantee their survival beyond the end of a main-sequence lifetime, and we wish to understand what requirements this imposes. In Section 2 we estimate how close we can expect the Sun (or an equivalent G-type star) to pass near another star, during the course of its main-sequence lifetime. In Section 3, we estimate how close a star is likely to come during the window of the stellar lifecycle when habitability first becomes threatened. In Section 4 we discuss the consequence when the star is not single but rather a member of a multiple star system. In Section 5 we estimate the requirements to actually find and observe a close encounter wherein a migration might be occurring at the present day, and in Section 6 we summarize our results.

2. How Close an Approach Can Be Reasonably Expected?

The distance of close passage will depend on the local density of stars and the local kinematics, so the ease of interstellar migration will depend somewhat on the location in the Galaxy. Since our most obvious application is migration from Earth to other stars, or from other stars to Earth, we begin with the solar neighborhood. Let us estimate the local density in two ways.

Bovy (2017) measured the local mass density in stars using Gaia DR1, and infers $n = 0.040 \pm 0.002 \, M_\odot \, pc^{-3}$ for the solar neighborhood. He measures a mass function for stars with $M > 1 \, M_\odot$ and extrapolates to lower masses using commonly assumed initial mass functions. To infer the number density, we use a Kroupa (2001) mass function to convert this to a number density of $n_{bd} = 0.113 \pm 0.006 \, pc^{-3}$ for stars between 0.08 and $8 \, M_\odot$. We note that there is also a comparable density of brown dwarfs in a Kroupa mass function ($n_{bd} \sim 0.093 \, pc^{-3}$), but we will ignore them as unsuitable locations (they are also poorly constrained by the method above because they make only a small contribution to the total mass budget). It is also worth noting that 81% of the main-sequence stars in this estimate have masses <0.5 $M_\odot$, i.e., we expect the bulk of the close passages to be with M dwarfs. The density, $n = 0.1 \, pc^{-3}$, that we adopt below implies an average nearest neighbor distance of 3.85 light years, i.e., the Sun has a very average distance to the nearest neighbor.

A more detailed picture can be obtained by looking at the stellar census of the local 10 pc volume by the REXplorer Consortium On Nearby Stars (RECONS) project (Henry et al. 2018). They count 357 total main-sequence stars in this volume to yield an estimate of $n_{sys} = 0.085 \, pc^{-3}$, only about 75% of the Bovy estimate. The greater detail of the RECONS sample is useful because it also identifies which stars are single and which are in multiple systems. If we count independent stellar systems, then there are 317 (232 single and 85 multiple), which is 89% of the total stellar count and so $n_{sys} = 0.076 \pm 0.009 \, pc^{-3}$. For simplicity, and including systematic errors, we adopt $n_{sys} = 0.10 \pm 0.02 \, pc^{-3}$ as an average of the two estimates in the calculations that follow.

As mentioned above, this stellar number density yields an average nearest neighbor distance between stars of 3.85 light years. However, such estimates rely on the standard snapshot picture of interstellar migration—that a civilization decides to embark instantaneously (at least, in cosmological terms) and must simply accept the local interstellar geography as is. If one were prepared to wait for the opportune moment, then how much could one reduce the travel distance, and thus the travel time?

To estimate travel times, we need to include Galactic kinematics. Anguiano et al. (2020) estimate the velocity dispersions for thin disk stars in the local solar neighborhood as $37 \, km \, s^{-1}$ in the radial direction, $24 \, km \, s^{-1}$ in the azimuthal direction, and $18 \, km \, s^{-1}$ in the vertical direction. If we average the three components in quadrature, we find $V \sim 48 \, km \, s^{-1}$ as an approximate three-dimensional velocity dispersion, which we take to be the average velocity of encounter. Combining this with the above number density, and the concept of a mean free path ($\equiv V \tau$), enables one to calculate a rate of encounter within some distance $R_0$, or an equivalent time $\tau$ between close passages

$$\tau = 1/(nV_\pi R_0^2).$$

With $n = 0.1 \, pc^{-3}$ and $V = 48 \, km \, s^{-1}$, we can estimate the rate $\Gamma$ at which a given star will encounter others within a distance $R_0$, as

$$\Gamma = 15.4 \, Myr^{-1} \left( \frac{R_0}{1 \, pc} \right)^2.$$  

The solar neighborhood is $\sim 8.5 \, kpc$ out from the Galactic center and of only modest stellar density; we expect higher encounter rates in some other parts of the Galaxy. Adopting the Besançon model for the Galactic structure (Robin et al. 2003), the density increases as we move through the disk toward the center, peaking at Galactocentric radii $\sim 2.2 \, kpc$, with a density $\sim 4.4$ times higher (and similar velocity dispersion). Thus, the

$^8$Gravitational focusing has little effect on these estimates because the focusing factor is $\sim GM_\odot/R_0V^2 \sim 8 \times 10^{-4}$ even for $R_0 = 500$ au.
stellar encounter rate can get up to \( \Gamma \sim 70 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \) in the inner parts of the Galactic disk. Interior to this location, the stellar density of the disk population drops, but the contribution of the Galactic bulge increases. In the center, the stellar density of the bulge approaches \( \sim 14 \text{ pc}^{-3} \) (Robin et al. 2003), with an increased mean velocity of 94 km s\(^{-1}\). Thus, the encounter rate in the bulge reaches \( \Gamma \sim 4 \times 10^3 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \).

Even higher stellar densities can be found in the nuclear star cluster at the Galactic center, where Magorrian (2019) estimates \( n \sim 30 \text{ pc}^{-3} \), with encounter velocities of \( \sim 200 \text{ km s}^{-1} \). This pushes the encounter rate up to \( \Gamma \sim 2 \times 10^4 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \). The highest encounter rates are found in globular clusters, where the stellar densities are higher and the velocity dispersions are lower. Characteristic (Harris 1996) velocity dispersions are \( \sim 10 \text{ km s}^{-1} \) and half-mass relaxation times are \( \sim 10^9 \text{ years} \), which yield characteristic encounter rates of \( \Gamma \sim 10^6 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \).

In such high encounter rate environments, it is empirically established that dynamical interactions modify not only planetary parameters (e.g., McTier et al. 2020) but the properties of the stellar population as well (Brahmian et al. 2013, and references therein).

There are also regions of the Galaxy with lower stellar density than the solar neighborhood. The density of stellar halo stars in the solar neighborhood is \( \sim 3 \times 10^{-4} \text{ of the total} \), and the averaged three-dimensional dispersion is \( \sim 189 \text{ km s}^{-1} \) (Robin et al. 2003). Away from the disk plane the encounter rate of halo stars with each other is \( \Gamma \sim 0.02 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \). The encounter rate for a given halo star is dominated by its passage through the Galactic disk, in which case it sees the full surface density of stars from the thin disk, but only for a fraction of its orbital period \( \sim 2 \times 2 \text{ kpc}/(2\pi \times 8.5 \text{ kpc}) \sim 0.08 \) (for solar neighborhood halo stars and a disk half-thickness of 1 kpc) of the time. Incorporating this into the overall estimate yields \( \Gamma \sim 4.5 \text{ Myr}^{-1}(R_0/1 \text{ pc})^2 \) for a halo star.

Related work with Gaia data supports the general estimates presented here. Attempts to locate the stars that will pass closest to the Sun in the near future or recent past produce a close encounter rate (Bailer-Jones et al. 2018) within 1 pc of \( \Gamma = 19.7 \pm 2.2 \text{ Myr}^{-1} \), in excellent agreement with our estimate in Equation (2). Based on this analysis, the star that is expected to make the closest passage to the Sun in the near future (Mülläri & Orlov 1996; Berski & Dybczyński 2016; Bailer-Jones et al. 2018) is a K7 dwarf Gl 710, which will pass within 13,900 au of the Sun in approximately 1.28 Myr.

We see that the rates of stellar encounter vary substantially from one Galactic environment to the next, and so the ease of interstellar migration will be a strong function of environment. We will now examine what constraints this places on the energetics of interstellar migration.

### 3. Minimum Encounter Distance

As the estimates in the previous section show, the rate of encounter varies dramatically from one environment to another within the Galaxy. In the highest density regions—globular clusters and the nuclear star cluster—it is well known that the rate of stellar encounters is high enough to substantially modify the stellar population in observable ways (e.g., Fabian et al. 1975; Bailyn 1995; Sigurdsson & Phinney 1995). This rate of encounters is also sufficient to substantially modify the population of planetary systems (Sigurdsson 1993; Davies & Sigurdsson 2001; Kremer et al. 2019; Wang et al. 2020). In such cases, the issue of long-term survival is likely to be determined by the dynamical evolution of the planetary system itself, rather than the change in the climate due to stellar evolution. Indeed, it has been suggested (Di Stefano & Ray 2016) that globular clusters may offer the optimally prosperous environment for long-term civilizations. However, these high stellar density environments contain only a small fraction of the stellar population of the Galaxy, and are all quite distant from the Sun, making observational probes difficult. Many of these environments are also quite metal-poor, and may have a lower frequency of planetary systems per star. The near field environment of the Sun is much less dense, and the influence of neighbors on the dynamical stability is minimal (after the dissipation of any potential birth cluster).

In the solar neighborhood, if we multiply the encounter rate of Equation (2) by \( \sim 4.6 \text{ Gyr} \) age of the Sun, we find that we expect the solar system to have experienced roughly one encounter within 780 au within that period of time. As the Sun evolves further, it will get brighter and heat Earth more. By the time the irradiation of the Earth reaches the point at which the greenhouse effect reaches the runaway limit (Kopparapu et al. 2013), the Sun will have reached an age of \( \sim 5.7 \text{ Gyr} \). Thus, a conservative estimate for the remaining interval of habitability is \( \sim 1 \text{ Gyr} \) (neglecting possible mitigation strategies such as mounting a sunshield at the inner Lagrange point). Within this timeframe, the median distance of closest approach is \( \sim 1500 \text{ au} \), with an 81% chance that there will be one within 5000 au.

Thus, an attempt to migrate enough of a terrestrial civilization to ensure longevity can be met within the minimum requirement of travel between 1500 and 5000 au. This is two orders of magnitude smaller than the current distance to Proxima Cen. The duration of an encounter, with the closest approach at 1500 au, assuming stellar relative velocities of 50 km s\(^{-1}\), is 143 years. In the spirit of minimum requirements, we note that our current interstellar travel capabilities are represented by the Voyager missions (Stone et al. 2005); these, which rely on gravity assists off the giant planets, have achieved effective terminal velocities of \( \sim 20 \text{ km s}^{-1} \). The escape velocity from the surface of Jupiter is \( \sim 61 \text{ km s}^{-1} \), so it is likely one can increase these speeds by a factor of 2 and achieve rendezvous on timescales of an order of a century.

This is, of course, a speculative exercise, but the important point to note is that one does not need to postulate significant advances in technological capabilities to bring interstellar migration within the realms of human possibility. In the time before Earth becomes uninhabitable, we can expect the Sun to experience a close enough passage to another star that travel can be achieved on timescales of an order of a century with only the gravitational assists from the giant planets of the solar system.

The odds improve further as we move through the Galactic disk closer to the center. As we noted in Section 2, the Besançon model has a peak disk density at \( \sim 2.2 \text{ kpc} \) from the center, yielding a higher encounter rate, which reduces the characteristic encounter distance to \( \sim 250 \text{ au} \) over the course of 10 Gyr (800 au if we only allow for the last 1 Gyr of the stellar lifetime).

Another important component of these rare encounters is the interval between encounters. Above we have estimated the minimum encounter distance within a fixed time frame. One could also set a minimum threshold distance for encounters. For instance, if we adopt a threshold distance of 2000 au, we
expect an encounter within this distance every $\sim 700$ Myr in the solar neighborhood. Thus, even if a civilization attempts to migrate every time a star approaches within this distance, the opportunity arrives roughly only once for every few orbits around the Galactic center. Any expansion under these conditions would not be a diffusion away from a central location, but rather a random seeding. The dispersion in stellar motions would make it difficult to associate any diaspora with its original location.

4. Binary Stars

The discussion in Section 3 is focused on single stars—therefore a civilization that orbits an evolving star is forced to consider migration to another, unbound, star. But many stars exist in gravitationally bound multiple systems. This changes the discussion because most binary companions would make a natural, and far easier, destination for migration. Since our principal interest is those stars which evolve off the main sequence in a Hubble time, we focus here on the stellar mass range of $\sim 0.7$–1.3 $M_\odot$. For these stars, the fraction found in multiple systems is 44$\pm$3% (Raghavan et al. 2010), so that the calculation in Section 3 applies to approximately half of the G-type stars in the Milky Way. For the other half, migration to the environs of the companion (most often an M-type star) would be an option.

The distribution of companion separations is approximately log-normal (Duchêne & Kraus 2013; Raghavan et al. 2010) and indicates that $\sim 80\%$ of all G-star binaries will have separations of 1000 au or less. Thus, civilizations that arise on solar-like stars in binaries will find it much easier to migrate to their lower mass, longer lived, companion than to a passing star. However, studies of main-sequence binary systems (Wang et al. 2014) and of binary systems composed of a main-sequence star and a white dwarf (Zuckerman 2014) both suggest that the origin and/or evolution of planets in main-sequence binary systems are disfavored when stellar separations are less than 1000 au. Planets orbiting members of wide binaries can be destabilized due to the eccentricity excitation of the binary by perturbations from passing stars (Kaib et al. 2013), but these effects occur primarily for planets with semimajor axes greater than 10 au, and so we will assume that this does not affect habitability. In summary then, for those binary systems that do spawn technological civilizations in orbit around the primary, the opportunity to migrate to the binary companion would typically be a far easier option than to another passing star.

5. Observing Close Passages

Attempts to search for evidence of extraterrestrial civilizations are hampered by the very large parameter space that needs to be searched—see Wright et al. (2018) for an attempt to quantify this. One interesting consequence of the hypothesis that interstellar migration occurs only during close stellar passages is that it allows one to define a finite set of stars where such events might be occurring at the present time and therefore where possible evidence of a migration in action might be observed. Let us consider the density of such targets in the solar neighborhood.

Based on the discussion in Section 3, let us focus on close encounters with impact parameters $R_0 < 2000$ au. We estimate these occur roughly every 700 Myr for a star in the solar neighborhood. If we define an encounter time $\sim 2R_0/V$, this implies that such events last $\sim 400$ years and so any given star spends $\sim 400/(7 \times 10^3) \sim 6 \times 10^{-7}$ of the time involved in such a close passage. We anticipate that one needs to search $\sim 2 \times 10^5$ stars to find one undergoing a close passage at the present day. Given the local stellar density of $\sim 0.1$ pc$^{-3}$, and assuming that $\sim 0.05$ of these are main-sequence G stars, this implies that we need to search out to a distance $\sim 500$ pc to find a G star undergoing a close passage within 2000 au at the present day.

The population of stars in binaries is a substantial foreground contaminant in such a search. As noted in Section 4, $\sim 44\%$ of the $2 \times 10^6$ G-type stars to be searched will have bound companions. Thankfully, this problem is mitigated by the fact that a substantial fraction of these binaries have separations less than 100 au (Raghavan et al. 2010; Duchêne & Kraus 2013). Using the log-normal period distribution from these references, we estimate that $\sim 10\%$ of G star binaries have separations greater than 2500 au. Given these considerations, we anticipate $\sim 10^7$ contaminating binaries within a distance of 500 pc.

Thus, searching for present-day cases of close passages is quite difficult—removing the binary contamination will require vetting of proper motions and radial velocities. Fortunately, on scales of $\sim 2000$ au, orbital velocities are far lower than the relative velocities from Galactic kinematics, so any statistically significant velocity discrepancies should be sufficient to rule out bound pairs. The prospects for investigating such a sample with Gaia may be possible, but nontrivial because of the spatial correlations of proper motion seen on small angular scales (Lindegren et al. 2018) and also systematic errors that are introduced for faint stars in the vicinity of brighter ones. Thus, extensive vetting of each candidate is required. A preliminary effort to do this is underway but is beyond the scope of this paper.

Searches for evidence of extraterrestrial technology tend to focus either on detecting communication signals (Tarter 2001; Horowitz et al. 2001) or evidence of waste heat in the infrared (e.g., Dyson 1960; Wright et al. 2014). A group of nearby stars undergoing close stellar encounters may provide an alternative set of targets for directed signal searches. Siemion et al. (2013; Harp et al. 2016; Enriquez et al. 2017; Tellis & Marcy 2017; Pinchuk et al. 2019). The large-scale engineering required for substantial interstellar migration could also generate an observable infrared excess, especially if an asteroid population was used to provide raw materials (Forgan & Elvis 2011). There are also astrophysical reasons to expect increased dust and cometary activity in systems undergoing close encounters, because 5000 au is approximately the inner edge of the solar system Oort cloud (Dones et al. 2015) and we anticipate that other stars will have similar structures because these scales are set largely by the perturbations of the gravitational field—see Tremaine (1993) for a simple scaling explanation. Thus, close stellar passages will penetrate deep into the Oort clouds orbiting other stars and so we can expect them to be sites of enhanced cometary activity anyway. An excess of transient absorptions due to infalling comets—which have been observed in a handful of stars (e.g., Lagrange-Henri et al. 1988; Beust et al. 1998; Welsh & Montgomery 2013; Rebollido et al. 2020)—may prove to be another signature marking a star as worthy of closer scrutiny.

Our results demonstrate that a technological civilization can substantially reduce the physical barrier to interstellar migration by waiting for the opportune moment to transfer to another
star. The capabilities necessary to make such a transfer are still largely a matter of speculation, but patience can reduce the distances required by two orders of magnitude relative to the long-term average distance between stars. If we translate this into a similar reduction in the speed required, it implies four orders of magnitude increase in the amount of transferable mass at fixed energy. Furthermore, travel at lower speeds is a major advantage because various techniques for acceleration and deceleration are available that are not relevant, or far more difficult, when applied to relativistic travel. Given the extreme energy costs required by interstellar transport, the feasibility of a large-scale transport of mass from one star to another is strongly weighted toward closer encounters.

Thus, even if it is difficult to observe a migration taking place at the present day, the consequences of migration should be reflected in the interstellar density of diaspora today. In our conservative model—where migration takes place only in the face of environmental collapse—there is no diffusion of civilizations away from the original planet, but rather a simple copying process, leaving the original star behind and transferring to a newer, less massive, and more long-lived star.

Therefore, even if life does not start on planets orbiting M dwarfs, some fraction of these systems should be repurposed by transplanted civilizations and thus should be relevant as a subject for studies of exoplanet habitability (e.g., Tarter et al. 2007). In order to estimate the frequency of these diaspora, let us start by assuming that a fraction $\alpha$ of all G-type main-sequence stars host potentially habitable planets. Only some fraction of these planets may ultimately produce technological civilizations capable of interstellar migration. Thus, we denote $\beta$ as the fraction of all G-type main-sequence stars that yield such civilizations, so that $\beta \leq \alpha$ by definition. The density of G stars within 10 pc of the Sun is $\sim 4.5 \times 10^{-3}$ pc$^{-3}$ (Henry et al. 2018). The density of white dwarfs is $5 \times 10^{-3}$ pc$^{-3}$. The initial mass function for main-sequence stars above a solar lifetime is $\sim 2 \times 10^{-3}$ pc$^{-3}$. This estimate does not take into account that a civilization —e.g., Tarter et al. 2007—rst is simple enough. If survival is the sole goal, then a civilization may respond to stellar evolution and not how such civilizations may pursue expansion as a goal in and of itself. Thus our discussion demonstrates the requirements for technological civilizations to survive the evolution of their host star, even in the event that widespread colonization is physically infeasible.

We wish to estimate the observational consequences of this minimal model. To that end, we provide three observational estimates.

The first is simple enough. If survival is the sole goal, then a civilization need only transfer once to a long-lived K or M dwarf to ensure its survival for a Hubble time. In that event, the average density of technological planetary systems will reflect the frequency with which they arise, except that the host stars will be biased toward lower masses even if life only starts on G-type stars. In Section 5 we estimated that the local density of M stars—both single and in binaries—hosting transplanted
The corresponding density of systems still in orbit about the original G star will depend on how quickly technological civilizations arise. If this happens quickly, then systems orbiting their original G stars will still outnumber diaspora. However, if it takes 4.5 Gyr for a civilization to become observable, then diaspora may outnumber the observable G star systems. In this case, and assuming $\beta \sim \alpha \sim 0.3$—an optimistic interpretation of current estimates of the frequency $\alpha$ (Zink & Hansen 2019; Bryson et al. 2021) of habitable planets around G stars—we would anticipate two systems within 10 pc of the Sun to host technological civilizations, and at least one of them to orbit a low-mass K or M star.

A second consequence of our hypothesis is that civilizations that form around G stars in binaries have the easiest route to migration to a gravitationally unbound star. M and K dwarfs orbited by white dwarfs are thus likely to be a fruitful sample to search for civilizations advanced enough to have achieved the feat of transferring from one star to another. In Section 4 we estimated the density of such systems to be $1.8 \beta \times 10^{-4}$ pc$^{-3}$. Although this is lower than the density of unbound diaspora, the energy requirements for migration are much less and so more reliable.

The third consequence is that we associate the migration with a particular astrophysical event that is, in principle, observable, namely a close passage of two stars. One could reduce the vast parameter space of a search for evidence of technology with a particular astrophysical event that is, in principle, observable, to a particular astrophysical event that is, in principle, observable, the possibility of Extraterrestrial Civilizations (New York: Charles Scribner’s Sons) Shkolnisky, I. S., & Sagan, C. 1966, Intelligent Life in the Universe (San Francisco, CA: Holden Day Inc.) Siemion, A. P. V., Demorest, P., Korpela, E., et al. 2013, ApJL, 767, 74 Sigurdsson, S. 1993, ApJL, 415, L43 Sigurdsson, S., & Phinney, E. S. 1995, ApJS, 95, 99 Silburt, A., Gaidos, E., & Wu, Y. 2015, ApJ, 799, 180 So illima, A. 2019, MNRAS, 489, 2377 Stone, E. C., Cummings, A. C., McDonald, F. B., et al. 2005, Sci, 309, 2017 Tarter, J. 2001, ARA&A, 39, 511 Tarter, J. C., Backus, P. R., Mancinelli, R. L., et al. 2007, AbSio, 7, 30 Tellis, N. R., & Marcy, G. W. 2017, AJ, 153, 251 Tremaine, S. 1993, in ASP Conf. Ser., 36, Planets Around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco, CA: ASP), 335 Wang, J., Fischer, D. A., Xie, J.-W., & Ciardi, D. R. 2014, ApJ, 791, 111 Wang, Y.-H., Perna, R., & Leigh, N. W. C. 2020, MNRAS, 495, 1453 Webb, S. 2002, If the Universe is Teeming with Aliens...Where is Everybody? (New York: Copernicus Inc.) Welsh, B. Y., & Montgomery, S. 2013, PASP, 125, 759 Wright, J. T., & Hart, M. H. 1995, Extraterrestrial Res. Where are they? (Cambridge: Cambridge Univ. Press) Zuckerman, B., & Hart, M. H. 1995, Extraterrestrial Res. Where are they? (Cambridge: Cambridge Univ. Press) Zuckerman, B., & Young, E. D. 2018, in Handbook of Exoplanets, ed. H. Deeg & J. Belmonte (Cham: Springer), 1545