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Characteristics of Extrasolar Planets

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Abstract. One hundred extrasolar planets have been discovered, all with ground-based Doppler observations. Most of the detected planets have masses ($M \sin i$) greater than Jupiter. However, with improved precision the Doppler technique should eventually reach down to Neptune-mass planets at separations of 1 AU or less. Here we present the characteristics of discovered planets and their host stars and we report two multiple planet discoveries.

1. Introduction

The detection of an extrasolar planet (ESP) around 51 Peg in 1995 (Mayor & Queloz) fueled an already intense search for planets orbiting nearby stars. Astronomers quickly realized that planet detection was a "numbers game" and by 1999, more than two thousand nearby FGKM stars had been subjected to Doppler surveys. In the past seven years, planet search teams have collectively discovered about 100 ESPs (for updates see http://exoplanets.org). The vast majority of these ESPs have velocity amplitudes above 30 m s^{-1} and semimajor axes less than 3 AU. That parameter space is so well sampled that it provides a statistical sample for this subset of ESPs. From this sample, we can derive a planet mass distribution and eccentricity distribution that reflect the early stages of planet formation.

Several multiple planet systems have now been detected. The residual velocity trends of stars with one known planet suggest that known planet-bearing stars harbor a distant companion (> 3 AU) more often than other stars on our surveys. In a few lucky cases, these multiple systems exhibit dynamical interactions that are measureable on decade-long timescales.

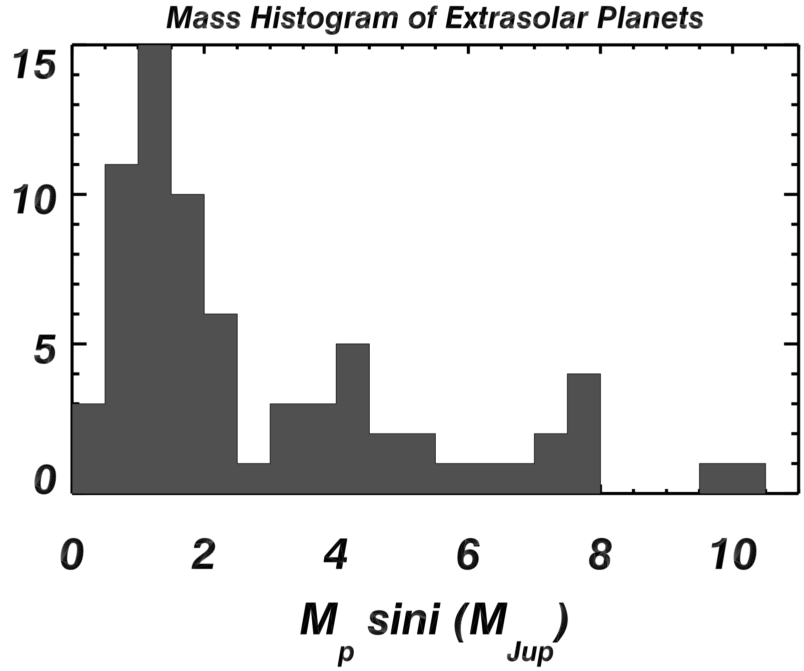

Figure 1. Mass distribution of extrasolar planets.

2. Planet Characteristics

2.1. Mass Distribution

The mass distribution (Figure 1) of ESPs rises rapidly toward low masses, demonstrating that Jovian-mass planets are more common than planets that are several times the mass of Jupiter. The rise toward low masses is all the more impressive because observational incompleteness is severe in this low–velocity amplitude regime. One intriging speculation is that by extrapolation of the mass distribution, there may be numerous ESPs with $M \sin i$ less than Saturn. If so, then improvements in Doppler precision will probe a new regime in the search for extrasolar planets.

At the high mass end of the distribution, the paucity of planets with $M \sin i$ > 5 $\mathrm{M_{JUP}}$ is unambiguous – out to several AU these planets are easily detected. Massive planets and brown dwarfs are rarely found in orbits closer than 10 AU. This observation supports a formation process whereby accretion is truncated in the protoplanetary disk.

Although the Doppler technique can only determine companion mass modulo $\sin i$, the undetermined inclination has little impact on the shape of the ESP mass distribution. On statistical grounds we expect that 86% of spectroscopic orbits will have inclinations such that the Doppler masses are within factor of two of the true mass. The $M \sin i$ distribution in Figure 1 is incompatible with a population of stellar or brown dwarf companions in randomly oriented orbits.

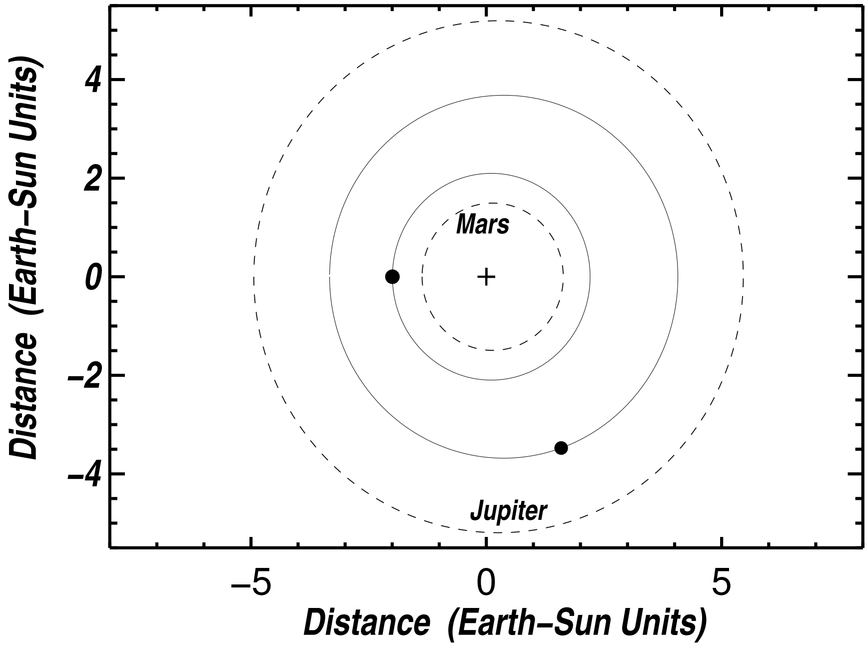

Figure 2. Orbit diagram for planets detected around 47 UMa. These two planets reside in low eccentricity orbits at semimajor axes of 2.1 AU and 3.7 AU. For scale, the solar system orbits of Mars and Jupiter are shown as dashed lines.

If, for example, most of the ESPs were actually brown dwarfs disguised by their unresolved $\sin i$, the mass distribution would be flipped, peaking in the brown dwarf regime with only an exponential tail at $M \sin i$ less than a few Jupiter masses.

2.2. Semi-major Axis Distribution

The Doppler detection of an ESP requires velocity measurements over one full orbital period. A natural consequence of this requirement is that there is a gradual harvesting of planets from the closest to the widest orbital separations. Nearly all of the ESP detections before 1999 resided in orbits with semimajor axes less than 1 AU. However, as current Doppler surveys continue over the next decade, we will begin to discover extrasolar planets at Jupiter-like separations.

All of the close-in, 51 Peg-like systems have now been culled from current Doppler samples. Likewise, most planets with $M \sin i > 1\ \mathrm{M_{JUP}}$ and semimajor axes less than 1 AU have already been found. In order to detect additional 51 Peg systems, new stars must be added to Doppler surveys. One caveat is that existing surveys are already complete to V=7.5 and nearly complete to V=8.5; new Doppler targets will typically be fainter than V=8 and will require large telescopes to attain $S/N > 200$, required for velocity precision of 3 m $\mathrm{s^{-1}}$.

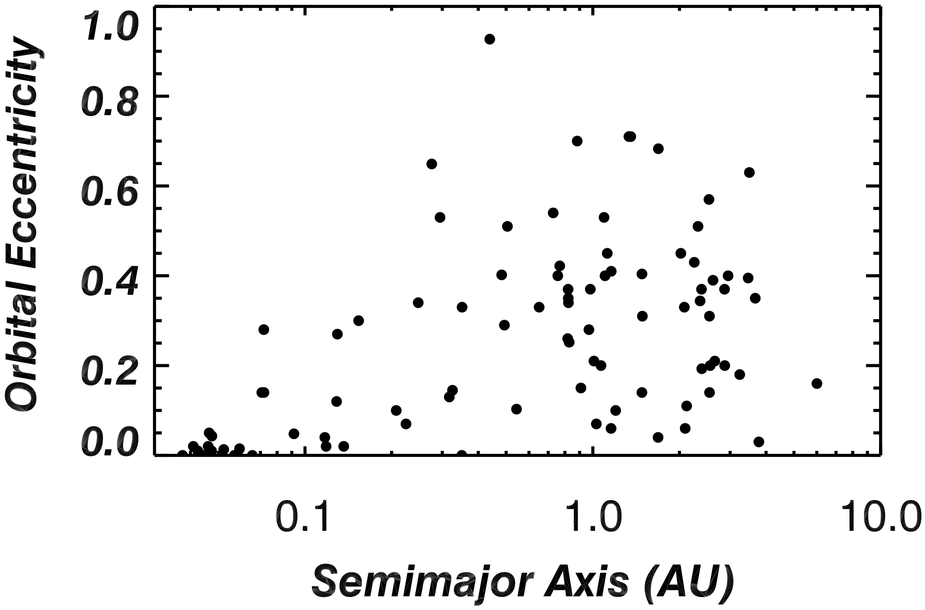

Figure 3. Eccentricity distribution plotted against semimajor axis.

One system with an architecture similar to our solar system orbits the star 47 UMa. As the orbit diagram in Figure 2 shows, there are two gas giant planets orbiting this star. The inner planet has a mass that is 2.5 M_{JUP} at a semimajor axis of 2.1 AU and the outer planet is 0.7 M_{JUP} and orbits at 3.7 AU. Both of these planets have very low eccentricity orbits. Initial simulations (Laughlin et al. 2002) showed that an earthlike planet would be dynamically stable in the habitable zone of 47 UMa. However subsequent analysis showed that if the two gas giant planets were in their present locations, gravitational resonances would have inhibited formation of a terrestrial planet at 1 AU. Indeed, an asteroid belt may reside at a 1AU orbital radius around this star. Nevertheless, this star remains an important target for the Space Interferometry Mission and other planet detection efforts.

2.3. Eccentricity Distribution

The eccentricities of ESPs (Figure 3) are strikingly different from the eccentricities of gas giants in our solar system. ESPs closer than 0.05 AU reside in circular orbits, enforced by tidal interactions with the star on timescales shorter than 1 Gyr (Terquem et al 1998). Beyond 0.05 AU, observed eccentricities become distinctly non-circular. Indeed, the tidal circularization boundary appears to be rather sharp. With semimajor axes of only 0.07 AU, the companions to HD 68988 and HD 217107 reside just outside of the tidal circularization boundary yet have orbital eccentricities of about 0.14. Although both of these host stars exhibit residual velocity trends suggestive of a sibling planet in a much longer period orbit, this is not an unusual characteristic; most of the tidally circularized planets also exhibit similar residual velocity trends.

Beyond 0.07 AU, there is a nearly uniform distribution of eccentricities with an upper boundary that rises gradually to a plateau eccentricity of 0.7. The high eccentricities are presumed to arise from dynamical interactions during the planet formation stage. Proposed mechanisms are tidal interactions between the protoplanet and the disk (Goldreich & Tremaine 1980, Lin et al. 1996, Bryden et al. 1999), gravitational scattering between growing planetesimals (Rasio & Ford 1996, Weidenschilling and Marzari 1996, Levison et al. 1998) and resonant gravitational interactions between planets or planetesimals in the disk (Murray & Holman 1999, Murray et al. 2002, Chiang et al. 2002). Such an active dynamical history may differ from a gentler evolution for solar system planets and may provide important constraints for a theoretical understanding of orbital evolution.

At semimajor axes beyond 2 AU the upper envelope of the eccentricity distribution appears to drop to more moderate eccentricities. Although there is a small number of objects in wide orbits, if a turn-over continues to be observed, this may also have important implications for dynamical evolution in extrasolar systems. Beyond 2 AU, we may be glimpsing a separation regime where orbital evolution was less disruptive.

3. Detecting a Solar System Analog

With current state-of-the-art Doppler precision, the detectable signpost of our own solar system is Jupiter. In an edge-on orbit, Jupiter induces a solar reflex velocity of about 13 m s^{-1} with an orbital period of 11.8 years. As Doppler observations approach a decade, it is likely that solar system analogs (stars with jovian-mass planets in low eccentricity orbits with orbital periods spanning a decade) will be detected. This detection requires single measurement errors of a few m s^{-1} and tight control of systematic errors over the entire orbital period.

To demonstrate what a solar system analog might look like, theoretical velocities for the Jupiter-Saturn system were simulated with normally-distributed (Gaussian) errors scaled to our Doppler errors. These simulated velocities are plotted in Figure 4 with the actual velocity curve overplotted as a solid line.

A periodogram analysis of the simulated data set shows two peaks: strong power at about 12 years and a weak secondary peak at 30 years. A Keplerian fit to the simulated data successfully recovered a companion with $M \sin i = 0.96$ $\mathrm{M_{JUP}}$ in a P=11.65 year orbit, but with an eccentricity of 0.18. The inflated eccentricity was derived because the Saturn-induced velocities were absorbed into the simple one-planet, jupiter model. Knowing the "answer in the back of the book" a linear trend was included in the single-Keplerian model. This reduced the eccentricity for Jupiter to 0.07. However, the inclusion of a linear trend might not have seemed compelling *a priori*. Without additional evidence for the more distant Saturn, the improved RMS fit of 0.7 m s^{-1} to the 1 $\mathrm{M_{JUP}}$ model might well have been dismissed as a linear drift arising from systematic errors.

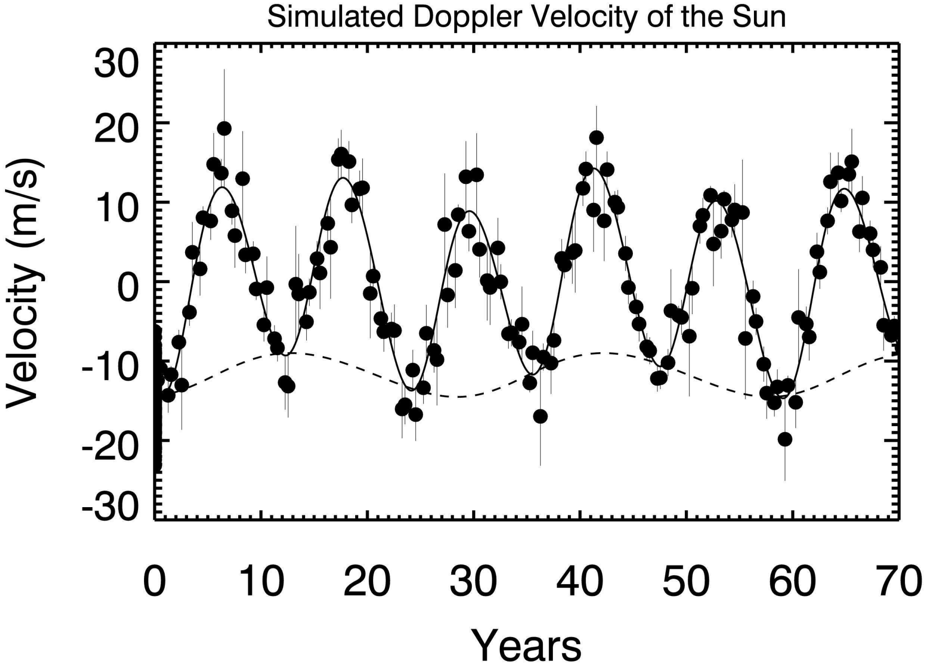

Figure 4. Simulated velocities with typical error bars for a Jupiter and Saturn system orbiting the Sun. The solid line shows the combined reflex velocity from Jupiter and Saturn and the dashed line emphasizes the velocity modulation by Saturn.

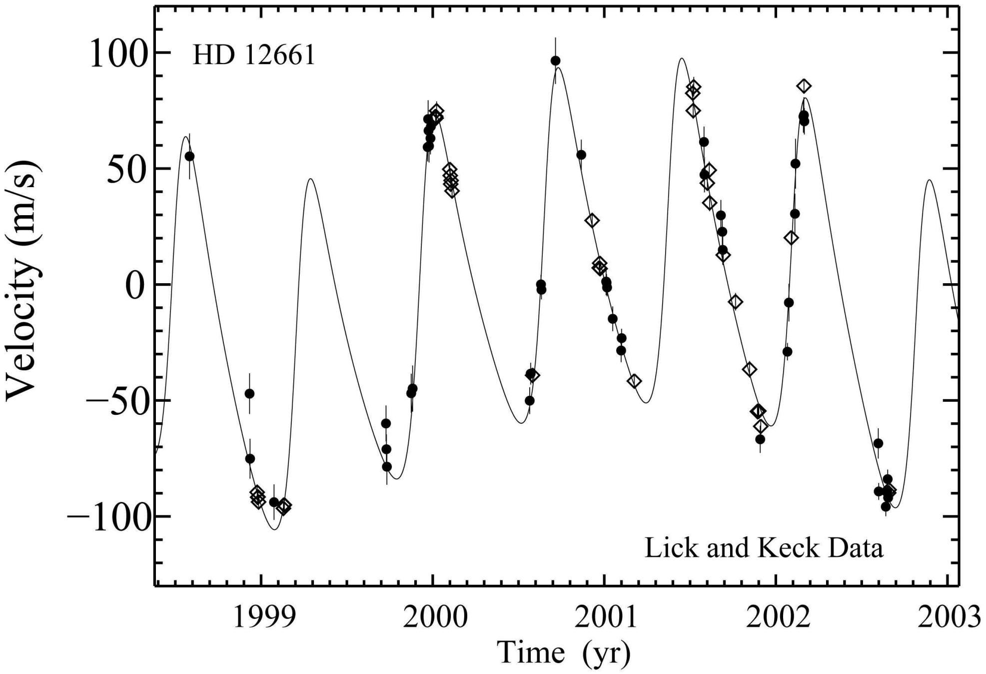

Figure 5. Radial velocities for HD 12661. Filled circles represent Lick observations and diamonds represent Keck velocities. The solid curve shows the two-planet model with $P_b = 263$ d, $ecc_b = 0.36$, $M_b \sin i = 2.3$ $\mathrm{M_{JUP}}$ and $P_c = 1436$ d, $ecc_c = 0.21$, $M_c \sin i = 1.56$ $\mathrm{M_{JUP}}$.

3.1. Multiple Planet Systems

Following the discovery of a triple planet system orbiting Upsilon Andromeda (Butler et al. 1999) a number of multiple planet systems have been discovered (HD 168443, GJ 876, HD 82943, HD 74156, HD37124, 47 UMa, HD 12661, HD38529, 55 Cnc). This is a deceptively small number of multiple planet systems because detection of the more distant planets may take several years. Fischer et al. (2001) found that among a dozen Lick stars with one detected planet and with at least 2 years of observations, 40% had residual velocities suggestive of additional planets. That fraction has risen; 60% of those same stars now show residual trends that can be modeled as additional planets.

Velocities for two recently detected double planet systems from Lick and Keck Observatories are shown in Figure 5 (HD 12661) and Figure 6 (HD 38529). HD 12661 is a G6V star with an inner planetary companion, $M \sin i = 2.3$ $\mathrm{M_{JUP}}$ that orbits in 263 days. The outer planet has $M \sin i = 1.56$ $\mathrm{M_{JUP}}$ and an orbital period of 3.9 years (Fischer et al. 2003). The orbital eccentricities of these two planets are 0.36 and 0.21 respectively. Dynamical simulations using a Burlisch-Stoerer algorith to integrate the derived orbital parameters forward in time demonstrate the long-term stability of this system.

HD 38529 is a G4IV star with an inner planet of $M \sin i = 0.79$ $\mathrm{M_{JUP}}$ in a 14.3 day orbit with an eccentricity of 0.28. The more distant planet in this system has

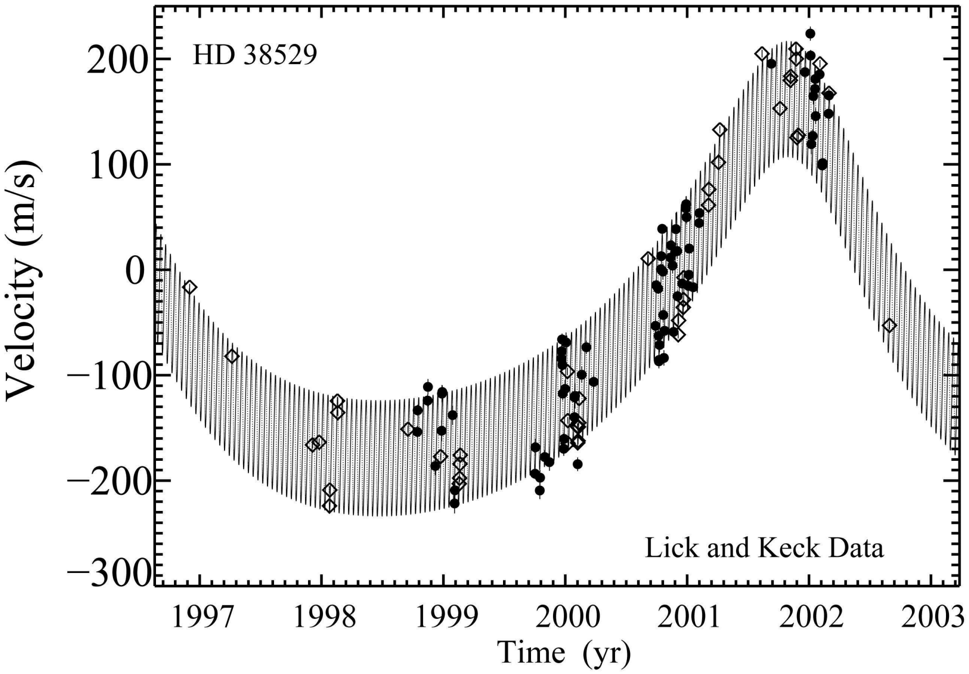

Figure 6. Radial velocities for HD 38529. The solid curve show the double Keplerian fit. The inner planet has $P_b = 14.3$ d, $ecc_b = 0.28$, $M_b \sin i = 0.79$ $\mathrm{M_{JUP}}$ and $P_c = 2176$ d, $ecc_c = 0.35$, $M_c \sin i = 12.74$ $\mathrm{M_{JUP}}$.

$M \sin i = 12.74$ $\mathrm{M_{JUP}}$, an orbital period of 5.97 years and eccentricity of 0.35 (Fischer et al. 2003). The wide mutual separation of the two planets ensures dynamical stability in this system as long as $M \sin i$ is substellar. The outer companion is one of 5 extrasolar planets discovered by Doppler observations with a minimum mass ($M \sin i$) that is at or above the deuterium-burning threshold. The host star is one of four subgiants with Doppler-detected planetary systems.

Perhaps the most interesting multiple planet systems are those that exhibit resonances. For example, GJ 876 has two planets, one in a 30.1 day orbit and the other in a 61 day orbit. This 2:1 resonance system exhibits dynamical interactions on timescales of several years and the best orbital solution requires numerical integration (Laughlin & Chambers 2001). Dynamical modeling has the added benefit of constraining the orbital inclination of the individual planets.

The planets have masses, $M_b \sin i = 0.56$ $\mathrm{M_{JUP}}$ and $M_c \sin i = 1.59$. These masses are high enough to have opened gaps in the nebular disk and the interplanetary disk material would have depleted rapidly. The resulting planet-disk interaction would exert a negative radial torque on the outer planet and a positive radial torque on the inner planet that could have forced the planets into the observed 2:1 resonance (Lee and Peale 2002).

4. Stellar Characteristics

Planet-bearing stars appear to be more metal-rich than field stars without detected planets (Gonzalez 1997, Butler et al. 2000, Santos et al. 2000) . This observation has led to speculation over whether high metallicity is a causal initial condition, or an effect from the accretion of gas-depleted material that pollutes the stellar convective zone.

In support of the causal view, high metallicity provides more raw materials, the grains that begin the process of planetesimal formation. The first generations of stars in our galaxy could not have developed planetary systems like our own because they lacked these planet building blocks. So, it seems clear that some threshold metallicity is required for planet formation, but it is not at all clear what that threshold might be.

To test the metallicity correlation, Gilliland et al. (2000) used HST to search for transits in the relatively metal-poor cluster, 47 Tuc ([Fe/H] -0.7). If the stars in this cluster had hosted 51 Peg-like systems similar to those found orbiting main sequence field stars, then the project should have detected as many as 17 transits. However, no transits were observed in the sample of 34,000 stars. The explanation for this result remains somewhat ambiguous because the crowded stellar environment in 47 Tuc is so different from that of field stars on Doppler planet search projects. Perhaps there were more planet-destabilizing dynamical interactions in the cluster environment. Or perhaps photoionization of protostellar disks by rapidly evolving cluster stars retarded the formation of giant planets in 47 Tuc.

We are carrying out spectral synthesis modeling of template spectra at Lick, Keck and the AAT. The first 500 stars have been analyzed and confirm that known planet-bearing stars have enhanced metallicity. We are determining abundances of volatile and refractory elements in order to look for signatures of accretion and will also consider correlations between metallicity and orbital elements such as eccentricity and semimajor axis.

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Forrest: How can you distinguish planets from Brown Dwarfs?

Fischer: Only through the statistics. We get Msini; so if i were large, then the mass could be large enough to qualify as a Brown Dwarf. However, we don't see the kind of tail in the distribution that would be indicative of a large population of Brown Dwarf s in our sample.

Artymowicz: What about systems that might contain a Brown Dwarf and a planet?

Fischer: This could be just a nomenclature issue—i.e what distinguishes a Brown Dwarf from a planet? Deuterium burning or the formation mechanism? However, in the case of multiple-planet systems, we can derive constraints on sini.

Beichman: It appears that at least some systems have complicated dynamics. Ups And [Note added in proof: we think the system referred to is really 16 Cygni] is a binary; although the separation (750 AU) minimizes the dynamical perturbations, there still could be some effect. Have you found any effects of binarity in your data?

Fischer: At least 20% of our systems are binaries, but we have seen no definitive effects as of yet. We are starting to find planets in M dwarf binary systems with small separations between the stars.