A SEARCH FOR EARTH-SIZED PLANETS IN HABITABLE ZONES USING PHOTOMETRY

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ABSTRACT

Several methods have been suggested for the detection of extra-solar planets. In the habitable zone, the radial velocity and astrometric methods are only sensitive to the detection of massive planets (greater than about ten to one-hundred Earth masses). However, the photometric method is sensitive to Earth-sized planets in inner orbits about solar-like stars. The methodology for conducting a photometric space-based search is described. The information that can be directly and indirectly derived from the observations about any planetary systems discovered is discussed.

INTRODUCTION

Detection of extra-solar short period planets, particularly if they are in the liquid-water zone, would be one of the most exciting discoveries of our lifetime. Several methods for the detection of extra-solar planets have been suggested (see the report "TOPS: Toward Other Planetary Systems", NASA, 1992 and Schneider (1994)). These methods include the use of astrometry, radial velocity measurements and photometry. The radial velocity and astrometric methods are only sensitive to the detection of massive planets (greater than about ten to one-hundred Earth masses) in the habitable zone as shown in Figure 1. On the other hand, photometry is sensitive to Earth-sized planets (ESP) in inner orbits about solar-like stars (Rosenblatt (1971), Borucki and Summers (1984), Borucki et. al. (1985), and Schneider and Chevreton (1990)), as shown in Figure 2. These planets and their locations in the habitable zone are the ones of interest at this conference.

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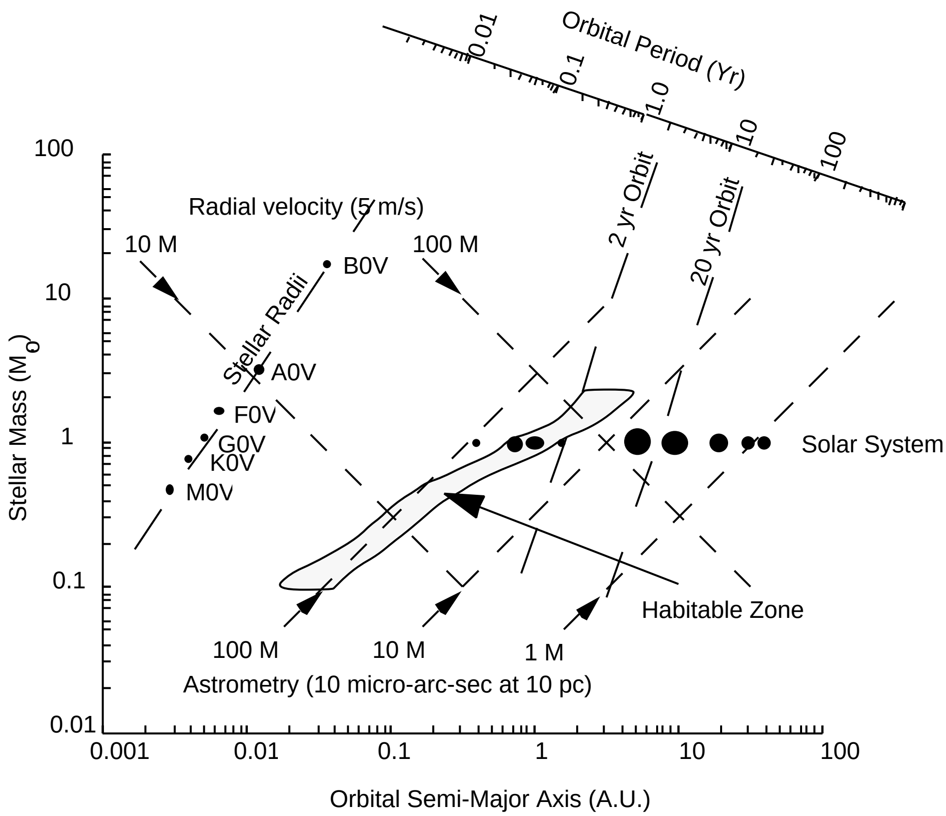

Figure 1 Minimum Detectable Mass for the Astrometric and Radial Velocity Methods. The figure depicts the size and mass of various spectral type dwarf stars. For these stars, any point on the plot defines a planetary mass, orbital semi-major axis and orbit period. The planets of the solar system are illustrated. The habitable zone (see Kasting, Whitmire, Reynolds 1993) is indicated by the shaded region. The contours for the minimum detectable planetary masses are indicated for the radial velocity and astrometric methods.

PROPERTIES OF TRANSITING PLANETS

Given a random orientation of orbital plane alignments with the line-of-sight to a star, the probability for proper alignment is the stellar diameter (D) divided by the planet's orbital diameter (D_p) as shown in Figure 3. Assuming our solar system to be typical (having two ESP whose orbits are not co-planar to within an angle of 2D / D_p), one would expect 1% of the stars monitored to exhibit planetary transits. To obtain a statistically

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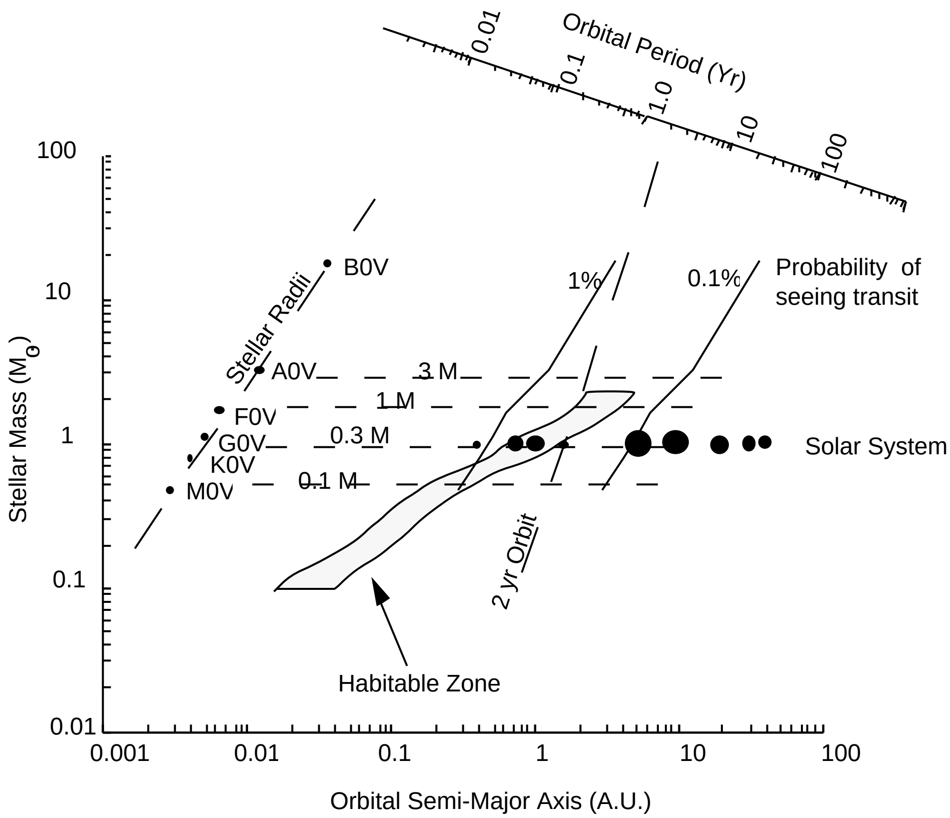

Figure 2 Minimum Detectable Planetary Mass for the Photometric Method. The plot characteristics are the same as in Figure 1. The contours for the minimum detectable planetary masses are indicated for the photometric method. The sensitivity is based on the method being capable of detecting a characteristic change of light of 1 part in 25,000 due to a planetary transit. The geometric random probability for detection is the stellar diameter divided by the orbital diameter. Contours for this probability are indicated.

significant result, several thousand stars need to be monitored, resulting in detection of about one transit per week throughout the mission. F-, G- and K-dwarfs are the most promising candidate stellar types.

ESP transiting solar-like stars will cause a decrease in the apparent luminosity of the star by one part in 12,000 with a duration of about 13 hours for a nearly equatorial crossing. Planets as far out as Mars will have equatorial transit times of 16 hours and those as close in

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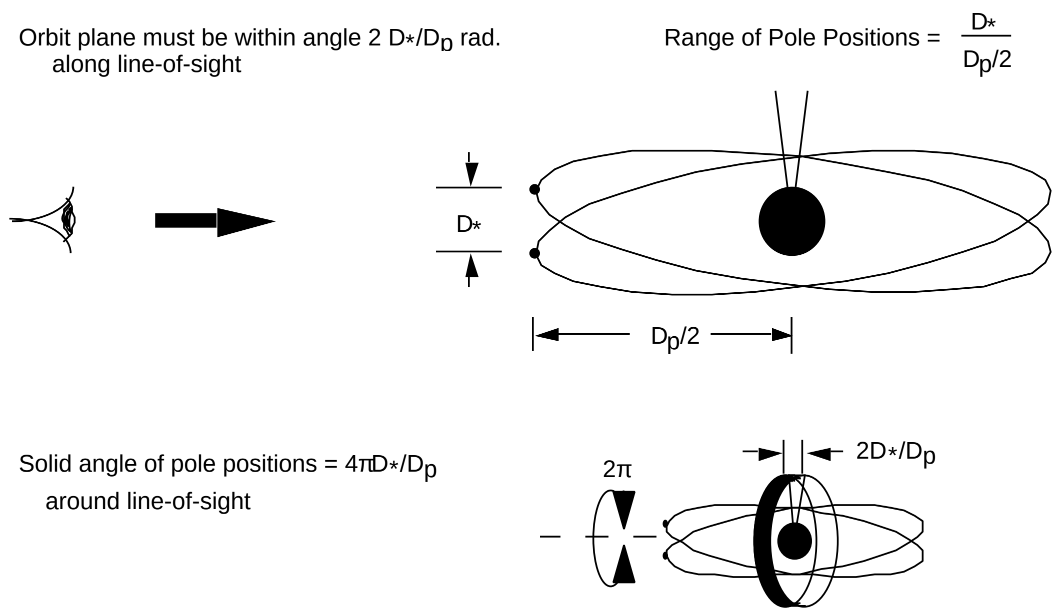

Figure 3 Geometric Probability For Transit Sightings. For a transit to be observable, the planet must pass in front of the stellar disk, that is the pole of the orbit must be within the angle D /(D_p/2), where D is the stellar diameter and D_p/2 is the planetary orbital radius. This is true for all 2π angles of pole positions about the line-of-sight or 4πD /D_p steradians. Thus the random probability for seeing transits is p=D /D_p.

as Mercury can be detected with a grazing transit time as short as four hours. The equatorial transit time is given by:

$$\tau = D\sqrt{R / GM} \qquad (1)$$

where D is the stellar diameter, R is the planetary orbital radius and M is the stellar mass. For the solar system., $\tau = 13.04\sqrt{R}$ hours, with R in AU. Not all transits will cross at the equator. However, 87% of the transits will have durations greater than half the equatorial transit time.

Discovery of a planet will require detection of multiple transits of the same amplitude, duration and correct period of occurrence. That is, after detection of two transits of the same amplitude and duration, the occurrence of a third and subsequent transits can be predicted to within a matter of hours. Planets in inner orbits will have periods of 0.3 to 2 years. Thus, a mission life of six years is required to detect a minimum of three transits by planets with orbits as large as that of Mars.

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MISSION DESCRIPTION

An instrument optimized for photometric observing of ESP around solar-like stars has the following features:

- It must have a photometric precision of ~1:36,000 (1 σ) per hour.
- It must be above the Earth's atmosphere, to avoid transparency variations that limit the photometric precision to less than 1:1000 over a large field of view.
- It must constantly view the same star field without interference from the Earth-limb or the Sun so as to obtain a continuous record on time scales from an hour to years. A 15,000 km, 10° inclination orbit has been selected with the telescope pointed in a region close to the equatorial and ecliptic polar.
- It must simultaneously monitor several thousand stars. A one-meter-class telescope with a large field-of-view (on the order of 10° diameter) is required. A Schmidt telescope design is currently being evaluated and a focal plane array of CCDs to perform the simultaneous monitoring is being tested to demonstrate that CCDs can meet the photometric precision requirement.
- It must be able to efficiently extract the brightnesses for the selected set of stars for data processing to be manageable.

SPECIFIC DETAILS FROM EACH PLANETARY SYSTEM DETECTED

Data from the photometric observations can provide information on the character of each planetary system detected. The basic information will be the orbital period, the depth of the transit and the transit duration, as well as the orbit plane inclination to a fraction of a degree .

The orbital period and stellar mass determine the orbital radius, where the stellar mass is determined from the spectral type and luminosity class of the star. From this one will know immediately if the planet is in the habitable zone for the given stellar type (see Figure 2), (Kasting, Whitmire, Reynolds (1993), Kasting (1994) and Whitmire (1994).

From the transit depth the ratio of the planetary diameter to the stellar diameter is determined. The spectral type and luminosity class of the star define the stellar diameter and thereby determine the size of the planet detected. Presuming the planet to be terrestrial (density of about

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5 g/cm^3) and given its size, a good approximation can be made for the mass of the planet and the value of its surface gravity.

From the stellar absolute magnitude and orbital radius, the stellar flux at the planet can be calculated. Given a range of albedos and assumptions on the amount and type of possible atmosphere, a range of surface temperatures can be estimated. Stellar activity data from this mission will provide further insight into fluctuations of the radiation which might affect the planetary climate.

If the planet is in a binary stellar system there are a number of other parameters to consider. From the timing of the transits with a close binary pair, the orbital eccentricity can be determined. Not only are the positions of the stars important in determining the amount of radiation reaching the planet, but also the variation in distance to each of the stars will affect the climate on the planet. The daylight variations can be calculated for the case of the planet in orbit around a close binary pair or the synodical variations can be calculated for an open binary system where the planet is in orbit around one of the pair. During part of the year in an open binary system when the planet is in-between the two stars, one can expect "night" to be as bright as 50 full Moons (stellar separation of 100 AU) to as much as 1/10 that of high noon (separation of 4 AU).

RESULTS FROM THE ENSEMBLE OF SYSTEMS

In addition to the information available about each specific planetary system detected, the ensemble of information from all of the planets detected will further our understanding of planetary formation theories. For the first time one will be able to derive the frequency of ESP for F-, G- and K-dwarf stars. Prior to these measurements, it has commonly been assumed that this frequency is close to one. If only a few or no planets are detected then one must conclude that ESP are rare, the models of planetary system formation need to be substantially revised, that the origin of the Earth must be reconsidered and that Earth itself might be unique. The value for the frequency of ESP can be used to predict the more general parameter for the frequency of planetary formation used in the Drake equation (Borucki & Koch, 1993).

The ensemble of photometric observations should provide size and radial distribution information which can be used to test calculations of planetary formation, such as those of Wetherill (1991 and 1994). Those calculations indicate that:

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- No planets much larger than Earth size are expected for orbital radii between 0.3 & 2 AU.
- These planets can occupy any position within these radii.
- The distribution of planets will be affected by the presence or absences of a Jovian planet.
- Two ESP are expected within these radii.
- The orbits should be nearly co-planar.

The results on the size and radial distribution of the detected planets will address these hypotheses.

During the six year mission, approximately one massive outer planetary transit should be seen. Ground based radial velocity observations are capable of detecting other massive planets in the systems provided they are in inner orbits. Follow-on ground-based photometry, even after the end of the mission, can confirm as well as search for massive planets in these systems. The depth of a Jovian transit is large, about one per cent, and the chances for proper alignment along the line-of-sight are good, about ten percent, since the orbit planes of the systems will be known to be close to the line-of-sight of the observer. These observations will help to further revise and refine models for planetary formation.

The co-planarity of orbits can be determined from the frequency of detection of multiple planetary systems (MPS). The probability for seeing multiple planets is given by:

$$P_{21} = \frac{2}{\pi}\sin^{-1}\left(\frac{D}{D_p \sin\varphi_i}\right) \qquad (2)$$

provided $D/D_p < \sin\varphi_i$, where φ_i is the relative orbital plane inclinations and D and D_p are as before and as illustrated in Figure 4. When $\sin\varphi_i < D/D_p$, the probability is near or equal to unity. For the Earth-Venus case, there would appear to be a 9.4% chance and for the Mars-Earth case there would be a 15% chance for an outside observer seeing transits by both planets. The frequency of MPS will provide a good measure of their co-planarity. i.e., if the detection of MPS is high, then φ_i must typically be less than D/D_p. Whereas if the detection of MPS is low, then φ_i must typically be greater than D/D_p or few systems have more than one ESP.

About half of the stars being monitored will be in binary stellar systems. However, binaries do not necessarily preclude planetary formation and detection (Brandmeier, 1994). Theoretical modeling has demonstrated that long-lived planetary orbits exist when the planet's orbital radius is three times greater than the stellar separation or the

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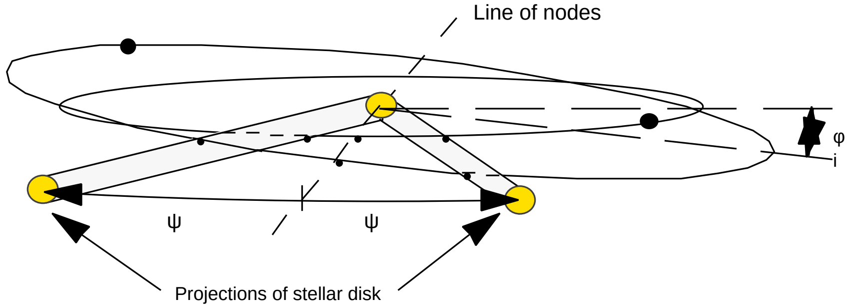

$\psi = \sin^{-1} (D_*/D_p \sin\varphi_i)$	Angle from Line of Nodes for which both transits can be seen
	D_*/D_p is the stellar angular radius viewed from a planet
$P= 4\psi/2\pi$	Total probability for seeing two planets on either side of both nodes
$P_{EV}= 0.094$	Probability for Earth-Venus case
$P_{ME}=0.15$	Probability for Mars-Earth case

Figure 4 Geometry for Multiple Planetary Sightings. When the observer is viewing a transit near the line of nodes for two inclined planetary orbits, then transits for both planets will be seen. If the relative inclination is small as compared to the apparent stellar angular diameter ($2D_*/D_p < \varphi_i$) as viewed from a planet, then it is likely that transits from both can be seen.

stellar separation is three times greater than the planet's orbital radius (Black and Pendleton, 1983 and Dobrovolskis, 1994). In the open binary case, planetary systems are even possible around both stars. Results from this mission should determine the frequency of ESP in binary system.

SUMMARY

The photometric method for planetary detection can provide for both the discovery of planetary systems, as well as a direct and an indirect measurement of many of the properties of the planetary conditions. In particular, it can provide information about the frequency of ESP in the habitable zone about solar-like stars, orbital radius and period, stellar flux at the planet and stellar variability. Further, from the ensemble of measurements, one can test models for planetary system formation, including the cases for binary star systems. If few or no planets are detected, than theories of stellar and planetary formation need to be revised, the origin of the Earth must be reconsidered, the

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concept of abundance of life in the Universe will have to be re-examined and the Earth might be unique.

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