DETECTION OF LARGE TERRESTRIAL PLANETS AROUND M AND K DWARF STARS BY TRANSIT PHOTOMETRY

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Abstract

A ground based transit survey of M and K-dwarf stars near the galactic plane should be able to determine the abundance of the lower end of the planetary radius function, i.e., extrasolar planets smaller than Neptune. We have shown (Doyle et al. 2000, ApJ 535, 338), that the ground-based detection of planets as small as 2.5 Earth-radii within the M-star circumstellar habitable zone (CHZ) is possible by applying signal detection techniques to differential stellar photometry. Telescopes of 4-meter size with wide-field imaging cameras (greater than one-half degree field of view) are capable of surveying about 35,000 stars in the galactic. In a candidate field near Orion, about 8000 stars would be G, 12500 be K, and another 8000 stars would be M-dwarf systems, at the magnitude range of 18 to 22. Observations of about 1000 hours, accumulated over a 5-year program, would cover both the full orbital phase of transit-aligned planetary orbits with periods less than 30 days, as well as provide a sufficient number of transit signals for reliable statistical detection confidence. An extrapolation of the mass function of known extrasolar planets predicts that a couple of hundred of these sub-Neptune/large-terrestrial planets might be detected in this way, some within the CHZs of the M2 to M5 stars.

Key words: Planets: exoplanets – detection, transits, terrestrial; stars - low mass, populations

1. Introduction

We are planning to observationally extend the lower-end of the planetary "radius" function towards terrestrial-sized planets, a size region that has never been explored, with one exception. This is the CM Draconis binary M4 V/M4 V system where the entire circumstellar habitable zone (CHZ) has been observationally covered down to planets of size less than about 2.3 Earth radii (R_e), that is, planets with expected masses of about 1-3% that of Jupiter (Deeg et al. 1998, 2000; Doyle et al. 2000a,b). To our knowledge this represents the first search for potentially habitable extrasolar planets.

While ground-based transit photometry cannot be expected to detect Earth-sized planetary transits across G dwarf stars - this will be left to space based missions - large-field ($> 0.5°$) imaging with 4-meter telescopes should allow the detection of terrestrial-sized planets (i.e. less than 3 Earth radii) of K and M dwarf systems. The small telescope size of the space based missions (about 1m) will not give good coverage of these systems. Taking the previous limits found for the CM Dra system with 1000 hours of R-band observations, planets as small as 1.8 Earth radii around single M-dwarfs can expect to be detected by their recurring transits.

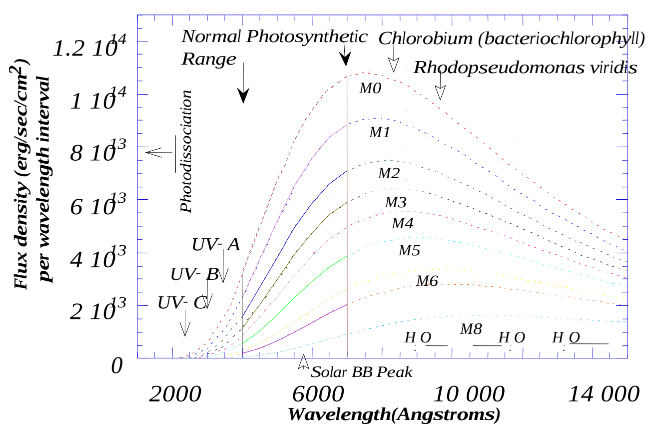

Figure 1. Black Body Curves for M0 through M8 Stars with spectral locations of relevance for planet habitability. As there is essentially no radiation to photodissociate H_2O, a moist runaway greenhouse effect is not possible, thereby setting the inner habitable zone boundary closer to the stars by up to 70%. The normal chlorophyll photosynthetic activity could probably still take place with fluxes of 3-30% of the solar one (at constant total flux), but bacteria exist (Chlorobium, Rhodopseudomonas) that use near IR light, without producing free oxygen. However, since there is no significant stellar UV, an Ozone layer is not required.

Low mass MS stars allow significantly smaller planets to be detected then solar like stars because of their smaller disk areas, since a given planet's brightness change during a transit is inversely proportional to the star's surface area. Additionally, the significantly lower luminosities of M dwarf stars place planets with periods as short as 10 days within their CHZ, depending, of course on whether one takes photodissociation energy, photosynthetic energy, or total energy as an inner boundary of the CHZ (Heath

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et al. 1999). Such short periods greatly improve the probability of detecting significant *numbers* of transits from such a system.

It has long been known that planets within the CHZ of M-dwarf stars will be tidally locked in their rotation. Thus the CHZ for M-stars are based on 3-dimensional atmospheric circulation models of *synchronously* rotating planets which also include effects of the M-star spectral range on surface heating and habitability (Haberle et al. 1996, Joshi et al.1998, Heath et al. 1999). These models show that with reasonable amounts of carbon dioxide (0.1-bar or so), liquid water may be maintained permanently on such a planet. Thus, at the lowest end of our search size, we should be able to detect planets with the potential, at least, to be habitable (Fig. 1).

In order to reach the required photometric precision of better then 0.5% for large numbers of M and K dwarf stars we have determined that moderately crowded fields at low angles from the galactic plane would be the best targets (as opposed to, for example, the galactic bulge which is too crowded at 22nd magnitude to allow isolation of M and K dwarf systems given the limitations of atmospheric seeing; Doyle et al. 2000c). At 20-22nd magnitude, M dwarfs will be at distances within a few hundred parsecs. At these distances, an observing beam at 5-10° galactic latitude will remain within the scale-height of the galactic disk. On the other hand, giant stars with these magnitudes will be several kpc away, and then be outside of the galactic disk, and their contribution will be significantly diminished.

Based on the Besancon Galactic Model (Robin et al., 2000), a potential target field of about 0.35 arcmin^2 in the Orion spiral arm region allows a photometric survey of approximately 35,000 stars within magnitude R=22. Over 95% of the systems in such a sample will be main-sequence stars, with 8000 being G, 12500 being K, and 8000 being M-dwarf stars (Figures 2&3). Models of this target region also show a mean metallicity of stars at 18-22nd magnitude of about [Fe/H] = -0.4, significantly above the metallicity of the globular cluster 47 Tuc, for example, where an HST survey found no giant planet transits (Gilliland et al. 2000). Giant inner planets may be expected to destroy any other inner terrestrial planets, as they might migrate inwards after their formation. There also appears be a trend toward giant inner planets being present around high metallicity stars with the majority in the range [Fe/H] = -0.1 to 0.3 (Gonzales 1997).

With the large abundance of hot giants around high-metallicity stars possibly suppressing the formation of Earth-like planets, Earth-like planets may predominantly form in the metallicity range of -0.6 $\leq$ [Fe/H] $\leq$ -0.1 (Lineweaver 2001). Also, as our proposed survey would comparatively easily pick up any giant inner planetary transits, new metallicity constraints would be placed on the giant planet formation process (Fig. 4).

In order to estimate the abundance of planets below the detectability of radial velocity techniques (i.e., sub-Neptune-sized), we have fit a power law to the mass distribution of the extrasolar planets discovered to date (Figure 5). An extrapolation to our detection limit of about $2R_e$ (corresponding to $0.02M_{\rm Jup}$) indicates that perhaps as many as 3/4 of main-sequence stars could have small planets. At an average 1% transit alignment probability with the 20,000 M and K dwarf stars in our expected field of view, this mass function predicts that a couple of hundred planets may be found. These results will have important consequences for existing theories of terrestrial planet formation.

At present, only a very few M-star eclipsing binaries - and therefore direct measurements of their stellar radii -

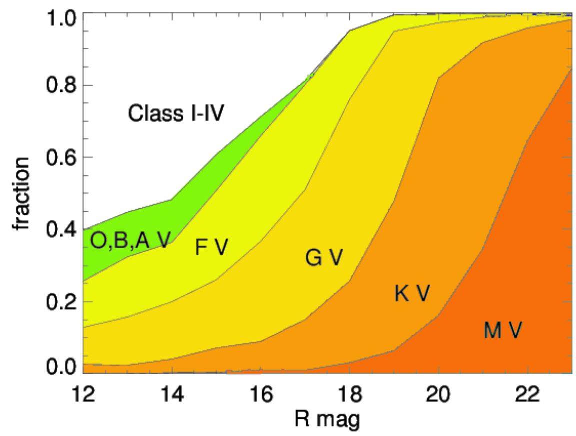

Figure 2. Stellar distribution (spectral type and luminosity class) with apparent R magnitude in a potential target field (in Orion, based on Besancon Galactic Model). The limit for the detection of transits with 4m telescopes is about R=22, whereas for 1m telescopes it is R≈ 19.

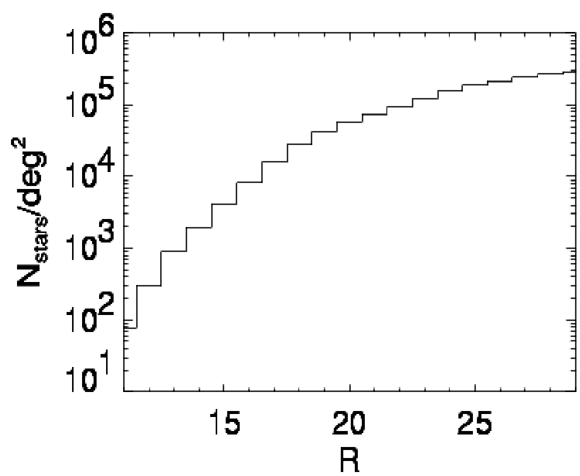

Figure 3. Cumulative number density of stars in the same target field. An 0.34 arcmin^2 field will contain about 30000 stars within R = 18 - 22.

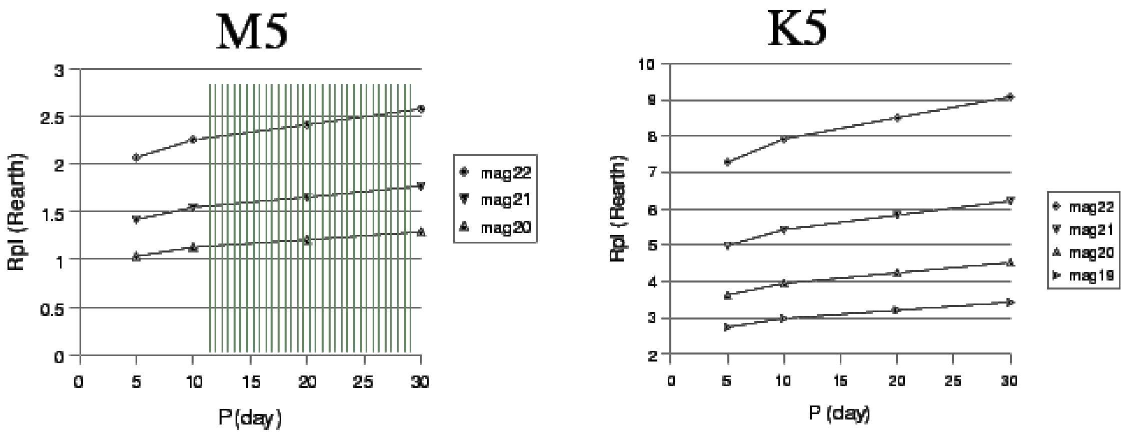

Figure 4. Minimum sizes of detectable planets with 1000 hours of photometry on 4m telescopes, for M5 V and K5 V stars, with respect to stellar brightness, and planetary period. For M5 stars, full coverage of the habitable zone (vertical stripes, based on Whitmire & Reynolds 1996) with p=11-30 days is possible. For K5 stars, the CHZ goes from 85-160 days. M0 to M4 stars would have parts of their CHZ covered.

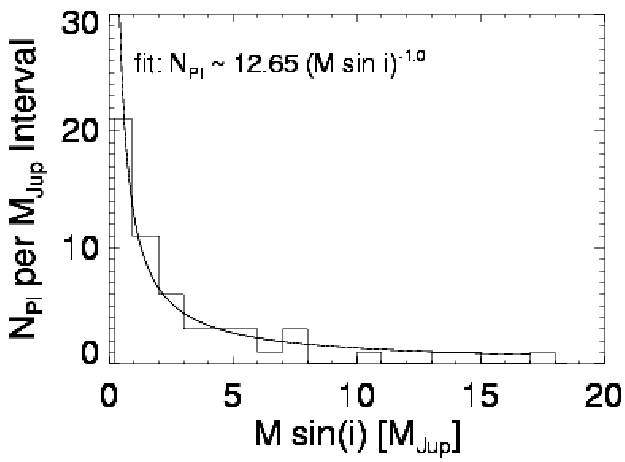

Figure 5. Numbers of known planets per Jupiter mass interval, fit with a power law. Beyond the limits of radial velocity detections (0.2$M_{\rm jup}$), large numbers of smaller planets are to be expected.

are known: CM Dra, YY Gem, and BW3-V38, are some of the few nearby examples. We should be able to provide a robust measure of the binarity of the M and K stars. (Fisher and Marcy, 1992, give a binarity for M-dwarfs of about 42% in the solar neighborhood.) Also, precise timing of the binary eclipses themselves may put constraints on the presence of outer non-transiting jovian-mass planets (Schneider and Doyle 1995, Deeg et al. 2000). One measures periodic variations in the eclipse times as the binary is offset across the binary/giant-planet barycenter.

In addition, repeated timing of the transit of a planet sufficiently far away from its star to have a stable moon could reveal such a moon's presence or absence by a quasi-periodic delay in the transit ingress. (The delay caused in the Earth's transit time across the Sun, if the Moon was orbiting in the lead, would be about 158 seconds, for example.)

In conclusion, a survey of M and K dwarf stars for sub-Neptune-sized extrasolar planets, especially within the CHZ of these systems, could provide valuable information on the lower-end of the planetary radius function thus also providing a guide to the planning of future spacecraft mission such as Eddington.

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