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EARLY-TYPE STARS: MOST FAVORABLE TARGETS FOR ASTROMETRICALLY DETECTABLE PLANETS IN THE HABITABLE ZONE

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ABSTRACT

Early-type stars appear to be a difficult place to look for planets astrometrically. First, they are relatively heavy, and for fixed planetary mass the astrometric signal falls inversely as the stellar mass. Second, they are relatively rare (and so tend to be more distant), and for fixed orbital separation the astrometric signal falls inversely as the distance. Nevertheless, because early-type stars are relatively more luminous, their habitable zones are at larger semimajor axis. Since astrometric signal scales directly as orbital size, this gives early-type stars a strong advantage, which more than compensates for the other two factors. Using the *Hipparcos* Catalog, we show that F and A stars constitute the majority of viable targets for astrometric searches for planets with semimajor axes currently in the habitable zone. Thus, astrometric surveys are complementary to transit searches, which are primarily sensitive to habitable planets around late-type stars.

Subject headings: astrobiology — astrometry — extraterrestrial intelligence — planetary systems — stars: early-type

1. INTRODUCTION

To date, extrasolar planets have been discovered by three methods: pulsar timing (Wolszczan 1994), radial velocities (RVs; Mayor & Queloz 1995), and transits (Udalski 2002; Konacki et al. 2003). While RV has been by far the most successful of these (Butler et al. 2002), it appears to be ultimately limited to 1 m s^{-1} precision by instabilities in the atmospheres of stars. For planets in $a \sim 1$ AU orbits around solar-type stars, this corresponds to a planetary mass $m_p \sim 10\ M_\oplus$. Hence, to find less massive terrestrial planets will probably require other techniques.

Of particular interest are terrestrial planets in the so-called "habitable zone." While the exact specifications of this concept are the subject of continuing study and debate, for purposes of this Letter, we will assume the habitable zone to be centered at

$$a_{\rm habit} = 1\ {\rm AU}\ \sqrt{\frac{L}{L_\odot}}, \qquad (1)$$

where L is the bolometric luminosity of the star. We emphasize that this definition of habitable zone means "could possibly be inhabited now" and ignores several questions related to the issue of whether life could have spontaneously arisen on the planet. For example, early-type stellar lifetimes (2 Gyr for F0 and 400 Myr for A0; Schaller et al. 1992) might be too short for biogenesis, while for late-type stars, long-term variability (Turnbull & Tarter 2003) or tidal locking (Joshi, Haberle, & Reynolds 1997) might be detrimental as well. We return to these issues in § 4.

A quick survey of various techniques reveals five with reasonable potential for detecting terrestrial planets: pulsar timing, microlensing (Mao & Paczyński 1991), transits, astrometry (Shao 1996), and direct imaging. However, only two of these, transits and astrometry, show prospects of detecting habitable planets in the reasonably near future. Pulsar timing has already found three terrestrial planets in one system, but the intense radiation field from the pulsar makes these almost certainly uninhabitable. Microlensing is probably the most efficient method for detecting Earth-mass (and even sub–Earth-mass) planets (Bennett & Rhie 2002). Microlensing sensitivity peaks near planet-star separations of an Einstein ring (Gould & Loeb 1992), which is roughly at $a \sim 4\ {\rm AU}(M/M_\odot)^{1/2}$, where M is the mass of the star. This is well outside the habitable zone. While this sensitivity does extend into the habitable zone, it is much reduced compared to the peak. Direct imaging surveys are now only in their planning stages.

Detection of terrestrial planets, including in the habitable zone, is the primary goal of four proposed space missions: *Kepler*[1] and *Eddington*[2] plan to search for these by planetary transits, while the *Space Interferometry Mission* (*SIM*)[3] plans to search for them via the astrometric wobble that they induce on their parent star. On longer timescales, the *Terrestrial Planet Finder*[4] hopes to image and take spectra of such planets.

Gould, Pepper, & DePoy (2003) showed that the transit technique is actually most sensitive to habitable planets orbiting low-mass stars because their low luminosity moves the habitable zone inward (see eq. [1]), where transits are most efficiently detected. This factor, together with the greater abundance and smaller radii of low-mass stars, more than compensates for the worse signal-to-noise ratio (S/N) due to their lower brightness. Here we ask whether the particularities of astrometry also influence which stellar population this technique is most sensitive to when searching for habitable planets.

[1] See http://www.kepler.arc.nasa.gov.
[2] See http://sci.esa.int/home/eddington/index.cfm.
[3] See http://planetquest.jpl.nasa.gov/SIM/sim_index.html.
[4] See http://planetquest.jpl.nasa.gov/TPF/tpf_index.html.

2. ANALYTIC INVESTIGATION

Consider a homogeneous population of stars of mass M, bolometric luminosity L, and space density n. Assume that astrometric wobbles of amplitude $\alpha_{\rm min}$ can be reliably detected. A planet of mass m_p in the habitable zone (as defined by eq. [1]) can then be detected out to a distance

$$d_{\rm max} = \frac{m_p}{M}\sqrt{\frac{L}{L_\odot}}\frac{\rm AU}{\alpha_{\rm min}}. \quad (2)$$

Hence, the total number of systems that can be probed is

$$N = \frac{4\pi}{3} n \left(\frac{m_p}{M}\right)^3 \left(\frac{L}{L_\odot}\right)^{3/2} \left(\frac{\alpha_{\rm min}}{\rm AU}\right)^{-3}$$
$$= 7.6\,\frac{n}{n_0}\left(\frac{m_p}{3\ M_\oplus}\right)^3 \left(\frac{M}{M_\odot}\right)^{-3} \left(\frac{L}{L_\odot}\right)^{3/2} \left(\frac{\alpha_{\rm min}}{1\ \mu{\rm as}}\right)^{-3}, \quad (3)$$

where we have normalized the density to $n_0 = 2.5 \times 10^{-3}$ pc^{-3}, the space density per M_V magnitude of solar-type stars. The key point to note is that in the neighborhood of $M \sim 1\ M_\odot$, the bolometric luminosity scales as $L \propto M^\beta$, where $\beta \sim 4.5$. Hence the mass and luminosity terms can be combined to yield

$$N \propto nM^{1.5\beta-3} \sim nM^{3.75}. \quad (4)$$

Although the number density of stars falls rapidly as a function of mass, because both fewer are formed and those that do form live shorter lives, this is somewhat compensated by the fact that these younger stars have a lower scale height $h(M)$ and so are more concentrated near the plane. That is, the star formation rate and lifetime combine to give the *column* density of stars, $\Sigma(M)$, but the quantity relevant for nearby-planet hunting is the local *volume* density, $\rho(M) \propto \Sigma(M)/h(M)$. The shorter lifetime scales as $t \propto M/L$, but this is relevant only for stars $M \gtrsim M_\odot$, whose lifetimes are shorter than the age of the Galactic disk. The falling mass function scales as $dn/d\ln M \propto M^{-x}$, where $x = 1.35$ is the Salpeter value. These factors can be combined to obtain

$$\frac{dN}{d\ln M} \propto \frac{M^{\beta/2-x-2}}{h(M)} \sim \frac{M^{-1.1}}{h(M)}, \qquad M \gtrsim M_\odot \quad (5)$$

and

$$\frac{dN}{d\ln M} \propto M^{1.5\beta-x-3} \sim M^{2.4}, \qquad M \lesssim M_\odot. \quad (6)$$

The inverse scale heights $h(M)^{-1}$ for $M_V = (0, 3, 5)$, corresponding to masses $M = (3.5, 1.4, 1.0)\ M_\odot$, scale as $(3.3 : 2.0 : 1)$ (Miller & Scalo 1979). Hence, the scale height factor in equation (5) roughly cancels the mass factor. That is, this equation implies that astrometric sensitivity should be roughly flat (in log mass) for masses $M \gtrsim M_\odot$, while equation (6) shows that it falls steeply toward lower masses.

While the fraction of stars with planets in the habitable zone may well be a function of mass (and this can be determined only by searching for them over a range of masses), it is important to note that there are no known factors that would favor one mass over another. That is, since habitability is believed to be roughly a function of bolometric flux, the logarithmic width of the habitable zone should be independent of stellar type (Kasting, Whitmire, & Reynolds 1993). The distribution in semimajor axis of extrasolar giant planets is roughly equal in logarithmic spacings, $dN/d\ln a \propto a^{-0.18\pm0.04}$ (Tabachnik & Tremaine 2002). Hence, it is reasonable to assume that a similar fraction of early- and late-type stars will have terrestrial planets in their currently habitable zones. Here, we divide "early" from "late" at solar-type stars. For the very latest stars, i.e., M stars, one of us (D. A. F.) finds only one giant planet detection out of an RV sample of 120, compared with 70 out of 1200 for F/G/K stars. Hence, if terrestrial and giant planet frequency is related, then M stars also may be deficient in terrestrial planets.

3. NUMERICAL EVALUATION

To obtain more definite estimates, we determine the minimum mass that can be detected for each star in the *Hipparcos* Catalog (ESA 1997), assuming that each has a planet in a circular orbit with semimajor axis as given by equation (1). We determine M_V using the Johnson V magnitude and parallax as given by the *Hipparcos* Catalog, and we find the bolometric corrections from the $V-I$ color by using relations derived from Binney & Merrifield (1998) and Bessell & Brett (1988) at the bright end and Reid & Gilmore (1984) at the faint end. [For $M_V < 6$, we use the $V-I$ from the *Hipparcos* Catalog, while for fainter stars, we use $V-I = (M_V - 2.89)/3.37$ from Reid 1991.] We estimate the mass using M_V and the mass-luminosity relation of Allen & Cox (2000, p. 489) (although we caution that this relation remains controversial for late-type dwarfs; e.g., Delfosse et al. 2000). We adopt $\alpha_{\rm min} = 1\ \mu$as, which is the current best estimate for 5 σ detections for a 5 yr *SIM* mission (M. Shao 2002, private communication). It corresponds to 50 measurements, each with 1 μas precision[5] for face-on orbits or 100 measurements for edge-on orbits.[6] We also allow that this performance will be a weak function of apparent magnitude, $\alpha_{\rm min} = (1 + 10^{0.4(V-11)})^{1/2}\ \mu$as, which has the correct form in both the systematics-limited and the photon-limited regimes. However, including the flux-dependent term has hardly any effect on the results. In addition, we arbitrarily assign all red giants (defined as $M_V < 4$ and $V-I > 0.7$) a mass $M = 1.00\ M_\odot$. Red giant masses are difficult to estimate, but this estimate is not likely to be far off in most cases. In addition, fixing the red giant masses at a unique value makes them easy to identify in Figure 1, which displays our results.

Planets with periods $P < 5$ yr are shown by crosses, those with $P > 10$ yr are shown by filled squares, and those in between by open circles. However, the red giants ($M \equiv 1\ M_\odot$) with $P > 10$ yr (of which there are 296) are not shown to avoid clutter. These period distinctions are important, because at the 5 σ S/N limit used here, planets cannot be reliably detected in less than one orbit.

[5] This precision is set by the systematics of the *SIM* instrument but as a practical matter could not be significantly improved without substantially increasing the *SIM* aperture as well: with the present ~0.25 m aperture, the precision is limited to 1 μas by the availability of $V = 10$ reference stars. The fundamental limit of this technique is not known. For target stars with ~1% spot coverage, the astrometric noise is ~0.1 μas $\times\ 10^{-0.2(V-10)}(S_V/S_{\odot,V})^{-1/2}$, where S_V is the V-band surface brightness. However, because spots are at a reduced temperature, it is possible to remove this noise by comparing astrometric signatures at a variety of wavelengths. Thus, the fundamental limit may be very small.

[6] Even for a ~12 σ detection, the mass can be measured with better than 30% accuracy only half the time and the error distribution has large non-Gaussian tails (Ford & Tremaine 2003). Hence 5 σ is close to the margin of detectability.

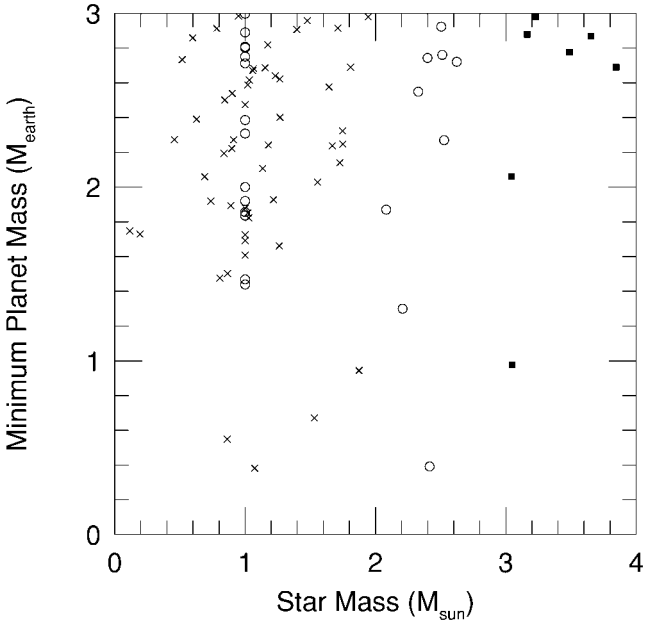


FIG. 1.—Minimum mass of detectable planets in the habitable zone as a function of stellar mass for stars in the solar neighborhood taken from the *Hipparcos* Catalog (ESA 1997). Planets with periods $P < 5$ yr (*crosses*), 5 yr $< P < 10$ yr (*open circles*), and $P > 10$ yr (*filled squares*) are shown separately. Red giants are all assigned a mass $M = 1\ M_{\odot}$, but the $P > 10$ yr giants are not shown to avoid clutter. For $P < 5$ yr, stars with $M > M_{\odot}$ outnumber those with $M < M_{\odot}$ by 30 to 19, while for $P < 10$ yr the ratio is 39 to 19.

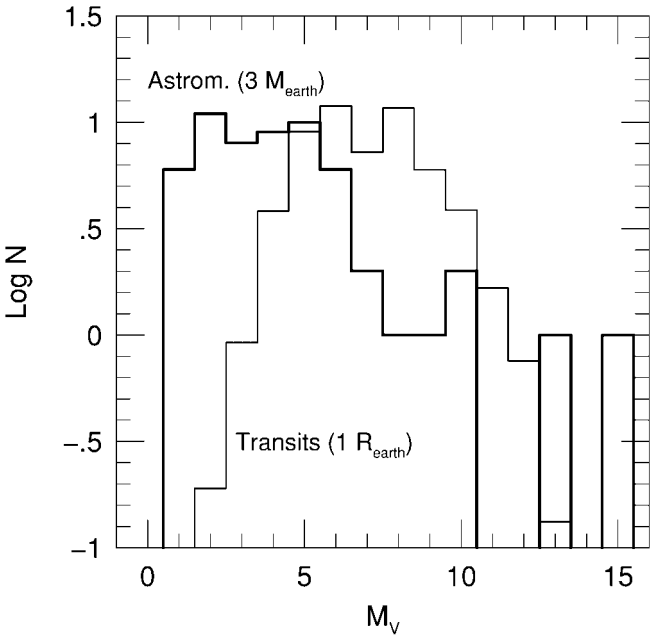


FIG. 2.—Histograms of sensitivities of astrometric and transit surveys to planets in the habitable zone. The astrometric curve shows the same stars as in Fig. 1, excluding all red giants and all stars with $P > 10$ yr. The transit curve is taken from Gould et al. (2003), who adopted the characteristics of the *Kepler* mission but (contrary to the *Kepler* Web site) assumed that faint late-type dwarfs would be included in the survey. Since astrometric surveys are sensitive to mass, while transit surveys are sensitive to radius, the two curves are not strictly comparable, but the relative trends with stellar type are robust.

Restricting consideration to planets with periods $P < 5$ yr, there are 19 stars that can be probed for planets of mass $m_p < 3\ M_{\oplus}$ with $M < M_{\odot}$ and 30 with $M > M_{\odot}$. In addition, there are four red giants. Some consideration is being given to extending the *SIM* mission from 5 to 10 yr.[7] For this case, the respective numbers are 19, 39, and 18. In either case, the early-type stars dominate over the late-type.

Note that for our purposes, *Hipparcos* is virtually complete. Using equation (2) together with the bolometric correction and *SIM* flux dependence described above, we find that the faintest star that can be probed for 3 $M_{\oplus}$ planets lies within the *Hipparcos* $V = 7.3$ mag limit for all stars $-2 \leq M_V \leq 9.5$. For dimmer stars, the limit gradually rises to $V_{\max} = 10.9$ at $M_V = 14$, at which magnitude *Hipparcos* is still effectively complete for such nearby ($d_{\max} = 2.4$ pc) stars. At $M_V = 15$, the only known star within $d_{\max} = 2$ pc is Prox Cen, which is in *Hipparcos*. There are no known stars satisfying the distance limit for fainter magnitudes, $M_V \geq 16$. Hence, there are few, if any, stars relevant to our study that are missing from *Hipparcos*.

4. DISCUSSION

The sensitivity of astrometric surveys to habitable zone planets around early-type stars makes them complementary to transit surveys. If these latter are properly executed (Gould et al. 2003), they will be sensitive primarily to habitable zone planets around late-type stars (see Fig. 2).

While early-type stars may have planets in the habitable zone, that does not necessarily mean that these can be inhabited by natural processes. On Earth, almost a gigayear was required before life took hold, and several more were required before it succeeded in radically transforming the atmosphere. Very early stars do not live long enough to permit this leisurely development. Moreover, as with all main-sequence stars, early-type stars evolve away from their zero-age main-sequence luminosity well before their death, so that the duration of continuous habitability is shorter than their lifetime. Therefore, a small fraction of the planets currently in the habitable zones of early-type stars will have been outside the habitable zone for most of the star's lifetime. However, there are a large number of targets with masses $M \lesssim 1.5\ M_{\odot}$, and these can live for $\gtrsim$2.5 Gyr. Moreover, it may be that life elsewhere in the universe develops faster than on Earth. Targeting these early-type stars for habitable planet searches is the best way to find out.

In fact, a related concern arises with respect to very late-type stars. As noted in § 1, there is some question about whether planets in the habitable zone around M stars can in fact be inhabited, because their hosts show long-term variability (Turnbull & Tarter 2003) and because they are tidally locked (Joshi et al. 1997). The latter authors study both effects and conclude that they can be, but this remains a subject of ongoing controversy. Our orientation to this question is the same as above: in the final analysis, it can be resolved only experimentally, by finding such planets and searching for life on them.

The time that red giants spend at approximately their current luminosity (and so that a planet at a given semimajor axis would remain in the habitable zone) is even shorter than the lifetime of many early-type stars. This would appear to give even less time for life to develop. However, if these stars had harbored planets in the habitable zone during their main-sequence phase, and if these planets gave rise to intelligent technologically advanced life, these beings could have moved their home to pro-

[7] The main reasons for an extended mission would be to push the sensitivity to lower masses by increasing the S/N as well as to find longer period planets. For consistency, however, in Fig. 1 we use the same 1 μas precision based on a 5 yr mission for all stars regardless of period.

gressively greater semimajor axes by orchestrating suitable interactions with an asteroid or comet, in order to maintain their planet's habitability as their star aged (Korycansky, Laughlin, & Adams 2001).

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