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Extrasolar Terrestrial Planets: Present Status and Future Prospects

The search for other planetary systems is still in a very rudimentary stage. Fewer than four years ago Mayor and Queloz (1995) and subsequently Marcy and Butler (1996) found the first objects of Jupiter-mass (M_J) orbiting nearby stars via Doppler studies (Figure 3.1). As of this writing, more than a dozen companions of mass in the range (0.5-5)$M_J/\sin i$, where i is the unknown inclination angle of the orbital plane to the line of sight, have been identified around nearby stars. Preliminary data suggest that ~5% of solar type stars are accompanied by close companions in this mass range; nothing is yet known about objects of smaller mass. To date, only one of these systems has shown clear evidence for multiple companions revolving around the central star. Many of the companions detected so far are located very close to their parent stars. While this tendency is at least partially due to an observational bias of the Doppler technique, the present data may pose problems to our theoretical understanding of the formation and orbital dynamics of planets. Are these companions planets formed by agglomeration of material in a proto-planetary disk or are they failed stars (also known as brown dwarfs) formed in separate fragments of a proto-stellar core yet bound or captured into tight orbits? If these are planets, why are they located so close to their parent stars? These and other questions are at the forefront of the research into the nature of nearby planetary systems.

The exciting results of the past few years will be greatly enhanced in the next decade as Doppler observations of enhanced sensitivity and data from new observational techniques reveal more companions with a broader range of masses and orbital locations. This chapter discusses how ground- and space-based observatories, in particular the Keck Interferometer and the Space Interferometry Mission (SIM), will set the stage for TPF by making a complete census of planets as small as 5 Earth-masses ($M_\oplus$) for stars within 10 pc and for planets as small as a few $M_\oplus$ around the nearest stars (<5 pc). TPF will build on the work of predecessor observatories to complete a census of planetary systems down to 1 $M_\oplus$ for stars out to 15 pc, before going on to study the physical properties of the terrestrial planets that SIM and TPF itself, will discover.

Figure 3.1. A schematic representation of recent detections, using the radial velocity technique, of objects of Jupiter-mass around nearby stars (courtesy of G. Marcy).

DETECTION TECHNIQUES

Three techniques can provide indirect evidence for the presence of companions (very low mass stars, brown dwarfs, or planets) to stars. Each has strengths and weaknesses that must be considered in assuring a balanced program of exploring other planetary systems in advance of TPF.

Doppler Measurements. Radial velocity, or Doppler, measurements can routinely be made of stars like the Sun with a precision of ~10 m s^{-1} (Figure 3.2; Marcy and Butler 1992; Cochran and Hatzes 1994; Noyes *et al*. 1997; Brown *et al*. 1994; Mayor and Queloz 1995.) With this precision, one or more companions of ~1 M_J can be detected within a few AU of a star, and companions of a Saturn-mass can be detected within 0.2 AU. Photospheric velocity fields limit the ultimate precision to ~3 m s^{-1}. This limit implies that the Doppler technique will not be able to detect companions much smaller than a Saturn, and at 5 AU, will not find planets under 1 M_J around solar-type stars.

Astrometry. Reviews of the astrometric approach to planet detection are provided by Gatewood (1987), Shao and Colavita (1992), and Colavita and Shao (1994). As a benchmark, a Jupiter-analog orbiting 5 AU from a solar-type star that is located 10 pc away would produce an astrometric amplitude of 500 microarcsec (µas); an Earth-analog orbiting 1 AU from the same star would produce an astrometric amplitude of only 0.3 µas. An astrometric planet detection provides a measure of a planet's mass—something that neither Doppler detections with their inclination-dependent ambiguity or even direct detections (i.e. images) can offer.

Pravdo and Shaklan (1996) have demonstrated a precision of 100 µas with direct, short CCD exposures from the Palomar 5 m and Keck telescopes. With the Palomar Testbed Interferometer, Colavita and Shao (1994) have achieved an internal precision better than 60 µas $\text{hr}^{-1/2}$, confirming the potential of narrow angle astrometry from the ground (Shao and Colavita 1992). The Keck Interferometer should yield an astrometric precision of 20 µas (Colavita and Shao 1994) enabling detections of planets of ~Uranus-mass in ~5 AU orbits for stars at 10 pc.

The Space Interferometry Mission (SIM) is a critical project for filling out the census of neighboring planetary systems in advance of TPF.

With a precision of 1 µas for planet searches using narrow-angle astrometry (Unwin *et al*. 1997; Boden *et al*. 1996), SIM will be able to detect planets with masses larger than ~5 $M_\oplus$ in 1 AU orbits around stars at 10 pc and planets of a few (~1-5) $M_\oplus$ around the nearest stars (<5 pc). Thus, if rocky planets occur with somewhat larger masses than Earth, and if such planets are relatively common, there is a good chance that SIM will find some of them. Discovery of such planets by SIM would expand the realm of planets that might potentially have habitable environments, and hence would be high-priority targets for TPF.

SIM and Keck will provide a wealth of information on the companions they detect, including mass, orbital radius, inclination, and eccentricity. From the astrometric data we will learn about the frequency and diversity of planetary systems, as well as begin to understand the characteristics that distinguish planetary and brown dwarf companions. Although astrometric studies will be capable of detecting Earth-mass planets only around the very nearest stars, the SIM and Keck catalogs of planetary-mass companions will provide critical guidance for TPF's searches.

TPF's images will be very important in unraveling the astrometric and Doppler data for systems containing multiple objects, i.e. planetary systems. Given the limited time baseline of the indirect observations, a simple image of the planetary system from TPF will place immediate and fundamental constraints on possible orbital solutions. TPF photometry will also yield information on the radius, temperature, and albedo of any detected objects. The combination of these data with mass information derived from the astrometric and Doppler data could provide a rough estimate of a planet's density and hence suggest whether its composition is rocky or gaseous. From this information it might be possible to infer the presence of a solid surface suitable, perhaps, for the development of life.

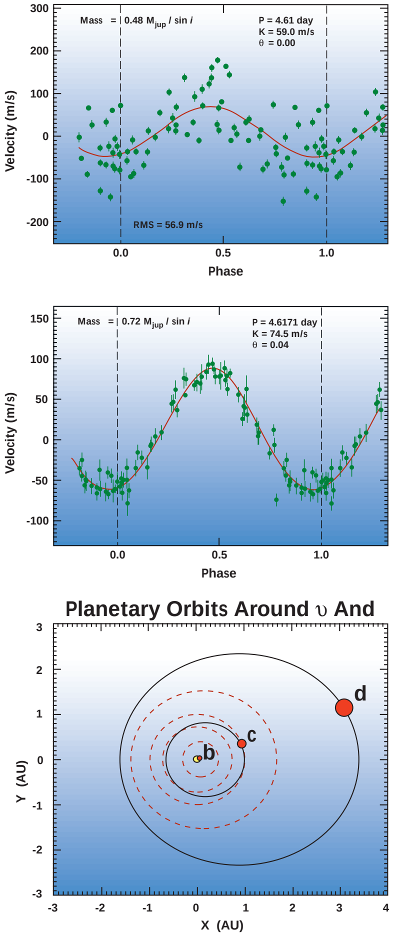

Figure 3.2. Radial velocity measurements have been used to infer the presence of multiple planets orbiting Upsilon Andromedae. The fit to the data for a single planet is relatively poor (top), while the fit for each planet is improved when the presence of three planets is taken into account (middle). Planets B, C, and D have orbital distances of 0.06, 0.85 and 2.5 AU, and Msin i of 0.73, 1.95 and 4.1 M_J, respectively (bottom). The orbits of the inner planets of our solar system are shown as dotted lines (Butler et al. 1999).

A limitation of the astrometric and Doppler techniques is that both require measurements over roughly half an orbital period to make a reliable detection of a companion, e.g. about 5 years for an object at Jupiter's distance from a solar type star or 15 years for an object at Saturn's distance. Finding the most distant planets in other solar systems will require many years of patient observation (and funding). Because of this limitation, every effort should be made to extend the lifetime of the SIM mission to at least 10 years.

Transits and Microlensing. Planets may be detected as they transit in front of the disk of a star. The fractional reduction in the light from the star is simply the ratio of the areas of the planet and the star. A transit by a Jupiter-sized companion will dim the light from a solar-type star by 1% for a few hours, with the duration depending inversely on the square root of orbital radius (Hale and Doyle 1994). Such photometry is possible from the ground and is being actively pursued by a number of groups. For randomly oriented orbital planes, the probability P that i will reside between 90° (edge-on) and i' is simply: $P(i'$ to $90^{o}) = \cos i'$. For a population of Jupiter-sized companions at 0.1 AU (51 Peg-like), 4.7% of them will produce observable transits. Approximately 2% of solar-type stars have such close Jupiter-sized companions (Marcy and Butler 1998). Transits yield the radius of the planet and hence, when combined with an astrometric or Doppler determination of mass, a rough estimate of the planet's density.

Transits by Earth-sized planets would dim the star by 0.01%. The requisite photometric precision requires a space-borne platform, wide-field camera, and a detector capable of photometric precision of a few parts in 10^5. While challenging, such a mission should reveal transits in ~1% of solar-type stars, if terrestrial planets at ~1 AU are common (Borucki *et al*. 1996). A transit search for Earth-size planets would provide useful information for the design of TPF, such as the occurrence rate and stellar characteristics that are associated with the presence of such planets. Such a mission would not, however, provide this information on nearby stars suitable for follow-up observations.

Gravitational microlensing of stars in the Galactic Bulge may also reveal the presence of planets in orbit around the intervening lensing objects. Intensive follow-up photometry of microlensing events by a global telescope network can reveal the short-term perturbations on the standard microlensing light curve caused by an attendant planet (Peale 1997; Griest and Safizadeh 1998). Microlensing is most sensitive to planets at a projected distance from the lensing star of about an Einstein radius, which corresponds to 3 to 6 AU for a typical Galactic Bulge microlensing event. The duration of the planetary perturbation on the light curve is proportional to the square root of the planetary mass. Microlensing is unique in its ability to detect Earth-mass planets in orbits with semi-major axes of several AU around main-sequence stars from the ground (hence inexpensively). Microlensing could demonstrate the existence of, and provide preliminary statistical information on, the occurrence of such planets. Follow-up study of these planets would be difficult due to their large distance (~5 kpc) and ambiguities in identifying the lensing object.

At least one candidate microlensing event involving an object of planetary mass has tentatively been identified in data from the Massive Compact Halo Object (MACHO) project, but more careful searches of the survey data and dedicated follow-up work are required before it will be possible to claim the detection of a low-mass planet with a high degree of certainty (Rhie *et al*. 1998).

Direct Detection. The challenge of direct detection of the light from extra-solar terrestrial planets is the focus of other chapters of this report. It should, however, be noted that the detection of giant planets in their young, high-luminosity phase is already possible for planets located a few arcseconds (tens of AU) from their parent stars. While not directly relevant to the search for terrestrial planets, this information will be important in understanding the general problems of the formation and evolution of planetary systems. Relevant results include the detection of a brown dwarf companion (~40 M_J) orbiting the star GL229 (Nakajima *et al*. 1995) and, more controversially, of two ~10 M_J objects associated with young T Tauri stars (Terebey *et al*. 1998; Becklin *et al*. 1998). While the planet-like nature of these latter two objects has yet to be confirmed, the results to date are encouraging in that they demonstrate that large telescopes such as Keck, HST, and NGST, if suitably equipped with adaptive optics and coronagraphic capabilities, could detect giant planets in the outer reaches of other planetary systems. Ground-based interferometers such as the Keck Interferometer, the Large Binocular Telescope, and the Very Large Telescope Interferometer will have the sensitivity and angular resolution to detect the infrared emission from giant planets that are heated by their parent stars, such as 51 Peg.

DOPPLER RESULTS TO DATE

Three major Doppler surveys have revealed the presence of low-mass companions to nearby stars. These surveys consist of the modest precision (300 m s^{-1}) survey of ~600 G and K spectral-type dwarfs by Mayor, Duquennoy, and Udry (Duquennoy and Mayor 1991; Mayor *et al*. 1999), and the two high-precision Doppler surveys of Mayor and Queloz (1995) and Marcy and Butler (1998), which surveyed 140 and 107 G and K stars respectively. Together these surveys have identified more than 15 objects with $M\sin(i) < 15\ M_J$ (Table 3.1; Figure 3.3). The orbital periods of the lowest mass objects range from 3.3 d - 2.5 yr, corresponding to semi-major axes, a, of 0.04 to 2.5 AU. However, 7 of the 11 planets have $a < 0.3$ AU. This "piling-up" of companions near their host stars appears to be a real effect, although enhanced by the selection effect that favors the detection of objects in small orbits (Lin *et al*. 1996).

Table 3.1. Orbits of Some Planetary-mass Companions

Star	*P* (d)	*A* (AU)	*K* (m s^{-1})	*e*	*M*sin *i* (M_J)
HD 187123	3.097	0.042	83	0.03	0.57
Tau Boo	3.3125	0.047	468	0.00	3.66
51 Peg	4.231	0.051	56	0.01	0.44
Ups And*	4.62	0.054	71.9	0.15	0.61
55 Rho^1 Cnc	14.65	0.11	75.9	0.04	0.85
Rho CrB	39.6	0.23	67	0.11	1.1
Gliese 876	61	0.21	217	0.27	2.1
70 Vir	116.5	0.47	316	0.40	6.73
16 Cyg B	799	1.6	50.3	0.687	1.67
47 U Ma	1092	2.1	47.3	0.09	2.38
14 Her	1620	2.5	75	0.36	3.3

*Multiple companions, see Figure 3.2

INTERPRETATION OF PLANETARY-MASS COMPANIONS

Detection Efficiency and Selection Effects. Figure 3.4 shows the detectability in the two-parameter space of semi-major axis and companion mass for both the astrometric and Doppler techniques. The companions detected to date are shown as lower limits due to the sin*i* ambiguity. The radial velocity limit of 10 m s^{-1} increases to the right and suggests that Doppler techniques will just be able to detect Jupiter-mass objects at 5 AU. Objects having masses less than 1 Saturn-mass will be very difficult to detect using Doppler techniques, and those less massive than Neptune will be impossible to detect via radial velocities. The lines decreasing to the right show the sensitivity of astrometric searches with the 1 µas goal of SIM shown at the lower left. Astrometric searches will be able to push to lower masses than Doppler searches for companions located at distances greater than 1 AU, but neither astrometry nor radial velocities will be able to detect planets less than few times the mass of the Earth around stars more than a few parsec away. A discovery by SIM that all the nearest stars have few $M_\oplus$ objects around them would have a profound effect on optimizing the TPF observatory since it is considerably easier to study planets around the nearest stars. However, even if the nearest stars should prove barren of terrestrial planets, TPF has the capability of finding Earth-sized planets well beyond SIM's range, out to ~15 pc compared with a few parsec for SIM.

Companion Masses. The small number of objects, the sin*i* ambiguity, and the selection effects of the Doppler technique (high mass and small orbits) make it difficult to interpret the existing observations unambiguously in terms of the true companion mass distribution. Efforts are underway to resolve these ambiguities. For example, the

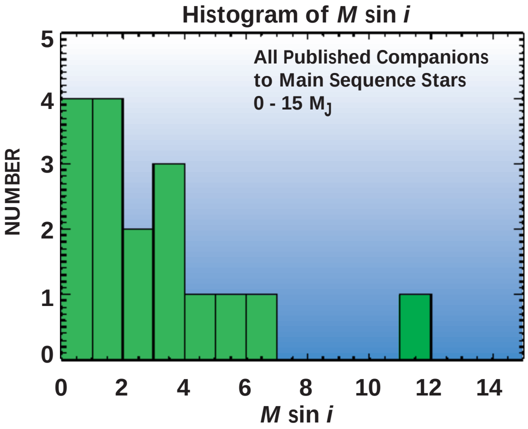

Figure 3.3. Distribution of Msin i for companion objects with Msin i <15 M_J (Marcy and Butler 1998) .

inclination of the 55 ρ^1 Cancri system has tentatively been determined to be ~27° by the detection of a circumstellar dust disk (Trilling and Brown 1998). The corrected mass of the companion is thus 1.9 M_J compared with the Doppler-inferred *M*sin*i* of 0.85 M_J. Determining the true distribution of companion masses will be an important part of the astrometric program for Keck and SIM.

One interpretation of the existing data, but by no means the only one, is that the larger companions were produced directly by the same collapse and fragmentation processes that led to the formation of the stars about which they orbit. These “brown dwarfs” are failed stars. Conversely, the companions with *M*sin*i* < 5 M_J may be either planets formed out of the material in the remnant proto-stellar disk of the parent star, or still lower mass examples of brown dwarfs. As the case of the highly eccentric, 1.5 M_J/sin*i* companion of 16 Cygni B (Cochran *et al*. 1997) suggests, the truth will undoubtedly be a combination of these two possibilities with plenty of room for surprises.

The detection of planetary-mass companions by different surveys provides estimates of the fraction of stars that harbor such objects. The Lick Observatory survey of 107 stars revealed 6 companions having *M*sin*i* < 7 M_J (Marcy and Butler 1998). With its 11-year duration, the Lick survey is sensitive to companions having semi-major axes as large as 5 AU. The survey precision of ~10 m s^{-1} implies that 2 M_J companions would be detectable at 5 AU and that 1 M_J companions would be detectable within 1 AU. Roughly, the Lick survey implies that ~5% of Solar-type stars harbor companions having *M*sin*i* ~ 0.5 - 5 M_J within 2.5 AU orbits. In general, however, the data are not yet available to assess the frequency of companions in the orbits characteristic of our solar system.

Finally, it is useful to note that the occurrence of “brown dwarf” companions in the next higher mass decade, 5 - 50 M_J, is at most 1% within 3 AU, based on surveys of ~600 stars. Brown dwarfs will not contaminate the TPF search for planets.

Companion Orbits. A significant fraction of low mass companions found to date have eccentric orbits despite the lack of an obvious observational selection effect to account for this tendency. The grav-

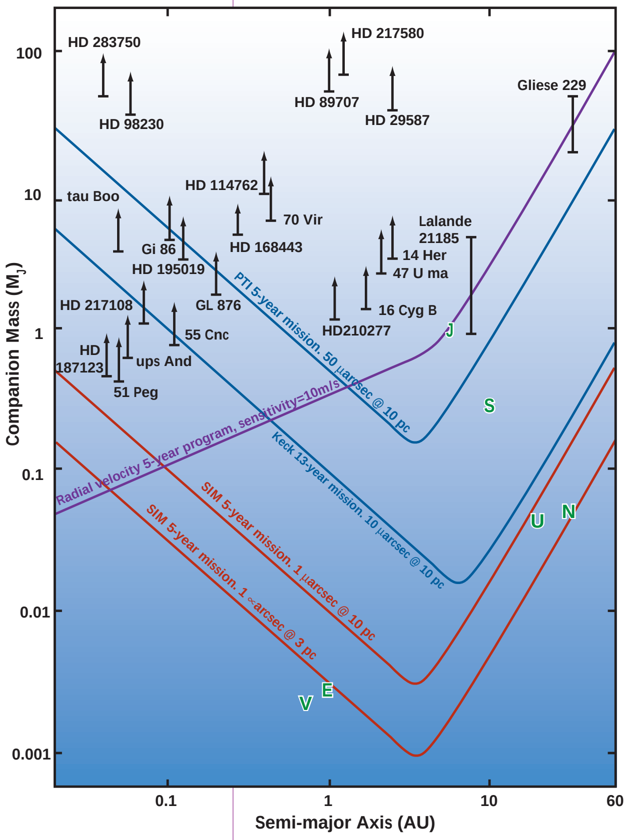

Figure 3.4. The sensitivity of astrometric and Doppler searches for planets of different masses and orbital locations. Planets detected via Doppler measurements are shown as lower limits due to the sin i ambiguity.

itational perturbation induced by such companions could have a profound influence on the orbits of smaller, terrestrial planets, possibly precluding them from spending an appreciable time in the habitable zone. Understanding the evolution of the orbits in planetary systems will be critical to knowing whether planets can remain within the habitable zone for long enough periods of time for life to form and evolve. A Jupiter-mass planet could acquire an eccentric or even a highly inclined orbit via many possible mechanisms. During the epoch of formation, the eccentricity of a protoplanet may be excited as a consequence of the interaction with the protoplanetary disk. In dense protostellar clusters, perturbations due to nearby stars might also seriously modify circular planetary orbits. Diversity may also be acquired during main sequence evolution through dynamical instabilities resulting from their long-term interactions with other planets and stellar companions. Observing many planetary systems with SIM, Keck, and ultimately TPF itself will help discriminate between “nurture versus nature” explanations for the dynamical evolution of planetary systems and lead to a better understanding of the survivability of Earth-like habitats.

Multiple Planets. It is reasonable to expect that a star having one planet should be accompanied by others as well. Indeed, there are hints of additional planetary-mass companions associated with at least two of the stars already found to have one low mass companion in a short period orbit. In the case of Ups Andromedae, the most recent data are consistent with the presence of 3 planetary mass companions–a true planetary system. (Figure 3.2). Eventually, we will want to probe the spatial distribution, mass and compositional gradient of the planets in other systems. The census of planets from SIM and the Keck Interferometer augmented eventually by images and spectra from TPF will expand the field of comparative planetology well beyond our Solar System:

- A broad range of orbital eccentricities and inclinations among planets within a system will provide important clues on the long term evolution of planetary systems.

- The distribution of zodiacal and Kuiper Belt dust (Chapter 5) may be related to the distribution of residual planetesimals and perhaps to the bombardment history of individual planets.
- Comparative atmospheric analysis for planets within a given system will provide clues to the importance of the greenhouse effect and volcanism.
- Periodic variations in the light curves observed by TPF might lead to the discovery of large moons or binary planets. In this case, tidal interaction may provide additional sources of energy for potentially habitable environments similar to Europa.

CONCLUSIONS

The available Doppler data show that there are stars with companions having masses, $M\sin i < 5\ M_J$. The nature and origin of these sub-stellar companions are still controversial with some researchers suggesting that the companions are planets formed in a circumstellar disk of solid material while others point out that the companions might be failed stars formed by the same processes as their more massive companions. This controversy may be resolved by more Doppler and astrometric observations that could reveal additional systems of multiple objects, possibly in the coplanar orbits expected of a planetary system formed out a protostellar disk.

The astrometric interferometers, Keck and SIM, will greatly advance our understanding of planetary systems, pushing the census down to a few $M_\oplus$, well into expected mass range for rocky planets. However, even after the astrometric missions have completed their work, we will still know only a little about Earth-like planets in our neighborhood since there is no proven technique for detecting and characterizing Earth-like planets beyond a few parsecs other than by direct detection with TPF itself. Although SIM may find a few terrestrial planets around the nearest stars, TPF will be the first observatory, on ground or in space, with the ability to detect and ultimately characterize Earth-sized planets around stars as far away as 15 pc.

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