



GLOBULAR CLUSTERS AS CRADLES OF LIFE AND ADVANCED CIVILIZATIONS

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ABSTRACT

Globular clusters are ancient stellar populations in compact dense ellipsoids. There is no star formation and there are no core-collapse supernovae, but several lines of evidence suggest that globular clusters are rich in planets. If so, and if advanced civilizations can develop there, then the distances between these civilizations and other stars would be far smaller than typical distances between stars in the Galactic disk, facilitating interstellar communication and travel. The potent combination of long-term stability and high stellar densities provides a globular cluster opportunity. Yet the very proximity that promotes interstellar travel also brings danger, as stellar interactions can destroy planetary systems. We find, however, that large portions of many globular clusters are “sweet spots,” where habitable-zone planetary orbits are stable for long times. Globular clusters in our own and other galaxies are, therefore, among the best targets for searches for extraterrestrial intelligence (SETI). We use the Drake equation to compare the likelihood of advanced civilizations in globular clusters to that in the Galactic disk. We also consider free-floating planets, since wide-orbit planets can be ejected to travel through the cluster. Civilizations spawned in globular clusters may be able to establish self-sustaining outposts, reducing the probability that a single catastrophic event will destroy the civilization. Although individual civilizations may follow different evolutionary paths, or even be destroyed, the cluster may continue to host advanced civilizations once a small number have jumped across interstellar space. Civilizations residing in globular clusters could therefore, in a sense, be immortal.

Key words: galaxies: star clusters: general – globular clusters: general – planetary systems – planets and satellites: dynamical evolution and stability

1. INTRODUCTION

Globular clusters are among the most ancient bound stellar systems in the universe. They contain $\sim 10^5$ to more than 10^6 stars in dense spheroids. Typical ages of the ~ 150 globular clusters in the Milky Way are larger than 10 Gyr, extending to ~ 13 Gyr (see, e.g., Monelli et al. 2015; Kaluzny et al. 2015 and references therein). Here we consider the possibility that globular clusters host planets, and that life and advanced civilizations can develop and evolve there. Such civilizations would be immersed in stellar environments so dense that distances between stars could be as small as hundreds or thousands of au: thousands to hundreds of times smaller than typical interstellar distances in the Milky Way’s disk, which is home to the Sun. Interstellar communication between neighboring stars could take as little as weeks to months, and only decades from the center of the cluster to its edges. At a time when astronomical tools and techniques are as developed as those we now have on Earth, most of the planets within the cluster would have been discovered, and the large numbers of photons incident from cluster stars would allow many detailed studies of exoplanetary atmospheres. Globular cluster civilizations, which reach a level of technical development comparable to our own at present, will, therefore, know a good deal about the nearest $\sim 10^5$ stars and an even larger number of planets. They will be able to send exploratory probes to nearby stars and receive data that takes only weeks or months to reach them. They may be able to travel to nearby planetary systems that are hospitable and establish self-sustaining colonies over timescales far shorter than seems possible for advanced civilizations which, like our own, inhabit the relatively diffuse Galactic disk. Independent outposts would increase the chances

of surviving threats, ranging from astronomical and geological events to biological threats and civil strife.

We will refer to the potent combination of the long-term stability of globular clusters and their high stellar densities as the *globular cluster opportunity*. In order for the globular cluster opportunity to be meaningful, planets must exist in globular clusters. We show in Section 2 that there are good reasons to expect that globular clusters do harbor populations of planets. Planets in globular clusters, however, face threats of a type rarely encountered in the Galactic disk. Because of the high ambient stellar densities, interactions with other stars are common and they are more likely to be ejected from their planetary systems or else captured into the planetary systems of other stars. Fortunately, not all orbital separations are equally dangerous.

We show in Section 3 that globular clusters can have large regions within which the following conditions are satisfied.

(1) The orbits of habitable-zone planets are stable with respect to interactions with passing stars. These regions correspond to the *globular cluster habitable zones* (GC-HZs), which may be thought of as extensions of the Galactic Habitable Zone (GHZ), the regions within a galaxy where life may exist (see, e.g., Gowanlock et al. 2011).

(2) Nearest-neighbor distances are small. The reason for this criterion is to allow for short interstellar communication and travel times. Here we will focus on situations in which nearest-neighbor distances are smaller than 10^4 au (Section 3.5).

We refer to regions satisfying both of these conditions as “sweet spots.” We conclude Section 3 by connecting these considerations to the existence and likely locations of free-floating planets, which may dominate the number density in globular clusters.

In Section 4 we turn to the issue of what the globular cluster opportunity means for the long-term survivability of any advanced civilizations that develop within globular clusters. To do this we use the Drake equation to compare conditions within globular clusters with those in the Galactic disk. Section 5 is devoted to an overview, a general discussion of the implications of the globular cluster opportunity for future searches for planets and for advanced extraterrestrial civilizations, and to the identification of globular clusters that may be ideal places to search.

2. PLANETS IN GLOBULAR CLUSTERS

Galactic globular clusters are old and their stars tend to have low metallicities (Harris et al. 2010). Because planet formation requires metals, it could have been the case that planets did not form in globular clusters. Indeed, a null result was derived by a search for planets in the globular cluster 47 Tuc. Gilliland et al. (2000) studied $\sim 34,000$ main-sequence stars in 47 Tuc to discover and measure the frequency of “hot Jupiters,” gas giant planets in close orbits with their stars. If the frequency of hot Jupiters in the observed portion of 47 Tuc, near its center, is the same as in the Solar neighborhood (about 1%), then this set of observations should have detected ~ 17 planets with radii $\sim 1.3 M_J$ and typical orbital periods of 3.5 days. No planet was detected. This suggests that Jupiter-like planets in close orbits are ten times less common in the center of 47 Tuc. This, however, does not place limits on Jovian planets in wider orbits or on planets with radii substantially smaller than Jupiter’s.

Because planets are rich in elements more massive than hydrogen and helium, the dearth of hot Jupiters in 47 Tuc could have been due to the relatively low metallicities of the cluster stars. An analysis of a sample of about 700 exoplanets (Mortier et al. 2012) found that the frequency of hot Jupiters declines with declining metallicity. A number of authors have established that more metal-rich stars have a higher probability of harboring a giant planet, e.g., the references cited in Mortier et al. (2012). In particular, Fischer & Valenti (2005) suggest that the formation probability for gas giant planets scales as the square of the number of metal atoms, and that the presence of multi-planet systems and the total detected planet mass also correlate with stellar metallicity. Note, however, that Fischer & Valenti (2005) consider FGK-type stars with masses primarily above $1 M_\odot$. Because we are concerned with present-day globular cluster stars, our interest is in stars with masses below the globular cluster turn-off mass, i.e., $\sim 0.8 M_\odot$. Moreover, as we argue below, our interest is primarily in lower mass planets rather than in gas giants.

Of particular interest to this investigation are planets in the habitable zones of low-mass stars because the majority of globular cluster stars are M-dwarfs. Through a detailed study of the *Kepler* data, taking into account detectability and selection effects, Dressing & Charbonneau (2013, 2015) estimate that as many as one in four M-dwarf habitable zones hosts an Earth-sized planet, i.e., a planet of radius $1 R_\oplus - 1.5 R_\oplus$. In addition, approximately one in five M-dwarf habitable zones hosts a super-Earth ($1.5 R_\oplus - 2 R_\oplus$). Because the frequency of low-mass planets does not follow the metallicity correlation found for hot Jupiters (Buchhave et al. 2012, 2014; Buchhave & Latham 2015), the same statistics may apply to globular clusters.

Thus, studies of metallicity effects in the field indicate that planets can form in globular clusters and in the habitable

zones of their host stars. It is worth noting that the range of host-star metallicities has significant overlap with the range of metallicities measured for globular clusters. Of the 1709 planets listed in exoplanets.eu as of 2015 December 6, 927 have $z < 0$, and 278 have $z < -0.25$. Of the 134 globular clusters with measured metallicity from the Harris catalog, 28 are more metal-rich than 47 Tuc, which has a metallicity of -0.76 . More than half of these higher- z systems have metallicities larger than -0.5 , and one is positive. Furthermore, some globular clusters exhibit multiple stellar populations, each apparently corresponding to a slightly different formation time, with stars formed at later times having higher metallicities (García-Hernández et al. 2015).

A second effect that could limit the frequency of planets is the high density of the the central field; stellar interactions may have eliminated hot-Jupiter systems. The survivability of planetary systems in 47 Tuc was studied by Davies & Sigurdsson (2001) who argued that wider planetary systems ($d \geq 0.3$ au) are likely to be broken up in the central regions of this globular cluster, but tighter systems in less dense regions of the cluster may survive. Extrasolar planetary dynamics in both open clusters and globular clusters were also considered by Bonnell et al. (2001) and Adams (2010); plausible evolutionary models of the clusters show that planetary systems with separations ≥ 1 au are likely to have suffered disruptive encounters. On the other hand, in open clusters with typical densities and lifetimes of $10^2 \text{ star pc}^{-3}$, $t \leq 10^9$ year, disruptions due to encounters occur primarily for systems with separations ≥ 10 au. Young stellar clusters also contain young massive stars whose ionizing radiation can damage protoplanetary disks and affect giant planet formation (Armitage 2000; Adams & Laughlin 2001; Adams 2010). Such massive stars are absent in present-day globular clusters, but may have affected the formation of planets in the early evolution of the globulars. Fly-bys involving planetary systems with properties similar to those of the gas giants in our solar system in open clusters can perturb the orbits of the planets, sometimes leaving the system in an unstable state, and over timescales of several hundred million years after the fly-by the perturbation can trigger planet–planet scatterings that can lead to, in 5%–15% of cases, ejections of planets (Malmberg et al. 2011).

Observations of the outer, less dense regions of 47 Tuc also failed to discover hot Jupiters (Weldrake 2008), suggesting that dynamical interactions were not the culprits. This was validated by dynamical simulations that found that, had there been hot Jupiters in the fields observed by Gilliland et al., they would have survived (Fregeau et al. 2006).

Because of the high ambient stellar densities, globular cluster planets are more likely to be ejected from their planetary systems or else captured into the planetary systems of other stars. Nevertheless, Meibom et al. (2013) reported the discovery of planets smaller than Neptune in the old (~ 1 Gyr) open cluster NGC 6811. This example, and other recent planet discoveries in open clusters (Quinn et al. 2012; Brucalassi et al. 2014), shows that planets can form and planetary orbits can survive in dense environments in spite of truncated protoplanetary disks found in some clustered environments (de Juan Ovelar et al. 2012) and the relative fragility of some planetary systems in these environments (Portegies Zwart & Jílková 2015). We note that the planetary systems may themselves be complex, as the *Kepler* mission has established that planet multiplicity is common (Lissauer

et al. 2011). In addition, not all orbital separations are equally dangerous. We will show in Section 3 that globular clusters contain large “sweet spots,” where planets in the habitable zones of low-mass stars can survive for many Hubble times.

Because globular clusters present crowded fields of dim stars, traditional methods to search for planets do not yet do as well within globular clusters as in the field. Globular clusters do have one advantage, however, which is that the high interaction rates produce low-mass X-ray binaries (LMXBs) that then morph into millisecond pulsars.

The precise timing of the pulses allows planets to be discovered through studies of the residuals. The globular cluster M4 contains PSR B1620-26, with a spin period of 11 ms (and mass $\sim 1.35 M_{\odot}$). The pulsar is part of a triple system with a planetary mass object of $1\text{--}2 M_J$ orbiting a neutron star-white dwarf binary system (Thorsett et al. 1993; Richer et al. 2003; Sigurdsson et al. 2003). The white dwarf companion of the inner binary containing the neutron star has a mass of $0.34 \pm 0.04 M_{\odot}$ in a low eccentricity $e \sim 0.025$ orbit. It is a young white dwarf, of age ~ 0.5 Gyr. From pulsar timing limits the planet has a 45 year orbit with eccentricity ($e \sim 0.16$) with a semimajor axis of ~ 25 au. The probability that a neutron star will interact with a particular globular cluster star is very low and is not significantly increased by the presence of a planet. The discovery of this one planet must, therefore, signal the existence of a large population of planets in M4. This planet then demonstrates that planets may be common even in a globular cluster with $z < -1$ and in a globular cluster with an interaction probability high enough to produce a millisecond pulsar. We note, however, that Beer et al. (2004) point out that globular clusters may provide channels of formation that are different from those proposed by Sigurdsson (1992, 1993, 1995). Because Beer et al. (2004) invoke both a common envelope and close stellar passage, there could be only a small number of planets in M4 and other clusters if their model describes the primary route to planet formation. The main motivation of Beer et al. (2004) was, however, the lower planet formation frequency associated with low metallicity, based on Fischer & Valenti (2005). As already pointed out above, the trend that is seen for gas giants in the galactic field may not be applicable for Earth-sized planets orbiting M-dwarfs in globular clusters, which show a range of metallicities and exhibit multiple stellar populations that may have had different initial conditions for planet system formation.

3. THE HABITABLE ZONE AND THE “SWEET SPOT”

3.1. Survival in the Habitable Zone

A star’s habitable zone is defined to be the region around it within which planets like Earth can sustain water in liquid form on their surfaces (for low-mass stars see, e.g., Scalo et al. 2007; Tarter et al. 2007). Although the planet’s atmosphere also plays a role in setting the surface temperature, a convenient and reasonable approximation to the radius, a , of a habitable-zone orbit is: $a = \sqrt{L/L_{\odot}}$ au, where L is the luminosity of the star. For each star, there is a range of orbits in the habitable zone, and we will use this expression as a guideline.

Because the luminosities of stars decline steeply with decreasing mass, the habitable zones of low-mass stars can have radii considerably smaller than an au. Small orbits are more stable with respect to stellar interactions, so that habitable-zone planets can have orbits that are stable over long

time intervals. Simulations of interactions between planetary systems and passing stars have been done by several groups. Their work provides estimates of the value of τ . We have found it convenient to use an expression taken from Spurzem et al. (2009): $\tau = \frac{3v}{40\pi G a \rho}$, where ρ is the mass density and v the ambient speed. This expression is well suited for evaluation in a simple cluster model and is in approximate agreement with simulations by Fregeau et al. (2006).

More work is needed to incorporate the full range of effects that play roles in determining lifetimes. These effects include interactions between planetary systems with multiple planets and with stellar systems that may be binaries or higher order multiples. Below we give a simple derivation showing that the uncertainty can be incorporated into a factor that is likely to change by less than an order of magnitude.

Consider a planetary system in which the stellar mass is m_* and the planet is in a circular orbit with radius a . The rate R at which stars pass within a distance s of this planet is dominated by gravitational focusing: $R = \pi n v s (2 m_t G/v^2)$. Here, v is the local average relative speed and n is the local number density. The combined mass of the two stars passing each other is m_t .

In order for a passage to significantly alter the orbit of the planet, leading, for example, to an ejection, exchange, or merger, the impact parameter s must be comparable to a : $s = f a$, where typically $f \approx 5\text{--}10$. The time between such close approaches gives an estimate of the orbital lifetime, which is a function of a : $\tau(a) = 1/R(a)$.

$$\begin{aligned} \tau &= \frac{v}{2\pi (10 a \times f/10) m_t G n} \\ &= 3 \times 10^8 \text{ year} \left(\frac{v}{20 \text{ km s}^{-1}} \right) \left(\frac{10^6 \text{ pc}^{-3}}{n} \right) \\ &\quad \times \left(\frac{0.1 \text{ au}}{a} \right) \left(\frac{0.5 M_{\odot}}{m_t} \right) \left(\frac{10}{f} \right) \\ &= 4 \times 10^8 \text{ year} \left(\frac{v}{20 \text{ km s}^{-1}} \right) \left(\frac{10^6 \text{ pc}^{-3}}{n} \right) \\ &\quad \times \left(\frac{0.2 M_{\odot}}{m_*} \right)^{1.15} \left(\frac{0.5 M_{\odot}}{m_t} \right) \left(\frac{10}{f} \right). \end{aligned} \quad (1)$$

The second line expresses τ in terms of a . The wider the orbit, the shorter its lifetime. In this expression and the one just below, the number density is scaled to a high value. The density in most portions of globular clusters is not this high, leading to longer planetary-orbit lifetimes. For each cluster, the density decreases as the distance from the center increases, making the lifetimes longer in the outer portions of the cluster.

Our focus is on planets in the habitable zones of their stars. On the third line of Equation (1) we utilize the mass–luminosity relationship for the lowest mass stars [$L_* \approx 0.23 (m/M_{\odot})^{2.3}$]. The lifetime of planetary systems is longest for planets orbiting the least massive stars. Interestingly, these stars also have very long lifetimes. Hence, there is a kind of serendipity; the stars, which can provide the most stable environments for life and evolution, can also harbor planets in habitable zones that are relatively safe.

3.2. Searching for a Globular Cluster’s “Sweet Spot”

What we are seeking is a kind of “sweet spot” in the cluster, where habitable-zone orbits are stable, but the density of stars is still large enough that interstellar travel can take less time. These two requirements are at odds with each other, since $\tau \propto 1/n$, with large τ preferred, and $D \propto 1/n^{1/3}$, with small D (the average nearest-neighbor distance) preferred.

We expect the sweet spot to be a spherical shell that starts at some distance $R_{\text{low}}^{\text{sweet}}$ from the cluster center and ends at a larger radius $R_{\text{high}}^{\text{sweet}}$. We will see that clusters which have low central densities and which are not highly concentrated will have sweet spots that start near the cluster center (small $R_{\text{low}}^{\text{sweet}}$) because survival times may be long even there. But in such clusters, the fall-off of density with distance from the center will mean that interstellar distances become large for stars far from the center, so that the value of $R_{\text{high}}^{\text{sweet}}$ could be significantly smaller than the cluster’s radius. For clusters that are more concentrated, the sweet spot starts at larger distances from the center and may continue almost to the cluster’s outer edge. Thus, increasing concentration tends to move the sweet spot out.

The concept of a sweet spot is similar to the concept of a stellar habitable zone or that of a GHZ. These concepts are useful in identifying regions that are most likely to harbor life, but their boundaries are not sharp, and there is some arbitrariness in how we choose to define them. In the graphs illustrating the results derived below, we have selected the sweet spots to begin at that distance from the cluster center where the survival time of a habitable-zone planet is equal to the age of present-day Earth, and to end at a place where average nearest-neighbor distances become larger than 10^4 au. After illustrating results for these choices in Sections 3.3 and 3.4, we will return to the general case in Section 3.5.

In globular clusters, the light from other stars can provide a significant amount of energy. The ambient stellar flux is therefore of interest when considering the opportunities available to advanced civilizations in globular clusters. This is the total flux provided by the combination of all cluster stars. We also want to know the flux provided by the brightest nearby star. Both the average incident flux and the maximum received from a single star are largest in regions where D is small. That is, in regions where the distance between nearest neighbors is smallest, planets may also be able to draw energy from stars they do not orbit. This is also true for free-floating planets where energy drawn from nearby stars could help to fuel any life they may harbor.

3.3. Method

To conduct a quantitative search for the sweet spot, we modeled both the cluster and its stellar population. We used Plummer models for the cluster, because they are simply characterized by a total cluster mass M and by a characteristic radius, r_0 . They allow us to derive analytic expressions for the mass interior to each radius, and the average local speed, v , as a function of radius. To model the stellar population, we proceeded as follows.

We selected the initial stellar population from a Miller–Scalo initial-mass function (IMF; Miller & Scalo 1979), considering all stars with masses above $0.08 M_{\odot}$. We took the mass of the present-day turn off to be $0.84 M_{\odot}$; stars with slightly higher

mass (up to $0.85 M_{\odot}$) were considered to be giants. Any star with an initially higher mass was considered to be a present-day stellar remnant; we included $0.6 M_{\odot}$ white dwarfs, $1.4 M_{\odot}$ neutron stars, and $7 M_{\odot}$ black holes derived from stars with initial masses of $[0.85 M_{\odot} < M(0) < 8.5 M_{\odot}]$, $[8.5 M_{\odot} < M(0) < 35 M_{\odot}]$, $[M(0) > 35 M_{\odot}]$, respectively. This produces a population in which 84.4% of the stars are main-sequence dwarf stars, 14.8% of the stars are white dwarfs, 0.2% are giants, and the remaining stars are primarily neutron stars. The sizes of globular cluster populations of neutron stars and black holes is difficult to predict, and only a small fraction of these compact objects can be discovered through their actions as X-ray binaries or recycled pulsars.

Compact objects make negligible contributions to the average flux, and their presence does not alter the average distances between stars. There are exceptions when a compact object accretes matter from a close companion, emitting X-rays. The brightest X-ray binaries in Galactic globular clusters (LMXBs) typically have luminosities of 10^{36} – 10^{37} erg s^{-1} . Their influence on any life associated with other stars is likely to be limited because (1) the numbers of bright LMXBs are small, with 15 known in the Milky Way’s system of globular clusters (Heinke 2010); (2) many have low duty cycles; (3) only planets relatively near to even a bright LMXB receive more light from it than from their host star. Furthermore, LMXBs tend to be in or near the cluster core, where the survival of habitable-zone planets would be challenging even in the absence of LMXBs, especially for the higher-mass stars that tend to be found there. The successors to LMXBs are recycled millisecond pulsars which can also be luminous. We will discuss them in Section 5.

We placed each star at a specific randomly chosen point within $10 r_0$ of the cluster center. We kept track of the total mass of stars that should be (according to the Plummer model) within each shell of thickness dr and stopped adding stars to a shell when it reached the appropriate mass. In this way the total mass generated by each simulation matched the total mass we had selected for the Plummer model, and the mass profile matched the analytically derived cluster profile.

We generated the luminosity of each star as follows. For main-sequence stars with masses below $0.43 M_{\odot}$, we set $l = 0.23 m^{2.3}$, where l is the luminosity of the star and m is its mass. For main-sequence stars of higher mass, we used $l = m^4$. Giants (compact objects) were arbitrarily assigned $100 L_{\odot}$ ($0.001 L_{\odot}$).

With each star assigned a position and luminosity, we computed the flux as a function of r by choosing a random point in each of 1000 spherical shells, centered on the cluster, with radii extending to $10 r_0$. At each randomly selected point we computed the total flux provided by all of the cluster stars, as well as the flux of the star that contributed the most to the total flux reaching that point. We also computed the distance from each randomly selected point to the nearest star. The results are shown in Figures 1 and 2, where we have computed moving averages for $D(r)$ and $\mathcal{F}(r)$, with $\mathcal{F}(r)$ in units of the solar flux received by Earth.

3.4. Results

We conducted a full set of calculations for two different cluster masses ($10^5 M_{\odot}$ and $10^6 M_{\odot}$). For each mass we used three separate values of r_0 : 0.1 pc, 0.3 pc, and 0.8 pc. Figures 1 and 2 each show results of calculations for a globular

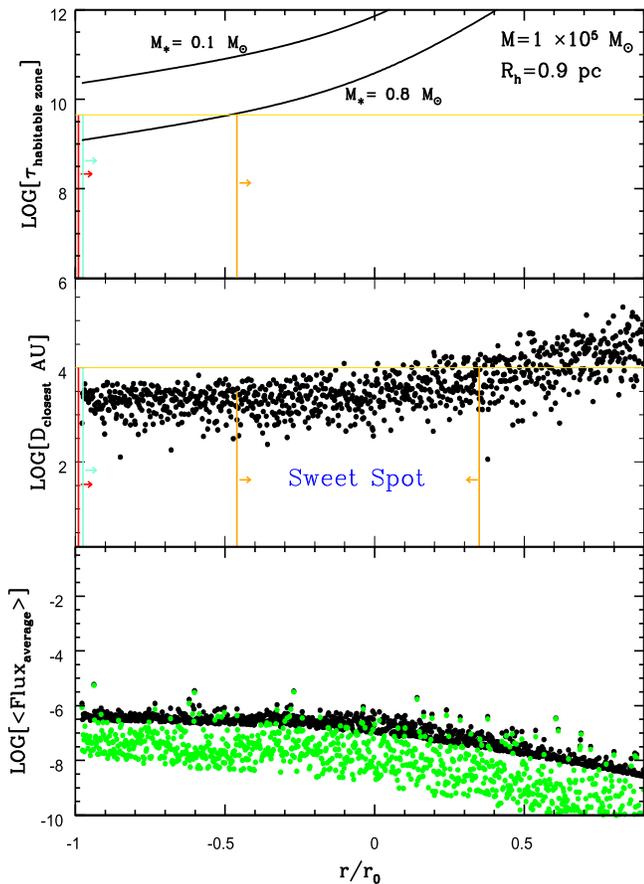


Figure 1. Globular cluster with $M = 10^5 M_{\odot}$ and with relatively low concentration ($r_0 = 0.9$ pc). In the top panel the logarithm (to the base 10) of the orbital lifetime in year for a habitable-zone planet is plotted against the logarithm (to the base 10) of r/r_0 . τ has different values for different stellar masses. Here, ($m_* = 0.1 M_{\odot}$, $m_* = 0.8 M_{\odot}$) in the (upper, lower) curve. In the middle panel the logarithm of the distance D_{closest} to the nearest star is shown. In the bottom panel the logarithm of the total flux received is plotted in black. In green is the flux provided by the single star that provides the most flux. The region marked “sweet spot” has values of r/r_0 high enough and densities low enough that a planet in the habitable zone of an $0.8 M_{\odot}$ main-sequence star can survive; it also has values of r/r_0 low enough and densities high enough that nearest-neighbor distances are smaller than 10^4 au. The sweet spots for $0.1 M_{\odot}$ stars (red) and also for white dwarfs of mass $0.6 M_{\odot}$ (aquamarine) end at the same place but start at the lower values of r/r_0 indicated by the right-pointing arrows near the left vertical axis.

cluster with mass $M = 1 \times 10^5 M_{\odot}$. They illustrate the trends we sought to explore. In Figure 1 (Figure 2) $r_0 = 0.9$ pc ($r_0 = 0.1$ pc), corresponding to low (high) concentrations. In the upper panel of each figure the logarithm to the base ten of the survival time in year is plotted versus the logarithm to the base ten of r/r_0 . The upper (lower) curve corresponds to orbits in the habitable zone of a main-sequence star of mass $0.1 M_{\odot}$ ($0.8 M_{\odot}$). A horizontal line at $\log(\tau) = 9.65$ is plotted to correspond to a survival time roughly equal to the present-day age of the Earth.

The globular cluster considered in Figure 1 has such a low concentration that planets in the habitable zones of stars with masses below roughly $0.4 M_{\odot}$ can survive throughout the cluster, even near the center. This is indicated by the red vertical line near $r = 0$, and the red arrow pointing toward larger values of r . The blue vertical line and its associated arrow indicate that survival near the center and throughout the cluster is also possible for planets in the habitable zones of

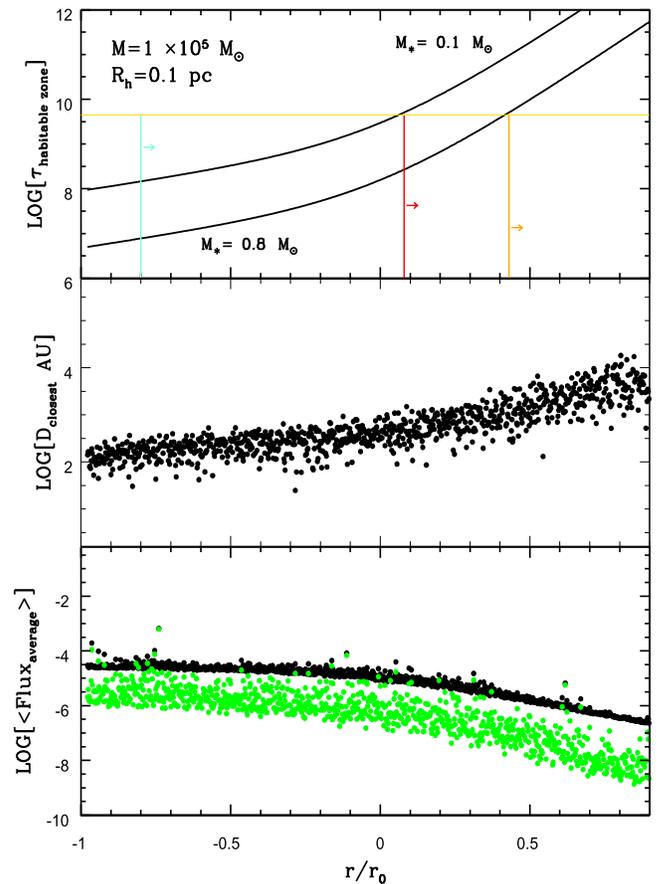


Figure 2. Same as in Figure 1, but with $r_0 = 0.1$ pc. This is a more highly concentrated globular cluster. The sweet spots for each type of star ($0.8 M_{\odot}$, orange; $0.1 M_{\odot}$, red; $0.6 M_{\odot}$, aquamarine) each start at higher values of r/r_0 , but they extend to the highest value of r/r_0 shown here. Of course, at the very edge of a globular cluster, stellar densities decline to the point that distances between stars are $>10^4$ au, and we would say that the sweet spots have ended.

$0.6 M_{\odot}$ white dwarfs (Agol 2011). For planets in the habitable zones of dwarf stars with masses of $0.8 M_{\odot}$, however, survival is possible only at somewhat larger values of r , as indicated by the orange line with the rightward pointing arrow.

In low-concentration clusters, the stellar density near the cluster’s outer edge can be comparable to the stellar density in the vicinity of our Sun. The globular cluster opportunity is therefore lost at large values of r . In the middle panel we have drawn a horizontal line corresponding to interstellar nearest-neighbor distances of 10^4 au. If we, rather arbitrarily, posit that, for interstellar distances larger than this the globular cluster opportunity is lost, then the “sweet spot” ends at the value of r/r_0 shown with an orange line and leftward pointing arrow in the middle panel of Figure 2. This example illustrates that, for globular clusters with low central concentrations, the globular cluster sweet spot is a large spherical shell.

Figure 2 shows the results for a globular cluster with a higher central concentration. In this case, survival of habitable-zone planets is possible only for larger values of r than when the stellar concentration is low. On the other hand, the stellar density remains high even as one approaches the cluster’s edge. Thus, the overall effect is that the sweet spot moves outward as the stellar concentration increases. Note that the edge of the sweet spot occurs at higher values of r than those shown here.

Real globular clusters exhibit a phenomenon known as mass segregation, in which more massive stars tend to be over-represented in the cluster’s central regions, while low-mass stars are over-represented in the outer regions. This effect could tend to place G dwarfs near the cluster center, where planets in their habitable zones are able to survive only for short times. Mass segregation may also place dwarf stars of the lowest masses near the outer edges of clusters. Thus, many low-mass stars and free-floating planets in low-concentration clusters may inhabit portions of the clusters where interstellar distances are large. To explore this effect we conducted simulations that modeled mass segregation. Because the factors that determine the distribution of masses within globular clusters are complex and dynamical in nature, we have employed a toy model, described below, which shows the general effect of mass segregation.

At each value of r we chose some of the stars from the Miller–Scalo IMF and some from a uniform distribution. To mimic mass segregation, we favored the uniform distribution near the center of the cluster, and the Miller–Scalo IMF toward the outer edges. Specifically, when our simulated location was a distance r from the cluster center, we generated a random number; if its value was smaller than $[1 - r/(10 r_0)]$, we chose from a uniform distribution, otherwise we chose from the Miller–Scalo distribution. For the more condensed cluster, 85% (27%) of stars of $0.1 M_{\odot}$ ($0.8 M_{\odot}$) occupy the “sweet spot” for stars of that mass. Thus, the “sweet spots” not only exist, but are occupied. For the less condensed cluster, the effects of mass segregation were small on the low- r side of the sweet spot, but the cut off at large r meant that only roughly 40% of G dwarfs, and 15% of M and K dwarfs are in the “sweet spot” at any given time. It is therefore important to note that stars move throughout the cluster. Thus, because low-concentration gives habitable-zone orbits very long lifetimes, most stars will spend a significant amount of time passing through the “sweet spot,” where stellar densities are high enough to decrease interstellar travel times significantly.

3.5. Stellar Habitable Zones, GC-HZs, and the Sweet Spot

Individual stars have habitable zones; regions in which it is neither too hot nor too cold to allow liquid water to exist on the surface of an Earth-like planet. The locations of habitable zone boundaries are not fixed numbers. This is not only because life may exist under a wider range of conditions than we know, but more specifically because several properties of stars, planets, and planetary orbits play roles in determining habitability. In the previous two sections, we have explored whether the orbits of habitable-zone planets can survive in a dense globular cluster environment. If the ambient stellar density is too high, passing stars are likely to steal, destroy, or eject the planets that had been in the habitable zone over time intervals too short for life to develop. The radius at which the stellar density drops to the point that a planet in the habitable zone of a star of mass m can survive marks the beginning of what can be called the GC-HZ for stars of that mass. The GC-HZ extends from that point outward to the edge of the cluster. The characteristics of the GC-HZ are the following.

The location of the inner edge of the GC-HZ (i.e., the inner edge of the sweet spot)

(1) depends on the survival time considered.

(2) has a strong dependence on stellar mass, because the stellar habitable zone is smaller for low-mass stars and interactions are less likely to disrupt small orbits.

(3) depends on the orbit of the star within the cluster. Stars within a globular cluster can travel from its central to its outer regions. Whether a specific planetary orbit survives depends on how much time the planetary system spends at different distances, r , from the center of the globular cluster.

The sweet spot incorporates a new concept, which is that the distances between stars can play a role in the long-term survivability of an advanced civilization. Large interstellar distances, such as those common in the Solar neighborhood, imply long two-way communication and interstellar travel times. It seems likely that, if interstellar distances are smaller by more than an order of magnitude, the time needed to establish independent outposts would also be shorter. The factor by which times need to be shorter is, at present, a matter of conjecture. If disk civilizations live long enough on average to establish outposts, then the factor may simply be unity. Here, we have assumed that a decrease in travel time (hence, in D) by a factor of 10, provides any advanced civilizations in globular clusters with a stronger opportunity to establish outposts. A limit on the value of D , the nearest-neighbor distance, determines the location of the outer edge of the sweet spot.

The value of D , the nearest-neighbor distance, in globular clusters versus its value in the Galactic disk allows us to relate the travel times required in these two environments. The nearest habitable planet in both cases may well be associated with another, more distant neighbor. In fact, it may be the case, in both the Solar neighborhood and in globular clusters, that the density of planetary systems in which members of a particular advanced civilization could find or make suitable habitats is significantly smaller than the overall stellar density. As long as the relative density of suitable habitats is either the same or larger in globular clusters, then the travel times to these suitable habitats would still be shorter than in the Solar neighborhood.

3.6. Free-floating Planets

Interactions involving planetary systems can have a range of outcomes. Some planets are exchanged into other planetary systems or else ejected as a result of interactions. Wide-orbit planets are more likely to be lost through interactions with passing stars. Furthermore, when their release velocities are comparable to their previous orbital velocities, the speeds are not generally large enough to allow escape from the cluster.

Thus, planets around stars are constantly being stripped away and joining the ranks of free-floating planets, many of which remain bound to the cluster. Free-floating planets may be found in every part of the cluster, but many will be ejected from regions near the center of the globular cluster. As they move away, they will receive a large but decreasing amount of radiant energy from the star that had been their host. The bottom panels of Figures 1 and 2 show that they will also continue to receive significant flux from the other cluster stars. This flux will be most significant in high-concentration clusters. Interestingly enough, in many cases, the dominant source of ambient light will be a single star not previously related to the free-floating planet.

If free-floating planets are to house life, they must have outer layers that shield the life from fluxes of comets and asteroids, from high-energy particles, and from some portions of the electromagnetic spectrum (see, e.g., Badescu 2011). In our own

Solar System, some moons of the outer planets are covered by ice that can serve as a shield for oceans (Hand & Chyba 2007). Furthermore, since life requires energy, any life on free-floating planets must have sources of energy independent of irradiation by a single star. We are now coming to understand that there are myriad sources of energy on which moons of the outer Solar System can draw, ranging from radioactivity to tidal interactions. Some of these could also be available to free-floating planets in globular clusters. Free-floating planets in globular clusters may be able to draw upon energy emitted by nearby stars. It is for this reason that we have included the lower panels of Figures 1 and 2, which depict the average flux received as a function of distance from the cluster’s center, as well as the flux received from the brightest nearby star.

We have no information at present about free-floating planets in globular clusters, but studies of both star-forming regions (Scholz et al. 2012) and microlensing events (Sumi et al. 2011) provide evidence for them in the disk. The numbers of free-floating planets inferred from the microlensing observations may be too large to be explained by mechanisms such as planet–planet scattering (Veras & Raymond 2012).

Free-floating planets must be considered as possible habitats for life and for advanced civilizations. Free-floating planets also interact with planetary systems. The expression for the rate of interactions is the same as the rate of interactions with stars (Section 3.1). The distances of closest approach associated with dramatic effects, however, tend to be smaller, yielding a smaller value for the rate of interactions per free-floating planet. To compute the total numbers of interactions with free-floating planets, we need to know their density. If their numbers are larger than the number of stars, the density may also be larger. However, mass segregation is an important feature of globular clusters, and free-floating planets have masses much smaller than those of the cluster stars. We therefore expect that, even though the cluster’s core may be the point of origin of many free-floating planets, they may spend the large majority of their time in the outer portions of the globular cluster. This means that, in spite of the large numbers of free-floating planets, their local spatial densities may tend to be low.

That any life on free-floating planets may need shielding by an outer layer at all times could promote survival when asteroids strike, or when the free-floating planet passes through regions with a high flux of radiation (e.g., near an LMXB or close to a normal star). Thus, if there is life on free-floating planets, it may be able to survive throughout the cluster. There would be no inner boundary to the sweet spot for free-floating planets. (That is, for free-floating planets where $R_{\text{low}}^{\text{sweet}} = 0$.) The outer edge of the sweet spot is determined by the same considerations as for bound planets: the value of D should be less than some value, which we have taken to be 10^4 au.

There would be an interesting corollary should it be that free-floating planets (1) exist in globular clusters, (2) are more numerous than bound planets, and (3) are able to support life. The most meaningful nearest-neighbor distance would be the distance to the nearest free-floating planet. The outer boundary of the sweet spot for both bound and free-floating planets would move to larger values of $R_{\text{high}}^{\text{sweet}}$.

4. SETI AND THE GLOBULAR CLUSTER OPPORTUNITY

Searches for extraterrestrial intelligence (SETI) started in the 1950s and 1960s (Cocconi & Morrison 1959; Dyson 1960;

Drake 1961; and references in Tarter 2001), before planets beyond the Solar System had been discovered. Today we know of more than 2000 exoplanets (see, e.g., exoplanets.edu), but there are many open questions about planets, the formation of life, the nature of intelligence, and the development and lifetime of advanced civilizations.

Let L_i represent the lifetime of an advanced civilization. Our premise is that, once a globular cluster civilization is able to set up independent outposts, the probability becomes smaller that a catastrophic event will eliminate all advanced civilizations descended from it. We also postulate that smaller interstellar distances decrease the time T_i it takes for a civilization to establish outposts.

These ideas incorporate several assumptions. First, interstellar travel must be possible in globular clusters. For example, the danger of impacts from small masses in interstellar space must not be too great. Second, it must be possible to establish outposts. If, for example, life is plentiful but incompatible in different planetary systems, it may be difficult to find hospitable environments. If both interstellar travel and the establishment of outposts can occur, it is reasonable to consider that smaller interstellar distances could allow the first self-sustaining outpost to be established by a globular cluster civilization at a time $T_i < L_i$.

4.1. The Drake Equation

The Drake equation, developed during the early years of SETI, identifies the factors that determine the number of communicating civilizations in existence in the Galaxy at a typical time. See, e.g., Drake (2008). There are many possible definitions of the term “communicating civilization.” To set a scale, we will classify Earth as a planet with a communicating civilization, with a lifetime L , so far, of 100 years.

The form most suitable for our purposes is the following, where \mathcal{N}_b is the number of communicating civilizations on planets bound to stars.

$$\begin{aligned} \mathcal{N}_b &= N_* \times f_b(\text{star|pl}) \times n_b(\text{pl}) \times f_b(\text{pl|life}) \\ &\quad \times f_b(\text{life|int}) \times f_b(\text{int|com}) \times \frac{L_b}{\tau_H} \\ &= N_* \times \mathcal{F}_b \times \frac{L_b}{\tau_H} \end{aligned} \quad (2)$$

N_* is the total number of stars in the disk, $f_b(\text{star|pl})$ is the fraction of stars with planets, and $n_b(\text{pl})$ is the average number of planets per star. The fraction of planets on which life develops and the fraction of these on which intelligent life develops, and the fraction of these on which communicating civilizations develop are, respectively, $f_b(\text{pl|life})$, $f_b(\text{life|int})$, and $f_b(\text{int|com})$. These factors are combined to form the overall factor \mathcal{F}_b , the average number of communicating civilizations formed per star. The number of communicating civilizations orbiting stars at any given time is proportional to L_b , the average lifetime of those communicating civilizations orbiting stars. The ratio L_b/τ_H is the fraction of a Hubble time over which there is a communicating civilization.

4.2. Comparing Globular Clusters to the Galaxy

Numbers of stars: The first element of our comparison is the ratio $R_* = N_*^{\text{gc}}/N_*$, where the numerator is the number of stars

in a globular cluster. This varies among globular clusters from under 10^5 to more than 10^6 .

$$R_* = 5 \times 10^{-6} \left(\frac{N_*^{\text{gc}}}{5 \times 10^5} \right) \left(\frac{1 \times 10^{11}}{N_*} \right). \quad (3)$$

If all other factors were equal, a population of a few times 10^3 communicating civilizations in the disk would correspond to ~ 1 in the Galaxy's population of ~ 150 globular clusters. A disk population roughly 100 times as large would correspond to ~ 1 communicating civilization within each of many globular clusters.

Value of \mathcal{F}_b : The second element of our comparison is the factor \mathcal{F}_b , the number of communicating civilizations formed per star. The fact that globular cluster stars are long-lived means that a large fraction of them provide environments stable enough for life to form and evolve on their planets. In fact, old planetary systems may have had several opportunities to produce civilizations during the past 12 Gyr. While the same is true for old stars in the disk, only a smaller fraction of them are as old as globular cluster stars.

In addition, evolution on globular cluster planets is less likely to be subject to interruptions. For example, astronomical events and excess exposure to radiation and winds can essentially “reset” the clock for evolving life and civilizations. These “resets” can delay evolution toward advanced civilizations or destroy them. Because globular clusters have little gas and dust they do not form stars or produce core-collapse supernovae or long gamma-ray bursts.

Of course, stellar passages have the effect of interrupting developments on those planets that are either ejected because of an interaction or else come to orbit another star after an interaction. We have shown, however, that large numbers of planets in the habitable zones of low-mass stars should be stable throughout significant portions of most globular clusters. From the perspective of developing and evolving life in a manner that may parallel what happened on Earth, these are the most important systems, and this is why \mathcal{F}_b may have values in globular clusters similar to those in the disk.

It is also important to consider, however, that orbits of many planets are disrupted through interactions. Ejection is especially likely for planets in wider orbits where liquid water could not have been sustained. Ejections transform these planets into free floaters. Life that had existed on a planet losing its star could expire and/or develop differently afterward.³ Finally, changes in orbit can be induced by stellar passages, even when a planetary system's architecture is not reconfigured. These effects, though more modest, could nevertheless influence life in a planetary system (in either a positive or negative way), and must be considered in more detailed work, similar to the way issues such as orbital eccentricity are now considered in computations involving the habitable zone.

³ There are other questions to be considered. For example, it would be difficult at present to assess the relative frequencies of asteroid strikes in globular clusters versus the disk. Stars in globular clusters cannot have extended asteroidal disks or clouds. This would tend to decrease the frequency of impacts. On the other hand, the ambient density of planetoids may be higher in globular clusters. Nevertheless, because asteroids and comets have very small masses, they would tend to migrate toward the outer edges of a globular cluster, helping to moderate the average density throughout much of the cluster. A second question is the rate of SNe Ia. Observations have established that they do not occur more frequently in globular clusters than in the field (Voss 2013; Washabaugh & Bregman 2013); these numbers will continue to be refined.

The enhanced stability of the globular cluster environment is part of what we can call the *globular cluster opportunity*.

Lifetimes of communicating civilizations: The final factor is the lifetime of communicating civilizations. Let $Y_i(p)$ be the number of planetary systems in which one or more communicating civilizations develop. We can classify a communicating civilization according to whether it remains within a single planetary system or whether it develops outposts outside of it.

$$\frac{L}{\tau_H} = \frac{1}{\tau_H} \times \sum_{i=1}^{Y(p)} \left[\sum_{j=1}^{C_i^1} L_i + \sum_{j=1}^{C_i^{>1}} (\tau_H - t_i(0)) \times \eta_i \right]. \quad (4)$$

The outer summation in Equation (4) is over planetary systems, the inner summation is over the sequence of civilizations in a given planetary system. The first term represents communicating civilizations that do not establish outposts. The second term represents communicating civilizations that do establish outposts. Once a set of independent, self-sustaining outposts has been established the cluster may always host descendants of the original “seed” civilization. Thus, the value of L is simply the difference between the present time and the start of the seed civilization. We include the factor $\eta < 1$ to recognize that effects we cannot anticipate may lead to the end of these civilizations in spite of the apparent opportunity to continue into the indefinite future.

The second part of the *globular cluster opportunity* is that relatively small interstellar distances may allow self-sustaining outposts to be developed over relatively short timescales. This would give globular clusters the potential to host communicating civilizations over a continuous very-long-lasting epoch.

4.3. Conditions for Globular Cluster Civilizations

Our discussion of the Drake equation has focused on the numbers of communicating civilization expected at present. It is useful to also consider the total number n of civilizations that are ever formed within a stellar population (either a galaxy or a globular cluster).

$$n = N_* \times \mathcal{F}. \quad (5)$$

Let us suppose that over the course of a Hubble time a certain minimum number, n_{min} , of communicating civilizations must arise within a specific globular cluster in order to ensure that one of them will be able to establish self-sustaining outposts. In order for this minimum value to be achieved, the value of \mathcal{F}^{gc} must be greater than $\mathcal{F}_{\text{min}}^{\text{gc}} = n_{\text{min}}^{\text{gc}} / N_*^{\text{gc}}$.

$$\mathcal{F}_{\text{min}}^{\text{gc}} = 10^{-5} \times \left(\frac{n_{\text{min}}^{\text{gc}}}{10} \right) \left(\frac{10^6}{N_*^{\text{gc}}} \right). \quad (6)$$

This equality translates a minimum value of n into a minimum value of \mathcal{F} , which can then be related, through Equation (2) into a condition on the factors whose product is \mathcal{F} .

For example, one way to achieve a value $\mathcal{F}_{\text{min}}^{\text{gc}} = 10^{-5}$ is if only 10% of cluster stars have planets that can support life, only 1% of planets with life support intelligent life, and 1% of planets with intelligent life produce communicating civilizations. These relatively low probabilities could be enough to ensure that every globular cluster hosts a long-lived communicating civilization, even if only one in ten globular cluster communicating civilizations succeeds in establishing outposts.

To place these values in context, we consider the galactic disk. Should \mathcal{F}^{gal} be as small as 10^{-5} , then 10^{11} disk stars

would produce 10^6 communicating civilizations in a Hubble time. If these each last for a time 10^{3+k} years, with k ranging from 1 to 7, there would be 10^{k-1} communicating civilizations at any one time. In the small- k limit, we could be the only communicating civilization active in the Galaxy today. In the large- k limit, the nearest communicating civilization would be on the order of 100 pc away.⁴

This example illustrates that many of the Milky Way’s globular clusters could presently host advanced communicating civilizations that have spread throughout the cluster, whether the disk of the Galaxy contains no other communicating civilizations or whether it is rich in communicating civilizations. Furthermore, if globular clusters do host advanced civilizations, they will tend to be old civilizations.

4.4. Free-floating Planets

The Drake Equation can be applied to free-floating planets. Let \mathcal{N}_f be the number of communicating civilizations on free-floating planets.

$$\begin{aligned} \mathcal{N}_f &= N_f \times f_f(\text{pl|life}) \times f_f(\text{life|int}) \times f_f(\text{int|com}) \times \frac{L_f}{\tau_H} \\ &= N_f \times \mathcal{F}_f \times \frac{L_f}{\tau_H} \end{aligned} \quad (7)$$

N_f is the total number of free-floating planets in the disk. The fraction of free-floating planets on which life develops and the fraction of these on which intelligent life develops, and the fraction of these on which communicating civilizations develop are, respectively, $f_f(\text{pl|life})$, $f_f(\text{life|int})$ and $f_f(\text{int|com})$. These factors are combined to form the overall factor \mathcal{F}_f , the number of communicating civilizations formed per free-floating planet. L_f is the average lifetime of those communicating civilizations on free-floating planets.

We do not know the number of free-floating planets. Based on microlensing surveys, the disk population of free-floating planets appears to be larger than the disk population of main-sequence stars (Sumi et al. 2011; Strigari et al. 2012). Setting N_f to $\phi \times N_*$, the value of \mathcal{F}_f needed to produce a certain number of communicating civilizations is proportional to $1/\phi$.

Thus, large values of ϕ mean that the value of \mathcal{F}_f can be even smaller than \mathcal{F}_b , to produce a number of communicating civilizations on free-floating planets comparable to the number of communicating civilizations on planets bound to stars. Put another way, the chance of a communicating civilization developing on a free-floating planet can be very small, making life extremely uncommon among free-floating planets; yet there may be more communicating civilizations developing on free-floating planets than on planets in the habitable zones of stars. Free-floating planets in globular clusters have an advantage in that the stars in their vicinity may provide significant energy. This is especially so if the civilization is advanced enough to build and transport large stellar-light collectors (Benford 2013; Guillochon & Loeb 2015).

⁴ This distance could be reduced, however, if galactic communicating civilizations produce self-sustaining outposts, and/or if globular cluster communicating civilizations spread to the disk.

5. IMPLICATIONS

5.1. Overview

Although only a single planet has so far been discovered in a globular cluster, several lines of reasoning suggest that globular cluster planets may be common. If there is a similarity to planetary systems in the disk, then low-mass cluster stars may host planets in their habitable zones. We have shown that there are large regions of globular clusters, “sweet spots,” in which (1) habitable-zone planetary orbits have long lifetimes, while (2) the distances between neighboring stars are small enough to significantly decrease interstellar travel times from what they are in the Galactic disk.

The existence of a “sweet spot,” possibly combined with long-term stability afforded by the lack of massive stars in globular clusters, is what we have referred to as the globular cluster opportunity. If life and advanced civilizations develop on the habitable-zone planets, then it is reasonable to consider the possibility that the lifetime of some globular cluster civilizations may exceed the time needed to establish independent outposts. Should this be the case, then globular clusters may host communicating civilizations that are old and are spread throughout the cluster.

5.2. Prioritized List of Globular Clusters

We aim to identify those globular clusters most likely to have large sweet spots. If the primary criterion we needed to impose was the existence of planets in stable orbits in the habitable zones of cluster stars, this would favor low stellar densities. We want, however, to also have relatively small distances between neighboring stars, which favors high densities.

We consider an analogy with LMXBs and their progeny, recycled millisecond pulsars. The formation of LMXBs has been explained in terms of interactions made possible by a high-density environment (Clark 1975). As a result of these interactions, a neutron star comes to have a binary companion that will donate mass to it. The interaction which led to the formation of this binary is likely to have involved one or more binaries in the initial state. Furthermore, before post-interaction mass transfer can start, the newly formed neutron star binary must generally survive for a significant length of time before the donor comes to fill its Roche lobe. These circumstances suggest that the cluster must include, not far from the core, regions of modest density where lifetimes of stable orbits remain long. In fact, the orbit of the planet in M4 has a large semimajor axis (~ 23 au), which would not survive in the cluster core.

This balance of higher and lower density is similar to the qualities we seek in a globular cluster that has a significant sweet spot. These points are demonstrated empirically in Figure 3, each of whose points corresponds to a globular cluster whose parameters have been taken from the Harris et al. (2010) catalog. Along the horizontal axis is the log of the central luminosity density, ρ . Along the vertical axis is the logarithm to the base 10 of the *half-mass concentration factor*, which we have defined to be $h = \log_{10}(R_h/R_t)$. We used this factor because the value of $R_h = 1.3 r_0$ (from the Plummer model) is directly tied to the overall fall-off of the cluster density with distance from the center.

In Figure 3, points with a yellow triangle superposed correspond to globular clusters that host millisecond pulsars.

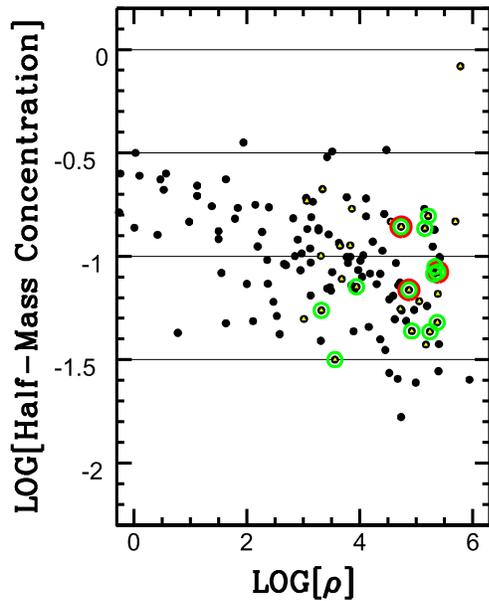


Figure 3. Logarithm (to the base ten) of the half-mass concentration factor, h , vs. logarithm (to the base ten) of ρ , which here is taken to be the central luminosity density (Harris et al. 2010). Points with a yellow triangle superposed correspond to globular clusters that host millisecond pulsars. Those surrounded by green rings contain at least 3 ms pulsars and those surrounded by red rings have 10 or more millisecond pulsars.

Those surrounded by green rings contain at least 3 ms pulsars and those surrounded by red rings have 10 or more millisecond pulsars. The figure displays two trends. First, there are no discovered millisecond pulsars in globular clusters with $\log_{10}(\rho) < 2.8$. Second, neither very high nor very low concentration factors are associated with multiple millisecond pulsars. While the trends in Figure 3 almost certainly reflect observational selection effects convolved with physical principles (for example, each cluster may host more millisecond pulsars than observed), they are consistent with the results of Section 3 for habitable-zone planets illustrated in Figures 1 and 2. In Table 1 we therefore use the numbers of millisecond pulsars as a proxy to help prioritize searches for planets and for intelligent life in globular clusters, keeping in mind that other factors may eventually be understood to be more important. The columns are: the cluster name; distance from us; metallicity; concentration factor computed from the ratio of the core to tidal radius; core radius; half-mass radius; concentration factor, h , as defined above; central luminosity density; and the number of known recycled pulsars.

5.3. Navigation

Millisecond pulsars provide strong, stable, periodic signals, which, in 19 of the globular clusters listed in Table 1, emanate from different directions. Timing precision allows the determination of their positions with great accuracy and this precision has in turn led to suggestions of using pulsar timing to navigate spacecraft (Downs 1974, see Deng et al. 2013 for a recent review). That is, measured timing residuals of multiple pulsars can be used to determine the spacecraft position with a precision that depends on the accuracy of the measured times of arrival of pulses (TOAs) and the stability of the pulsars. Because pulsar observations using radio telescopes require a large collecting area of the telescopes that are impractical for

spacecraft, X-ray observations of pulsars using much smaller X-ray telescopes have been proposed for spacecraft navigation (Chester & Butman 1981) (see also Sheikh et al. 2006 and US Patent 7197381B2). With an ensemble of four millisecond pulsars and realistic timing accuracy, Deng et al. (2013) show that the position of a spacecraft can be determined to an accuracy of 20 km on a trajectory from Earth to Mars. Since in a globular cluster environment a set of pulsars will be within a typical distance < 10 pc, the pulsars appear far brighter than when viewed from the Solar System, thousands of parsecs away. The potential use of small radio antennae could allow radio pulsar timing with the precision needed for navigation.

5.4. Search for Planets

The crowding of dim globular cluster stars at distances larger than a kpc (Table 1) makes it challenging to discover globular cluster planetary systems. The progress made during the past several years in discovering planets in open clusters is, however, a positive development. Transit studies of the outer regions of globular clusters would allow us to focus on planets in the habitable zone while taking advantage of mass segregation. The most numerous stars would be very low-mass M-dwarfs, and their small sizes would optimize the chances of discovering the small planets that are expected.

High resolution studies like those conducted by Gilliland et al. (2000) with *Hubble Space Telescope* (*HST*) could be effective in regions of higher density. In the core, however, mass segregation could mean that the most common main sequence stars are those of relatively high mass. Orbital periods of planets in the habitable zone could be dozens or hundreds of days. It would therefore be more productive to study dense regions located outside the core. Even so, the baselines would need to be long enough for the discovery of planets in orbits that have periods up to a few tens of days.

Nascimbeni et al. (2012) searched for transiting planets and variable stars in a stellar field of the globular cluster NGC 6397 among 5078 stars using over 126 orbits of the *HST*-Advanced Camera for Surveys (ACS), which is one of the deepest ACS fields observed. This included the analysis of light curves of a selected subset of 2215 M-type dwarfs (ranging between spectral classes M0–M9). Although no high-significance planetary candidates were detected they mentioned a very small photometric jitter is found for early-M stars in this cluster that show ≤ 2 mmag variations and that these may be worth targeting in the future with better optimized searches. Comparing their null detection with the results from *Kepler* discoveries, they did not find any strong evidence of lower planet incidence among their sample. Their null detection corresponds to an upper limit of the fraction Φ_p of stars hosting a $P < 5d$ Jupiter sized planet with about $\Phi_p = 4.8\%$ of stars at 1σ confidence. This is not unusual in terms of the underlying planetary population studied by *Kepler*. Nascimbeni et al. (2012) was, therefore, unable to make any firm conclusion about the giant planets in relatively tight orbits around their stars in NGC 6397. Another important step would be to discover free-floating planets. Discoveries of free-floating planets in the field have been reported by microlensing teams (Sumi et al. 2011). Microlensing is ideally suited for these discoveries, because gravitational lensing is sensitive to mass; light from the planet is not required. As it happens, several globular clusters lie in fields studied by an optical monitoring team. Excess events along the directions to these clusters have

Table 1
Globular Clusters Ordered by Numbers of Recycled Pulsars

Cluster	D (kpc)	[Fe/H]	c_{core}	R_c	$R_{1/2}$	$c_{1/2}$	ρ	N_{msp}
Terzan5	8.0	-0.28	1.74	0.18	0.83	1.08	5.38	35
NGC 104	4.3	-0.76	2.04	0.37	2.79	1.16	4.87	23
NGC 6626	5.7	-1.45	1.67	0.24	1.56	0.86	4.73	12
NGC 7078	10.2	-2.22	2.50	0.07	1.06	1.32	5.37	8
NGC 6624	7.9	-0.42	2.50	0.06	0.82	1.36	5.24	6
NGC 6440	8.0	-0.34	1.70	0.13	0.58	1.05	5.33	6
NGC 6266	6.7	-1.29	1.70	0.18	1.23	0.87	5.15	6
NGC 6752	3.9	-1.55	2.50	0.17	2.34	1.36	4.92	5
NGC 6205	7.0	-1.54	1.49	0.88	1.49	1.26	3.32	5
NGC 5904	7.3	-1.29	1.87	0.40	2.11	1.15	3.94	5
NGC 6517	10.5	-1.37	1.82	0.06	0.62	0.81	5.21	4
NGC 6441	9.7	-0.53	1.85	0.11	0.64	1.09	5.31	4
NGC 5272	10.0	-1.57	1.85	0.50	1.12	1.50	3.56	4
NGC 6522	7.0	-1.52	2.50	0.05	1.04	1.18	5.38	3
NGC 7099	7.9	-2.12	2.50	0.06	1.15	1.22	5.05	2
NGC 6760	7.3	-0.52	1.59	0.33	2.18	0.77	3.86	2
NGC 6749	7.7	-1.60	0.83	0.77	1.10	0.68	3.34	2
NGC 6656	3.2	-1.64	1.31	1.42	3.26	0.95	3.65	2
NGC 6544	2.5	-1.56	1.63	0.05	1.77	0.08	5.78	2
NGC 6838	3.8	-0.73	1.15	0.63	1.65	0.73	3.06	1
NGC 6652	9.4	-0.96	1.80	0.07	0.65	0.83	4.55	1
NGC 6539	7.9	-0.66	1.60	0.54	1.67	1.11	3.68	1
NGC 6397	2.2	-1.95	2.50	0.05	2.33	0.83	5.69	1
NGC 6342	9.1	-0.65	2.50	0.05	0.88	1.25	4.72	1
NGC 6121	2.2	-1.20	1.59	0.83	3.65	0.95	3.83	1
NGC 5986	10.3	-1.67	1.22	0.63	1.05	1.00	3.31	1
NGC 5024	18.4	-2.07	1.78	0.37	1.11	1.30	3.01	1
NGC 1851	12.2	-1.26	2.24	0.08	0.52	1.43	5.17	1

been reported (Di Stefano 2014; Jetzer 2015). The rate of lensing events due to globular cluster stars is expected to be small (Paczynski 1994). But with the improved monitoring now being conducted, enough globular cluster lensing events will have been discovered that it should be possible to discover or place limits on free-floating planets in globular clusters. Furthermore, knowing the distance and proper motion of the cluster would allow the mass of each planet so discovered to be measured.

5.5. SETI

In 1974 a radio message was beamed from Aricebo to the globular cluster M13 (<http://www.seti.org/seti-institute/project/details/arecibo-message>). If that message is received and answered promptly, it will take almost 42,000 years for us to receive a response. Although other globular clusters are closer, almost all are more than a kpc away, making short-term two-way communication problematic.

If, therefore, we are to find evidence of extraterrestrial intelligence in globular clusters, it will be through signals that originated in the clusters long ago. These signals may represent attempts at communication with advanced civilizations in the Galactic disk. Or they may be signals generated incidentally as a globular cluster society carries out its normal functions. With more than 50 years of work on this topic, many ideas have been developed (Tarter 2001).

If communicating civilizations are common in the Galaxy, globular clusters may be good targets for SETI simply because they are dense, well-defined stellar systems. In Section 4, we showed that even if communicating civilizations are rare in the disk of the Milky Way, they could occupy multiple Galactic

globular clusters, and could be very advanced. Although discussions of long-lived advanced civilizations are necessarily speculative, it may be easier to detect signals from an advanced civilization. If the signals involve energetic phenomena, such as X-ray emission from LMXBs, they could be detectable even if they emanate from globular clusters outside the Milky Way. There are many thousands of globular clusters within 10 Mpc. Radio emission from globular clusters within the Milky Way is regularly studied, and X-ray emission is studied from Milky Way globular clusters and, at least on occasion, from thousands of globular clusters in galaxies as far from us as the Virgo cluster. These data are studied with the goals of learning more about accreting compact objects. It may be worthwhile to enhance the analysis for subtle additional signatures that could be signs of intelligent life.

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