EXTRASOLAR PLANETS

Conference participants (*photo: Seth Shostak*)

Geoff Marcy, whose team has discovered most of the known planets (*photo: Seth Shostak*)

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Extrasolar Planets and Prospects for Terrestrial Planets

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Abstract. Examination of ~2000 sun–like stars has revealed 97 planets (as of 2002 Nov), all residing within our Milky Way Galaxy and within ~200 light years of our Solar System. They have masses between 0.1 and 10 times that of Jupiter, and orbital sizes of 0.05–5 AU. Thus planets occupy the entire detectable domain of mass and orbits. News & summaries about extrasolar planets are provided at: `http://exoplanets.org`. These planets were all discovered by the wobble of the host stars, induced gravitationally by the planets, causing a periodicity in the measured Doppler effect of the starlight. Earth–mass planets remain undetectable, but space–based missions such as Kepler, COROT and SIM may provide detections of terrestrial planets within the next decade.

The number of planets increases with *decreasing* planet mass, indicating that nature makes more small planets than jupiter–mass planets. Extrapolation, though speculative, bodes well for an even larger number of earth–mass planets. These observations and the theory of planet formation suggests that single sun–like stars commonly harbor earth–sized rocky planets, as yet undetectable. The number of planets increases with increasing orbital distance from the host star, and most known planets reside in non–circular orbits. Many known planets reside in the habitable zone (albeit being gas giants) and most newly discovered planets orbit beyond 1 AU from their star. A population of Jupiter–like planets may reside at 5–10 AU from stars, not easily detectable at present. The sun–like star 55 Cancri harbors a planet of 4–10 Jupiter masses orbiting at 5.5 AU in a low eccentricity orbit, the first analog of our Jupiter, albeit with two large planets orbiting inward.

To date, 10 multiple–planet systems have been discovered, with four revealing gravitational interactions between the planets in the form of resonances. GJ 876 has two planets with periods of 1 and 2 months. Other planetary systems are "hierarchical", consisting of widely separated orbits. These two system architectures probably result from gravitational interactions among the planets and between the planets and the protoplanetary disk out of which they formed.

1. Introduction

Among the 200 billion stars in our Milky Way Galaxy, our Sun has a typical mass, age, and chemical composition. The stellar properties of our Sun render it undistinguished in the Galactic neighborhood. However its planets, asteroids, and comets, which reside in a flattened plane with one predominant direction of orbital motion, likely formed in a flattened protoplanetary disk of gas and dust around the young Sun (e.g., Lissauer 1995).

Such protoplanetary disks are found to exist around over 50% of young stars during their first million years (Hillenbrand et al. 1998; Haisch et al. 2001). In these disks, the growth of dust particles is expected to be the first step toward planet formation (e.g., Beckwith, Henning, & Nakagawa 2000) and indeed there is evidence of such growth (Throop et al. 2001; Webster & Welch 2001). Thus, the observational evidence and theory of planet formation provide a consistent framework suggesting that planet formation will commonly occur around young stars. Details of this paradigm are provided beautifully by Beckwith & Sargent (1996).

Binary star systems may gravitationally disrupt attendant planets if the the stars approach within a few AU of each other. Approximately 30% of all sun-like stars have such a close stellar companion. The remaining 70% of stars that are single likely come into existence with a complement of multiple planets. Planets are constructed from the accumulation of small particles into rocky cores that subsequently grow, if conditions persist, toward the largest planets. The standard planet–formation theory suggests that large Saturn and Jupiter–sized planets form only if the disk retains its reservoir of gas long enough for giants planets to gravitationally accrete that gas. Thus, the Saturn and Jupiter planets found already around nearby stars may represent the visible tail of a larger population of smaller rocky planets.

At the time of writing (2002 Oct), there are 97 extrasolar planets known that orbit hydrogen–burning stars, similar to our Sun. The planets were all found by measuring the reflex motion of the host star as inferred from precise Doppler–shift measurements of the starlight (e.g., Butler et al. 1996). The best Doppler techniques can determine the line–of–sight velocity of the star with a precision of 3 m s^{-1} . For reference, Jupiter causes our Sun to wobble with a speed of 12.5 m s^{-1} , rendering analogs of our Jupiter detectable. Such Doppler measurements allow determination of the mass of the planet multiplied by the unknown trigonometric sine of the inclination ($\sin i$), where i is the tilt of the orbital plane relative to the imaginary plane of the sky. Thus the technique can reveal the minimum mass of the planet, $M \sin i$, which is statistically about 25% less than the actual mass of the planet.

The term "planet" remains loosely defined because several mechanisms of formation have been proposed (e.g., Lissauer 1995; Boss 2000; Youdin & Shu 2003). The observed distribution of masses, however, exhibits a declining number of planets having masses from 3 to 10 times the mass of Jupiter (M_{JUP}) as shown in Fig. 1. The number of planets declines so dramatically from 1 M_{JUP} to 8 M_{JUP} that we set an upper limit for planets at 13 M_{JUP} which also corresponds to the mass above which Deuterium–burning occurs. Orbiting objects with mass between 13–75 M_{JUP} are commonly called brown dwarfs. They burn deuterium in nuclear reactions but not hydrogen as do stars.

Most known extrasolar planets have $M \sin i$ <2 M_{JUP} and reside in non-circular orbits (Marcy, Cochran & Mayor 2000). We provide an almanac of all known planets and news updates, at the website: `http://exoplanets.org`.

In addition to planet mass, the Doppler measurements reveal the orbital period P and the orbital eccentricity e. The average orbital distance (semimajor axis a) is related to the orbital period by Kepler's 3rd law:$P^2 = (4\pi^2/GM_{\rm star})a^3$. The masses of the stars are known to within 5% by their spectral type.

The Doppler technique has limitations in several respects. The precision of 3 m s^{-1} limits the detectable amplitudes to 10 m s^{-1} for secure planet detections. Thus planets at 1 AU (earth–sun distance) must have masses of at least one Saturn mass (1 M_{SAT}) to be securely detected. The Doppler amplitude of the star varies as $1/\sqrt{a}$, so lower mass planets can be detected that orbit closer than 1 AU. Another limitation is that it remains difficult to detect planets having an orbital period over 10 yr which corresponds to the duration of the Doppler surveys. Orbits that are nearly face–on render their planets undetectable, but such inclinations are rare and play only a minor role in the detectability and mass estimates (Jorissen et al. 2001).

The most remarkable observed property of extrasolar planets are their non-circular orbits. The eccentricities extend from 0 to 0.93 unlike the circular orbits of the planets in our Solar System. The origin of these eccentricities and the steep planet mass distribution remain unexplained characteristics. The Doppler method will soon be able to detect orbital periods longer than 10 yr matching the domain of our Jupiter and Saturn, and will detect planet masses less than 1 M_{SAT}, approaching 10 earth–masses.

2. Characteristics of Extrasolar planets

Several teams have detected extrasolar planets, with most found by the Geneva team (Santos et al. 2002; Udry et al. 2002) and our team (e.g., Butler et al. 2003; Fischer et al. 2003). Here we include only the most secure detections from `http://exoplanets.org`. These two teams have surveyed 2000 nearby stars, all having masses between 0.3 and 1.5 $M_\odot$. Most stars within 150 ly have now been surveyed with Doppler measurements obtained several times per year, during the past 5 years. About 100 stars have been surveyed at Haute Provence over 8 years and another 100 stars have been surveyed at Lick Observatory for 13 years (Marcy, Cochran, & Mayor 2000). For the lowest mass stars (M dwarfs), the Doppler planet surveys only extend to distances of 50 ly because only the large Keck and VLT telescopes have sufficient aperture to achieve a Doppler precision of 3 m s^{-1} . Our Keck survey of 120 M dwarfs is now only 3 years along.

From these stellar samples, the 97 detected planets immediately imply that at least 5% of all stars have a large Saturn or Jupiter–mass planet orbiting within 3 AU, the detectable mass and orbital domain. It is tempting to extrapolate the 5% occurrence rate to include the undetected domains of mass less than Saturn and orbits larger than 3 AU. Such extrapolation is dangerous because no empirical information is available. However, planet–formation theory predicts that there will be numerous low mass, rocky planets for each gas giant. Theory also predicts that more planets will reside beyond 3 AU (the current outer detection limit) than within 3 AU. The gas giants found so far probably represent only a small fraction of all the gas giants that reside from 0–20 AU. A rough extrapolation suggests that at least 10% of single stars will harbor such a saturn mass or jupiter mass planet. Theory predicts that each of these giant planets is accompanied by numerous rocky planets. Thus, at least 10% of all single stars harbor rocky planets of terrestrial size, strewn throughout the inner regions of the planetary system including the zone where temperatures are between 0–100°C.

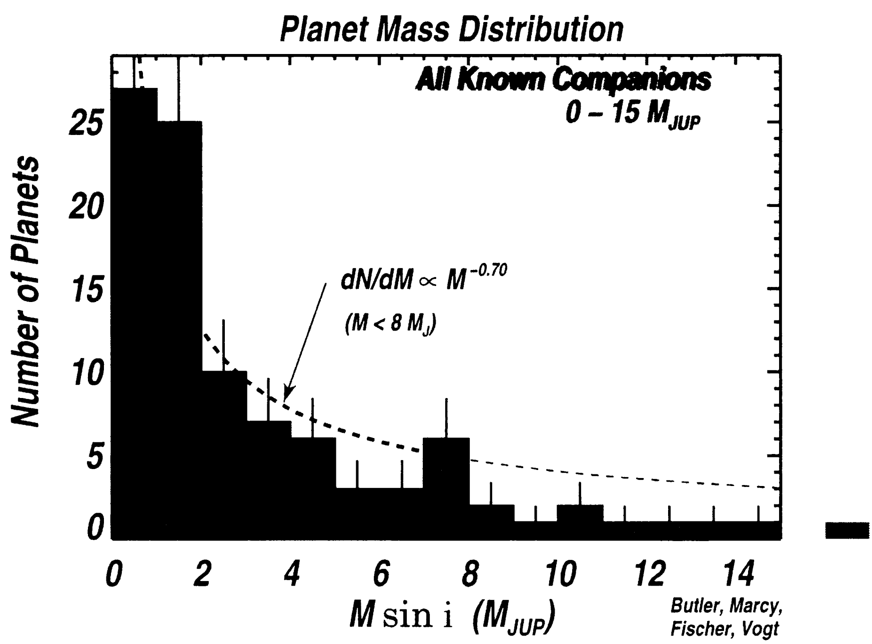

Figure 1. Mass histogram of all 97 securely known extrasolar planets. The horizontal axis represents $M \sin i$ which is statistically only 25% lower than the actual planet mass. The numerous planets of lowest detectable mass (~1 M_{SAT}) are clearly visible and the mass distribution is best fit by $dN/dM \propto M^{0.7}$ for masses less than 8 M_{JUP} . Planets less than 1 M_{JUP} are the most difficult to detect, implying an even steeper rise after correction.

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2.1. Planet Masses

The mass distribution of all known extrasolar planets is shown in Fig. 1, showing a rise toward lower masses, down to 1 M_{SAT} (Marcy & Butler 2000). A fit gives $dN/dM \propto M^{-0.7}$ but the actual rise is probably steeper because the lowest mass planets (below 1 M_{JUP}) remain more difficult to detect. While only $M \sin i$ is measured, Jorissen et al. (2001) has shown that the correction for $\sin i$ is very small (statistically for the entire histogram).

The rising mass distribution suggests, albeit by extrapolation, that planets of mass less than 1 M_{SAT} are even more abundant still. The failure of the power law (which has no mass scale) to adequately fit the observed mass distribution above 8 M_{JUP} (see Fig. 1) implies that a planet mass scale exists at a few M_{JUP} . For higher masses, the mass distribution falls faster than the power law. We identify the mass distribution shown here with planets formed in protoplanetary disks for which lower mass planets should more abundant then higher mass planets (Lissauer 1995). For masses above ~8 M_{JUP} it remains plausible that brown dwarf companions also orbit stars within ~5 AU. The semantic distinction between planets and such brown dwarfs carries little meaning without the associated physical processes of formation.

2.2. Eccentricities

The known orbital eccentricities are plotted against semimajor axis in Fig. 2. Planets within 0.06 AU all reside in circular orbits, likely a result of tides raised on the planet by the star. Torques on the planet tend to circularize the orbit (Marcy et al. 1997). The remaining planets exhibit eccentricities distributed nearly uniformly between 0 and 0.7. There is an apparent upper limit at e=0.7 and an apparent trend in the upper envelope between a=0.1–0.5 AU. The star HD 80606 (Naef et al. 2001) has a stellar companion, possibly responsible for its extreme eccentricity of 0.93, off the plot.

The origin of the eccentricities for single planets is not well understood. Plausible mechanisms include gravitational forces acting on a planet from other planets or from orbiting stars in a binary system. The protoplanetary disk may gravitationally pull the planet into eccentric orbits (Rasio & Ford 1996; Lin & Ida (1997); Marzari & Weidenschilling 2002; Goldreich & Sari 2003; Malhotra 2002). Eccentricity pumping among multiple planets is quite promising (Lee & Peale 2002; Chiang, Fischer, & Thommes 2002; Marcy et al. 2001).

2.3. Semimajor Axes and Planet Temperatures

The temperature of the surface of a planet is determined by a balance between the amount of stellar light energy that is absorbed by the planet with the thermal infrared light that is emitted by the planet, modified by the greenhouse effect. Thus the luminosity of a star and the semimajor axis of the planet's orbit determine the approximate temperature of the planet's surface.

The semimajor axes, a, of all 97 known extrasolar planets are easily determined from the orbital period, P, and Kepler's 3rd Law. The distribution of orbital semimajor axes is shown in Fig. 3. Many planets reside approximately 1 AU from the host star, well within the habitable zone. A paucity of planets occurs at 0.3 AU, suggesting that giant planets may form farther out and mi-

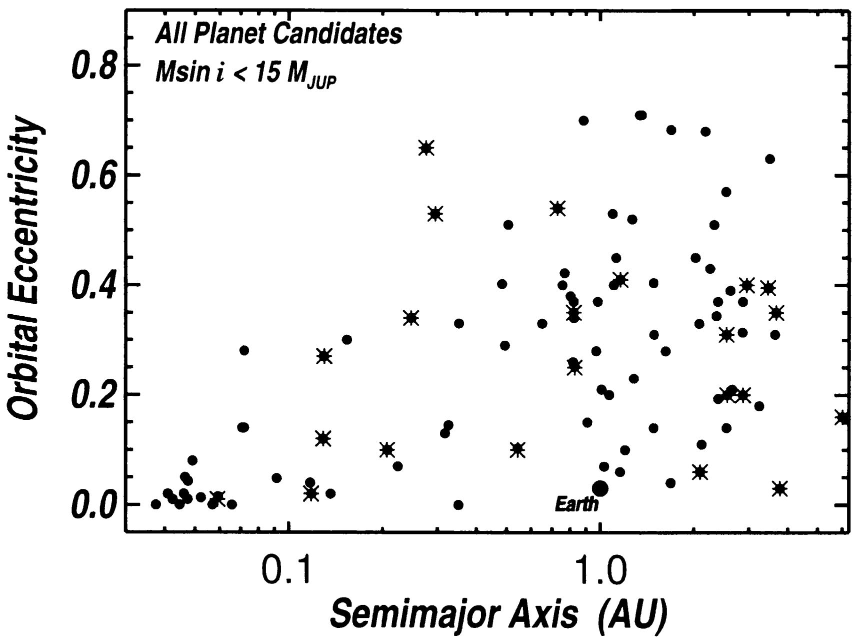

Figure 2. Eccentricity vs. Semimajor Axis for all known extrasolar planets. Planets in multiple–planet systems are displayed with asterisks. Eccentricities scatter nearly uniformly between 0.0 and 0.7. There is an increasing upper envelope between a=0.1–0.5. Planets in multi–planet systems have eccentricities similar to single planets.

grate inward toward the star, (e.g., Lin et al. 1996) but they rarely stop near 0.3 AU (Jones et al. 2003). Figure 3 shows that the number of planets increases for semimajor axes larger than 0.3 AU, extending out to 3 AU, the limit of current planet surveys. Figure 3 reveals a rise in the distribution of planets with increasing orbital distance from the host star. More known extrasolar planets orbit beyond 1 AU than within.

We have estimated the surface temperatures for all extrasolar planets by scaling the temperature of the Earth to that of each planet. The temperature is related to luminosity and semimajor axis by:

$$T \propto L^{1/4}/a^{1/2} \tag{1}$$

This approach yields temperatures accurate to about 100 K, except for extreme cases of greenhouse effect, as with Venus. We computed the stellar luminosity, L, from the absolute visual magnitude of each star, M_V. The resulting planet temperatures are shown in Fig. 4. Extrasolar planets have surface temperatures between 125 and 1700 K, with many planets having a temperature between 273 and 373 K, the region in which water could be in liquid form. Of course, the known planets are almost certainly gaseous, making liquid water unlikely, except in microscopic droplets in cloud decks. The prospects of Galilean-like satellites is not known but such rocky surfaces could support liquid water if the escape velocity enforces retention.

Our survey of 50 sedate, older stars at Lick Observatory has proceeded since 1987, allowing detection of planets in long-period orbits. Two have emerged, namely 55 Cancri d and 47 UMa c, both in somewhat circular orbits (Marcy et al. 2002; Fischer et al. 2002). While extrasolar giant planets known so far reside in mostly eccentric orbits, it remains to be seen if giant planets orbiting beyond 3 AU also reside in eccentric orbits. These early results suggest that circular orbits may be more common for the giant planets that reside in wider orbits, reminiscent of the giant planets in our Solar System.

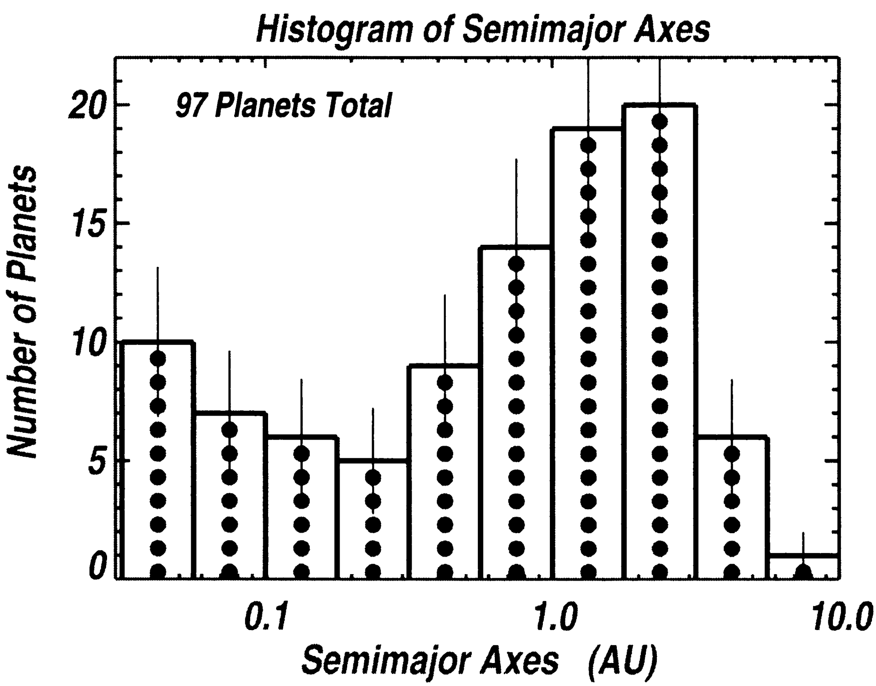

Figure 3. Distribution of Semimajor axes among extrasolar planets (in equal log intervals) showing a minimum at 0.3 AU, and a rise toward 3 AU. Incompleteness is severe beyond 3 AU, increasing the likelihood that the number of giant planets increases with semimajor axis from 0.3–3 AU.

The increasing numbers of planets in larger orbits is consistent with models that invoke orbital migration and a contemporaneous clearing of the gaseous disk to explain the final positions of giant planets (Armitage et al. 2002; Trilling et al. 2002). Many planets beyond 5 AU are simply left stranded when the disk gas vanishes. Such models predict the existence of a population of giant planets that still reside at 5 AU, never having migrated inward. Giant planets beyond 5 AU could be more numerous than the extrasolar planets discovered so far and

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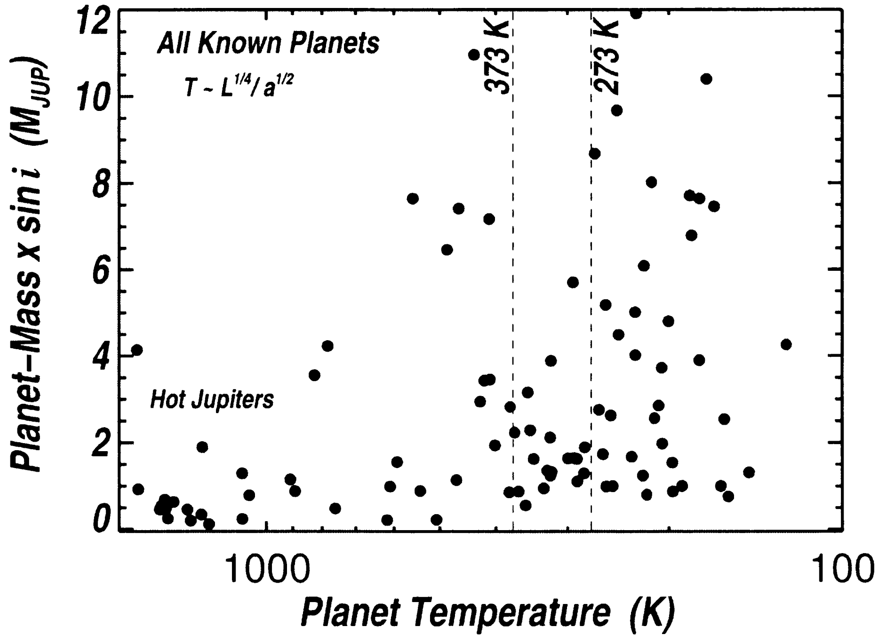

Figure 4. Temperatures of the surfaces of known extrasolar planets, with the minimum planet mass, $M \sin i$, on the vertical axis. Temperatures are between 125–1700 K, and many planets have temperatures between 273 and 373 K, the nominal freezing and boiling points of water.

they may have suffered few gravitational perturbations, leaving them in circular orbits.

3. Multi–Planet Systems

Approximately 50% of the stars that show clear evidence of one planet, eventually show Doppler evidence of additional planets (Fischer et al. 2001, 2002). Remarkably, 10 multiple–planet systems are now known, including Upsilon And, 55 Cnc, GJ 876, HD 37124, HD 12661, 47 UMa, HD 168443, HD 38529, and HD 82974 and one or two candidate systems. The properties of the planets in multiple planet systems may be compared to those of single giant planets, and the overall structures of the multi–planet systems seem to fall into two classes, interacting and hierarchical, as described in this section.

The first multi–planet system discovered happened to have three planets, namely Upsilon Andromedae (Butler et al. 1999). The current data and three–planet fit are shown in Fig. 5.

Dynamical calculations show that the outer two planets reside in a "secular resonance" in which the orbital axes are nearly aligned (Chiang, Tabachnik, &

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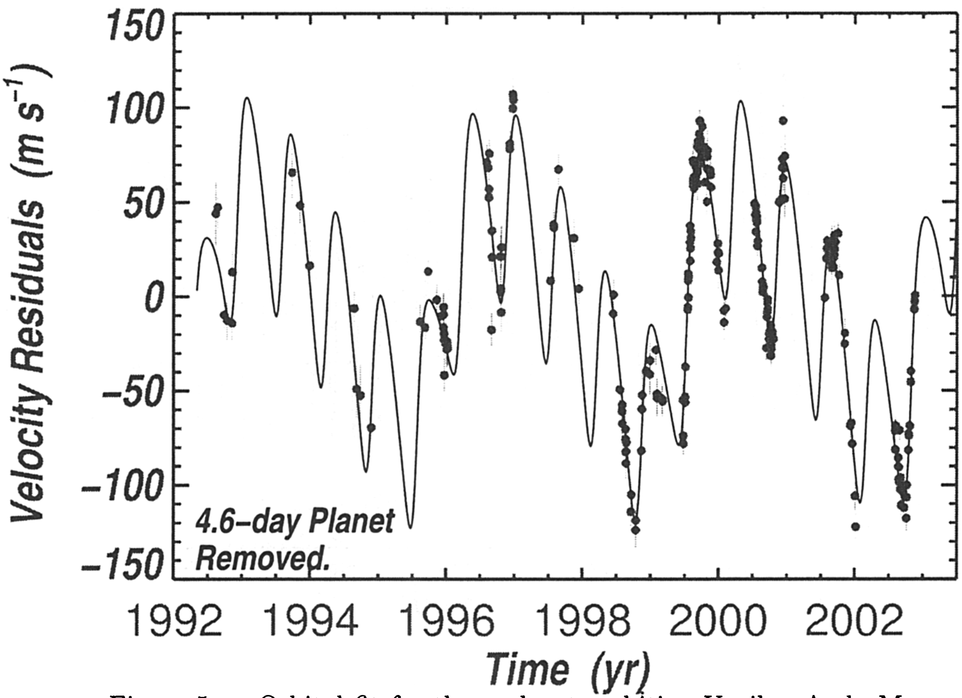

Figure 5. Orbital fit for three planets orbiting Upsilon And. Measured velocities (dots) and the best–fit model (line) consisting of three Keplerian orbits independently perturbing the star. Both the velocities and model are shown after subtracting the effects of the inner (4.6 d) planet, for clarity.

Tremaine 2001; Lissauer & Rivera 2001). Gentle migration of the two planets into this delicate resonance is likely, possibly involving excitation of the eccentricity of the outer planet, d, by the disk (Chiang & Murray 2002).

The star GJ876 has mass 0.35 $M_{\odot}$, making it the lowest mass star with extrasolar planets. Its measured velocities can be fit with a model of two planets (Marcy et al. 2001), as shown in Fig. 6. Remarkably, the orbital periods are 30.1 and 61.0 days, indicating the possibility of a 2:1 dynamical resonance (Rivera & Lissauer 2001; Lee & Peale 2002). The planets will librate about this 2:1 ratio of orbital periods indefinitely. Establishment of this resonance may have involved convergent migration of the two planets (Lee & Peale 2002).

Only a model that includes the planet–planet gravitational interactions yields a satisfactory fit to the velocities (Rivera & Lissauer 2001; Laughlin & Chambers 2002). Recent astrometric measurements of the wobble of GJ 876 confirm the inclination of the orbital plane to be near 80 deg, i.e. nearly edge–on (Benedict et al. 2002), similar to that predcited by the models of interactions.

3.1. 55 Cancri

The star 55 Cnc revealed an inner planet with orbital period of 14.6 d and minimum mass, $M \sin i = 0.9$ M_{JUP} (Butler et al. 1997). But subsequent Doppler

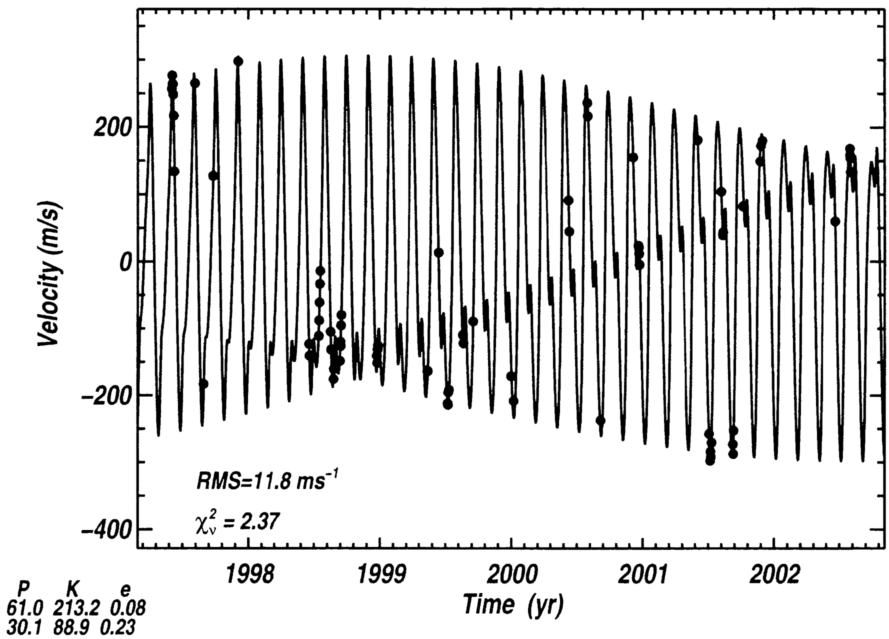

Figure 6. Velocities and two-Keplerian fit for GJ 876. The high value of χ^2 and RMS are a result of planet-planet interactions.

measurements have revealed evidence for a total of three planets orbiting this star (Marcy et al. 2002). The raw velocity measurements for 55 Cnc are shown in Fig. 7 (left) for which the best fit invokes three planets. In Fig. 7 (right) the Doppler variation caused by the inner two planets was removed, revealing the wobble of the star caused only by the outer planet.

The 55 Cancri system clearly has an outer planet at nearly ~5.5 AU, as shown in Fig. 7 (right). A two-planet fit to 55 Cancri leaves residuals that exhibit a periodicity of 44 days, possibly caused by a third planet. However, the rotation period of the star is 35–42 days, as shown by Henry et al. (2000a) from periodicities in the CaII H&K line. Thus a danger exists that the 44-day period in the velocities may be caused by stellar surface inhomogeneities.

The outer planet, 55 Cnc d is the first extrasolar planet orbiting beyond 5 AU from its star, making it the extrasolar planet most reminiscent of our Jupiter at 5.2 AU. However, 55 Cnc d has a large mass, at least 4 M_{JUP}, and the architecture of the 55 Cnc system as a whole, with its two inner Jupiter-mass planets, clearly differs from that of our Solar System. N-body simulations by G. Laughlin (Marcy et al. 2002) show that a terrestrial-mass planet would be stable in orbit between 55 Cancri c and d.

4. Hierarchical Planetary Systems

Among the 10 multi-planet systems known to date, 6 consist of two planets in widely separated orbits. Two such cases are HD 37124 and HD 12661.

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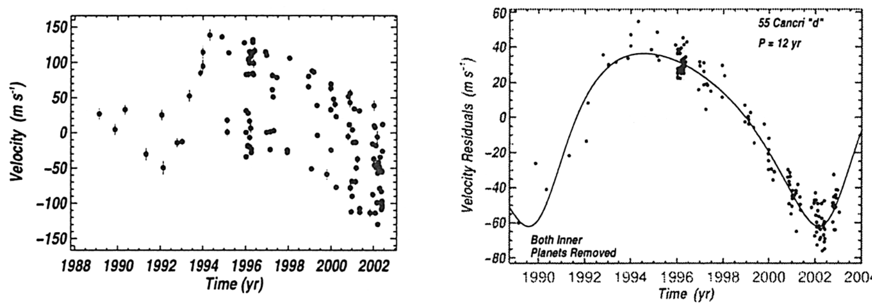

Figure 7. Three planets orbiting 55 Cancri. Left: Raw velocities versus time. Right: The best three–planet fit to the velocities, after subtracting the inner two planets. The third planet resides ~5.5 AU from the host star, not unlike the orbit of Jupiter.

Velocities for HD 37124 reveal an inner planet with a period of 155 d and $M \sin i = 1.0$ (Vogt et al. 2000) and an outer planet (Butler et al. 2003) having $P = 1500 \pm 300$ d as shown in Fig. 8. This system typifies a growing number of multiple–planet systems in which dynamical considerations impose constraints on the plausible orbits.

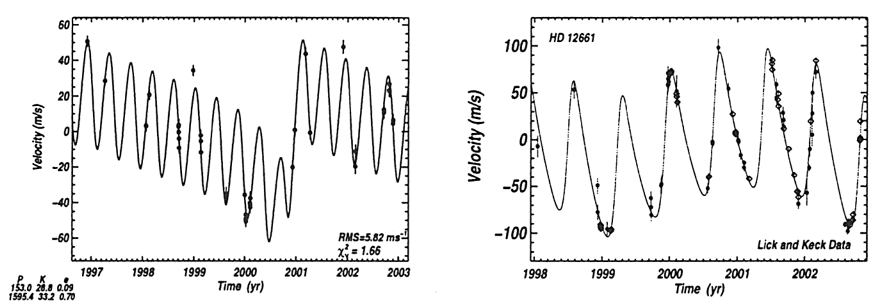

Figure 8. "Hierarchical" double–planet systems HD 37124 (left) and HD 12661 (right). The velocities are fit with a double–Keplerian model (solid line). The widely separated periods render these systems "hierarchical" (see text). For HD 12661, the velocities are from Keck (diamonds) and Lick (dots).

Widely separately planets are deemed "hierarchical" as the planets are unlikely to be engaged in mean–motion or secular resonances. For HD 37124, the periods are 155 and 1500 d, clearly representing the hierarchical class of double planets.

Another "hierarchical" double–planet system is HD 12661, with two planets having periods of 260 and 1407 d. Figure 8 shows the current best two–planet fit, using velocity measurements from both Lick and Keck observatories (Fischer et al. 2003). A resonance is unlikely to be currently active in this system. With eccentricities of 0.3 and 0.2, it remains possible that interactions played a role in shaping their current orbits and that an ongoing interaction actively exchanges eccentricities (Chiang et al. 2002).

5. Eccentricities and Resonances among Single and Multiple Planets

High orbital eccentricities are common among single planets and resonances are common among multiple–planet systems. One wonders if there is a connection between these two unexpected properties. Are eccentricities pumped in single planets by a different mechanism than in multiple–planet systems? To investigate this, one may compare the eccentricity distributions among single and multiple–planet systems.

Figure 2 shows orbital eccentricity vs. semimajor axis for all 97 securely known planet systems, showing with asterisks those planets that reside in multiple planet systems. There are 22 such planets, residing in 10 multiple systems, two of which are triple. *The distribution of orbital eccentricities among the planets in multi–planet systems is indistinguishable from that of the single planets.* Moreover, the distribution of semimajor axes of planets within multi–planet systems is indistinguishable from that of the single planets shown.

The similarity in the eccentricities and semimajor axes of single planets and multiple–planets suggests that the origin of the eccentricities may be qualitatively similar. Several mechanisms have been proposed to explain the orbital eccentricities, namely planet–planet interactions and planet migration leading to resonance capture (Marzari & Weidenschilling 2002; Lee & Peale 2002; Chiang & Murray 2002; Chiang, Fischer, & Thommes 2002). Goldreich & Sari (2003) also consider planet–disk interactions as does Chiang (2003).

6. The Future: Jupiter Analogs and Earth–Like Planets

During the next decade, Doppler searches lasting 20 years will be able to detect jupiters in orbits from 3–6 AU. Their orbital eccentricities will shed light on the prevalence of analogs of Saturn and Jupiter. A true Solar–System analog is yet to be found, but jupiter–mass planets in circular orbits of radius 5 AU would be a signpost of such analogs.

Jupiter–mass planets may be imaged with a space–born coronograph, especially one having a deformable mirror to correct wavefront errors. Such a spaceborn telescope would not only constrain the orbits and masses of giant planets but also would gather color and spectrscopic diagnostics of their chemical composition and atmospheric structure.

Searches for Earth–mass planets are planned by several missions, namely Kepler, COROT, and the Space Interferometry Mission (SIM). These missions are designed to determine the occurrence rate of earth–like planets and their masses. A future mission, such as the *Terrestrial Planet Finder* or *Darwin* will be required to obtain spectroscopic diagnostics of earths. At the present time, an optical coronograph seems more feasible than a spaceborn mid–IR interferometer in part because the astronomy community has more technical experience with coronographs. Moreover, simple broadband optical photometry will reveal the presence of reflective oceans and darker continents as they rotate over the visible hemisphere of an unresolved planet (Ford, Seager, & Turner 2001).

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