A SURVEY OF MULTIPLE PLANET SYSTEMS

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Abstract. To date, over 30 multiple exoplanet systems are known, and 28% of stars with planets show significant evidence of a second companion. I briefly review these 30 systems individually, broadly grouping them into five categories: 1) systems with 3 or more giant ($M \sin i > 0.2 \mathrm{M_{Jup}}$) planets, 2) systems with two giant planets in mean motion resonance, 3) systems with two giant planets not in MMR but whose dynamical evolution is affected by planet-planet interactions, 4) highly hierarchical systems, having two giant planets with very large period ratios ($> 30 : 1$), and 5) systems of "Super-Earths", containing only planets with ($M \sin i < 20 \mathrm{M_\oplus}$).

It now appears that eccentricities are not markedly higher among planets in known multiple planet systems, and that planets with $M \sin i < 1 \mathrm{M_{Jup}}$ have lower eccentricities than more massive planets. The distribution of semimajor axes for planets in multi-planet systems does not show the 3-day pile-up or the 1 AU "jump" of the apparently-single planet distribution.

1 Introduction

The first multiple exoplanet system was discovered in 1992, when Wolszczan & Frail(1992) detected two very low-mass objects orbiting the pulsar PSR B1257+12 using pulse timing methods. Seven years later, Butler et al.(1999) announced the first multi-exoplanet system around a normal star from radial velocities, υ Andromedae.

Since then, the ever-improving precision and ever-growing temporal baseline of radial velocity searches has rapidly increased the number of known multiple planet systems, and today at least[1] 30 such systems are known.[2] Thus, this conference

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[1] This and the other numbers herein will be out of date at the time of this manuscript's publication – indeed, most were out of date by the end of the conference! At least three recently announced additional multiple planet systems require mention, though they are not included in the statistics here: Bouchy et al. announced that HD 47186 and HD 181433 harbor highly hierarchical systems, and Marois et al. imaged three young objects orbiting the A star HR 8799.

[2] We should not neglect a 31st known system, and the best understood – our own Solar System,

comes at a special time in the field of multiple planet systems: there are just few enough systems now that this is likely the last conference where each system can still plausibly be discussed individually, but there are enough such that this is the first conference where we can construct something like a statistically significant sample of planets in multiple systems to divide into subsamples or to compare with apparently single-planet systems.

Multiple planet systems provide an increasingly powerful way to probe the dynamical origins of planets (e.g. Ford(2006)). Single-planet systems, because their orbits are strictly periodic, provide most of their information on the typical migration and interaction histories of exoplanets statistically as an ensemble. But each individual multiple planet system has the potential to serve as a case study of planetary system evolution.

2   The Known Multi-Planet Systems

I have divided the known multi-planet systems heuristically into five broad, nonexclusive categories: 1) systems with 3 or more giant ($M \sin i > 0.2 \mathrm{M_{Jup}}$) planets, 2) systems with two giant planets in mean motion resonance, 3) systems with two giant planets not in MMR, but whose dynamical evolution is affected by weaker planet-planet interactions, 4) highly hierarchical systems, having two giant planets with very large period ratios ($> 30 : 1$), and 5) systems of "Super-Earths", containing only planets with ($M \sin i < 20 \mathrm{M_\oplus}$). The summaries below represent a brief and necessarily incomplete description of each system.

2.1   3+ Giant Planets

Five systems are known to comprise three or more giant planets.

2.1.1 υ Andromedae

Butler et al.(1999) announced the first multi-exoplanet system around a normal star, υ Andromedae, detected using precise radial velocity measurements from Lick Observatory. The pattern of the discovery is typical of many multiplanet systems: after a strong, short-period signal from a 4.6 d, $M \sin i = 0.68 \mathrm{M_{Jup}}$ planet was discovered (Butler et al.(1997)), continued monitoring revealed significant structure in residuals that far exceeded the expected measurement uncertainties. After 2.5 y, two additional, superimposed Keplerians consistent with planets of $\sim 2 \mathrm{M_{Jup}}$ and $\sim 4 \mathrm{M_{Jup}}$ became apparent with periods of ~ 240 d and ~ 1300 d.

Interacting systems such as υ Andromedae are our most powerful probes of the dynamical histories of exoplanets. To select just one example, Ford et al.(2005) showed how υ Andromedae shows good evidence that a single, strong, planet-

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whose planets' circular orbits belie a violent history of planetary collisions and ejections.

planet scattering event is the origin of the modest eccentricities of the outer two planets.

2.1.2   HD 37124

Vogt et al.(2000), using velocities obtained with HIRES at Keck Observatory, detected an apparently Jupiter-mass planet with $P \sim 150$ d orbiting HD 37124, a metal-poor G4 dwarf. Further data showed significant deviations from the predicted velocities, and allowed Butler et al.(2003) to attempt a double-planet fit including an outer planet with $P \sim 6$ y. Goździewski(2003) showed that this fit was unstable, and further Keck data revealed the reason: Vogt et al.(2005) reported the detection of a third planet in the system, though with an ambiguity in its period. Today, Keck data has resolved this ambiguity.

This system has been particularly difficult to unravel because the radial velocity amplitudes of the three planets are similar and their periods are long: they have $P \sim 155$, 840, and 2300 d, and $M \sin i = 0.64$, 0.62, and $0.68 M_{\rm Jup}$. Goździewski et al.(2006) find that the outermost planet's orbit is still not very well constrained, and note that in this system, planet-planet interactions are sufficiently strong that kinematic (sum-of-Keplerian) models of the radial velocities are not sufficient to describe the system.

2.1.3   HD 74156

Naef et al.(2004) announced a double system with planets of $M \sin i = 1.86$ and 6.2 $M_{\rm Jup}$ in 52 d and 5.5 y orbits respectively around HD 74156 from data taken with ELODIE at Observatoire de Haute Provence. Combining published data from ELODIE, CORALIE at La Silla Observatory, and new data acquired by HRS on HET, Bean et al.(2008) announced a third, intermediate planet with $M \sin i = 0.4 M_{\rm Jup}$ and a period near 1 year. Barnes et al.(2008) studied the system dynamically and found two, stable, qualitatively different solutions to the published RV data. They described the detection of the third planet as vindication of a prediction by Raymond & Barnes(2005) of a planet of that mass and orbital distance based on their "Packed Planetary System" hypothesis.

2.1.4 μ Arae = HD 160691

Butler et al.(2001) announced a $P \sim 700$ d planet with 2 $M_{\rm Jup}$ orbiting μ Ara based on radial velocities from UCLES on the Anglo-Australian Telescope, and soon thereafter Jones et al.(2002) announced that further observations revealed a linear trend in the residuals, indicative of a long-period, outer companion. Further AAT observations allowed McCarthy et al.(2004) to update the fit, note that the linear trend then showed clear signs of curvature, and suggest a family of possible orbits including one with $P = 8.2$ y and $M \sin i = 3.1 M_{\rm Jup}$.

Nearly simultaneously to the latter work, Santos et al.(2004), using HARPS at La Silla Observatory to perform high-cadence, high-precision radial velocity work,

detected a $M \sin i = 10 M_{\oplus}$ companion in an inner 9.6 d orbit, and confirmed the outer planet. Finally, Pepe et al.(2007) used a combination of old and new HARPS data and the published UCLES data to detect a fourth planet with P=310 d, $M \sin i = 0.5 M_{\mathrm{Jup}}$ and determine good orbital parameters for the outer planet for the first time in a full, dynamical, 4-planet fit. For the outer planet they found $M \sin i = 1.8 M_{\mathrm{Jup}}$ and $P = 11.5$ y, and they revised the orbit of the b component, finding $M \sin i = 1.7 M_{\mathrm{Jup}}$ and $P = 643$ d.

Note that there is ambiguity in the literature regarding the nomenclature for these planets, with some authors referring to the outer planet as the e component (since it was the last to be characterized), and others referring to it as the c component (since it was the second to be detected).

2.1.5   55 Cancri = ρ^1 Cancri

Along with υ And b, Butler et al.(1997) also announced 55 Cnc b, a "51 Pegasi-type" planet with $M \sin i = 0.84 M_{\mathrm{Jup}}$ and $P = 14.6$ d. Further Lick data allowed Marcy et al.(2002) to announce a second planet at 5 AU with $M \sin i = 4 M_{\mathrm{Jup}}$, the first extrasolar Jupiter analog (in terms of orbital distance). They also announced a signal from what appeared to be a third planet with $P \sim 45$ d (roughly three times the period of the inner planet) and $M \sin i \sim 0.2 M_{\mathrm{Jup}}$, but at the time stellar rotation could not be ruled out as the cause.

Using a combination of new and old Lick, ELODIE, and HET velocities and Hubble Space Telescope Fine Guidance Sensor astrometry, McArthur et al.(2004) confirmed the 42-d planet and announced a very low amplitude 2.8-d planet with $M \sin i = 14 M_{\oplus}$, one of the first of a new class of "Hot Neptunes". Wisdom(2005), analyzing the published radial velocity data, challenged the reality of the 2.8 d planet, and noted a weak 260-d signal possibly due to a planet with $M \sin i \sim 30 M_{\oplus}$.

Using a combination of new and old Lick and Keck data, Fischer et al.(2008) found a good orbital solution for all four published planets and announced the fifth, $M \sin i = 0.14 M_{\mathrm{Jup}}$, 260-d planet, making 55 Cnc the first (and, to date, only) known quintuple planet system. They also found that despite the near-commensurability of their orbital periods, the b and c components are not likely in a 3:1 mean-motion resonance because a dynamical integration shows that their resonant arguments do not librate. They note that, as with HD 37124, Keplerian models are inadequate descriptions of the existing RV data, and differ from the best Newtonian (dynamical) fits by > 25 m/s.

2.2   Resonant Doubles

These six systems contain two giant planets in or suggested to be in mean-motion resonances (MMRs). While it is difficult to understand how such planets could have formed *in situ*, differential migration could explain how planets formed outside of resonance could become trapped in such an MMR (e.g.

Lee and Peale(2001)). The frequency and character of such MMR systems could thus be a probe of the nature of planetary migration in systems with multiple giant planets.

2.2.1   GJ 876

Marcy et al.(1998), using data from Keck Observatory, and Delfosse et al.(1998), using ELODIE and CORALIE data, nearly simultaneously announced the presence of a 61-d, $M \sin i \sim 2\mathrm{M_{Jup}}$ planet orbiting GJ 876, the first known M-dwarf planet host. After 2.5 y of further observations at Keck, Marcy et al.(2001a) showed that the signal was actually the superposition of signals from two planets in a 2:1 mean-motion resonance, with the inner planet having P= 30 d and $M \sin i = 0.6\mathrm{M_{Jup}}$, making GJ 876 b and c the first system clearly shown to be in a mean motion resonance (MMR). Further Keck data allowed Butler et al.(2004) to detect a very low-amplitude, low-mass planet in a 2.6-d orbit.

This MMR is so strong that the orbital elements of the planets change on timescales shorter than the span of the extant observations of the system. The arguments of periastron of the two components precess in ~ 11 y, an effect clearly seen in the radial velocities and which complicates multi-component Keplerian fits. A dynamical fit of the Keck velocities based on numerical integrations allowed Rivera et al.(2005) to weakly constrain the inclination of the system and estimate the true mass of the inner planet to be $7.5\mathrm{M_{\oplus}}$.

2.2.2   HD 82943

Mayor et al.(2004) described their discovery of the second known pair of planets in a 2:1 MMR orbiting HD 82943 (which had been publicly announced in 2000 and 2001) based on data from CORALIE. Lee et al.(2006) combined the published CORALIE data with new Keck data to derive a dynamical solution to the system, showing that the only stable solutions consistent with the data are those describing a 2:1 MMR. The planets have $P = 219$ and 441 d and $M \sin i = 2.0$ and 1.8 $\mathrm{M_{Jup}}$, respectively.

2.2.3   HD 128311

From an analysis of Keck data, Butler et al.(2003) announced a $P = 422$ d, $M \sin i = 2.2\mathrm{M_{Jup}}$ planet around the chromospherically active K dwarf HD 128311, for which high precision (< 10 m/s) can be difficult due to stellar "jitter". Vogt et al.(2005) used additional Keck data to detect an outer companion of similar amplitude with $P = 928$ d and $M \sin i = 3.2\mathrm{M_{Jup}}$, and used dynamical simulations to show that the system is almost certainly locked in a 2:1 MMR. Sándor & Kley(2006) suggested that since the system appears not to show apsidal corotation, it may owe its present state to a strong scattering event in its past.

2.2.4 HD 73526

Tinney et al.(2003) used data from UCLES to report the detection of a $P = 188$ d planet orbiting HD 73526. Another three years of data allowed Tinney et al.(2006) to report a second planet in a 378 d orbit and show that these planets ($M \sin i = 2.9$ and $2.5\mathrm{M_{Jup}}$) are in 2:1 resonance. Sándor & Kley(2006) showed that the published solution was chaotic found alternative, non-chaotic (regular) orbital solutions for the system, and argued that, like HD 128311, the system's dynamical state showed evidence of a perturbative event such as a strong scattering event.

2.2.5 HD 108874: 4:1?

Butler et al.(2003) used Keck data to report a $P \sim 400$ d Jovian planet orbiting HD 108874, and noted that a good fit required a linear trend be used in the model, suggesting a more distant companion was present in the system. By mid-2005, these residuals had turned over, revealing a $P = 1600$ d outer companion. They noted that while these orbital periods are consistent with a 4:1 MMR, that resonance is narrow and non-resonant stable configurations consistent with the data exist.

2.2.6 HD 202206: 5:1?

Udry et al.(2002) used CORALIE data to detect a large "superplanet" or brown dwarf with $M \sin i = 17.5\mathrm{M_{Jup}}$ orbiting HD 202206 in a 255-d orbit, one of only a few detections in the "brown dwarf desert". Further CORALIE data allowed Correia et al.(2005) to announce a second, outer companion with $P = 3.8$ y and $M \sin i = 2.4\mathrm{M_{Jup}}$. They report that while the system experiences strong planet-planet interactions, stability is protected by a 5:1 resonance.

   This system is especially interesting because it resembles a circumbinary planet. Goździewski et al.(2006) confirmed the 5:1 MMR and showed that the system is dynamically quite interesting, having different qualitative behavior depending on the inclinations of the companions.

2.3 Interacting Doubles

These eight systems contain two giant planets not in any mean motion resonance, but for which planet-planet interactions can be important in the dynamical modeling of the system. In many cases, such as with HD 12661, the planets are in secular resonances.

2.3.1 HD 12661

Fischer et al.(2001) reported a planet orbiting the G6 dwarf HD 12661 based on observations at Lick and Keck Observatories. Subsequent observations allowed Fischer et al.(2003) to report that the system is actually a double. Today's best

parameters (Butler et al.(2006)) show the b and c components having $P = 263$ and 1822 d, and $M \sin i = 2.3$ and 1.8 $M_{\rm Jup}$, respectively.

Goździewski(2003) found the system to be locked in a secular resonance near the 6:1 MMR, and referred to its "Janus head" of anti-aligned apsidal lines.

2.3.2   HD 155385

Cochran et al.(2007) used HET data to announce the lowest-metallicty planet host, the G subgiant HD 155385. The system is a double, with no MMR but significant planet-planet interactions leading to eccentricity exchange with a period of ~ 2700 y. The b and c components have $P = 195$ and 530 d, and $M \sin i = 0.98$ and 0.5 $M_{\rm Jup}$, respectively.

2.3.3   HD 169830

Naef et al.(2001) used CORALIE data to announce a $P \sim 230$ d planet with $M \sin i = 2.9 M_{\rm Jup}$ orbiting the F8 dwarf HD 169830[3]. Further data allowed Mayor et al.(2004) to identify a second, $P = 5.8$ y, $M \sin i = 4 M_{\rm Jup}$ planet in the system. Goździewski & Konacki(2004) showed that there are large exchanges of eccentricity between the components in coplanar configurations and that the system is stable for a large range of inclinations.

2.3.4   HD 183263

Marcy et al.(2005) used Keck data to report an $M \sin i = 3.7 M_{\rm Jup}$ planet in a 634 d, eccentric orbit around HD 183263, and note a strong residual linear trend. Wright et al.(2007) showed that by 2007 the residuals had significant curvature, and Wright et al.(2009) showed that the orbit, though still incomplete, was sufficient, in combination with stability analysis, to constrain the mass and period of the outer companion to $P = 8.4 \pm 0.3$ y and $M \sin i = 3 - 4 M_{\rm Jup}$ under the assumption that no additional companions are contributing to the radial velocities.

2.3.5   47 Ursa Majoris

The third star known to host exoplanets was 47 UMa, announced by Butler & Marcy(1996) as hosting a $P = 3$ y planet on a circular orbit as determined from data taken at Lick Observatory. This was the first planet strongly reminiscent of the gas giants in our Solar System. Fischer et al.(2002) studied another 5 years of Lick data and reported a second planet in the system, having $P \sim 1100$ d and $M \sin i = 2.5 M_{\rm Jup}$. Naef et al.(2004) and Wittenmyer et al.(2007), using ELODIE and HET data, respectively, have noted that a second planet with the reported parameters is not apparent in their data. Future observations should clarify the situation.

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[3]Not to be confused with HD 69830, the triple "Super-Earth" system of §2.5.2

2.3.6   HIP 14810

Butler et al.(2006) included HIP 14810 b in the *Catalog of Nearby Exoplanets* based on preliminary data from Keck Observatory taken as part of the N2K survey (Fischer et al.(2005)), and further observations allowed Wright et al.(2007) to provide an orbital solution for two planets, having $P = 6.7$ and 95 d and $M \sin i = 3.9$ and 0.76 M_{Jup}. Because the outer planet's orbit is currently poorly sampled, further observations will help clarify the nature of this system and allow for it to be better studied dynamically.

2.3.7   OGLE-2006-BLG-109L

Gaudi et al.(2008) announced the remarkable detection of a double-planet system around the distant ($d = 1.5$kpc) star OGLE-2006-BLG-109L during a microlensing event. Due to the great distance to this system and the non-repeating nature of microlensing detections, the study of the dynamics of this system with specificity is difficult (but see Malhotra & Minton(2008)). This detection demonstrates the promise of microlensing as a method to build up statistics of multi-planet systems, including those composed of rocky planets at a few AU. The most likely minimum masses and orbital distances of these planets are $M \sin i \sim 0.71$ and $0.27 M_{Jup}$ and $a \sim 2.3$ and 4.6 AU, making this system around a K star a "scaled-down Juipter-Saturn analog"

2.3.8   HD 102272

Niedzielski et al.(2008) used HET to announce two companions orbiting the giant star HD 102272. The inner, $M \sin i = 5.9 M_{Jup}$ planet orbiting at 0.6 AU is the closest known companion to a star with $M > 1.5 M_{\odot}$. Correlated residuals to a one-planet fit indicate a second planet of uncertain orbital period and mass, but the velocities are consistent with a period of $P \sim 520$d, suggestive of a 4:1 resonance.

2.4   Highly Hierarchical Doubles

These seven systems have orbital period ratios greater than 30:1, and so have little interaction between their components and can usually be well-modeled without resort to n-body simulations.

2.4.1   HD 168443

From Keck data, Marcy et al.(2001b) discovered a pair of massive, highly hierarchical companions orbiting HD 168443: a close-in $P = 58$ d inner planet with $M \sin i = 8.16 M_{Jup}$ and an outer object with $P = 4.8$ y and $M \sin i = 18.4 M_{Jup}$. Like HD 202206, this system has wide separation between its components and contains a "super-planet", but here the orbit of the lighter object is of the "s-type" (it orbits one, not both of the massive companions).

2.4.2 HD 187123

Using Keck data, Butler et al.(1998) announced an $M \sin i = 0.5\mathrm{M_{Jup}}$ planet in a 3-day orbit around HD 187123, a solar "twin". Further observations allowed Wright et al.(2007) to report the existence of an outer companion with orbital period ≥ 10 y, and to constrain its minimum mass to be planetary. Using subsequent observations of the apparent closing of the orbit, Wright et al.(2009) constrained its orbit to have $P = 10.5 \pm 0.5$ y and $M \sin i = 2.0 \pm 0.1 \mathrm{M_{Jup}}$, under the assumption that no other planets are influencing the observations.

2.4.3 HD 68988

Vogt et al.(2002) used Keck data to report a 6.3-d, $M \sin i = 2\mathrm{M_{Jup}}$ planet orbiting HD 68988. Subsequent observations have revealed a long-period outer companion of uncertain mass and period, with Wright et al.(2007) constrained to be $11\mathrm{y} < P < 60$ y and $6\mathrm{M_{Jup}} < M \sin i < 20\mathrm{M_{Jup}}$.

2.4.4 HD 38529

Fischer et al.(2001) used Lick and Keck data to report a 14.3-d, $M \sin i = 0.8\mathrm{M_{Jup}}$ companion to the old G subgiant HD 38529, and noted that the residuals to the fit suggested an outer companion. Further observations allowed Fischer et al.(2003) to confirm an outer, $P = 5.9$ y, $M \sin i = 13.2\mathrm{M_{Jup}}$ companion. Spitzer observations by Moro-Martín et al.(2007) reveal that HD 38529 has infrared excess consistent with dust-producing planetessimals at around 5 AU (outside both planets).

2.4.5 HD 217107

Fischer et al.(1999) used Lick data to discover the first, inner $P = 7.1$ d, $M \sin i = 1.3\mathrm{M_{Jup}}$ planet around the G7 dwarf HD 217107. Vogt et al.(2005) used new and old Lick and Keck data to identify a long period outer companion of uncertain mass and period. Further observations at Keck allowed Wright et al.(2009) to constrain the outer companion's mass and period to be $P \sim 11.7$ y and $M \sin i \sim 2.6\mathrm{M_{Jup}}$ under the assumption that no other planets are contributing to the radial velocities.

2.4.6 HD 11964

Butler et al.(2006) announced a $M \sin i = 0.6\mathrm{M_{Jup}}$ planet orbiting the slightly evolved star HD 11964 in a 5.3 y orbit. Subsequent observations suggested a low mass inner planet with $P = 38$ d (Wright et al.(2007)), and further monitoring allowed Wright et al.(2009) to confirm this signal as being to due a $M \sin i = 23\mathrm{M_{\oplus}}$ companion.

2.4.7   GJ 777 A = HD 190360

Naef et al.(2003) used data from ELODIE and the AFOE spectrograph at Whipple Observatory to detect[4] a long-period, Jovian planet around GJ 777 A. Vogt et al.(2005) used Keck data to confirm the outer planet and revise its orbital parameters, and to announced a second, close-in, low-mass companion. The b and c components have $P = 8.0$ y and 17.1 d, and $M \sin i = 1.6 M_{\mathrm{Jup}}$ and $19 M_{\oplus}$.

2.5   Systems of "Rocky" planets and "Super-Earths"

These four systems compose the present-day bookends of multiple-planet systems. The pulsar triple-planet system is the first exoplanetary system known and remains a fascinating example of the potential limits of multiple-planet detection. The latest frontier of exoplanet research with radial velocities is the hunt for rocky planets, and these latest detections of multiple "Super-Earths", all from the HARPS spectrograph, represent the penultimate step toward the definitive detection of rocky planets.

Because they do not transit, the actual compositions and masses of these planets is unknown, and so the monicker "rocky" is probably only truly appropriate for the pulsar planets.

2.5.1   PSR B1257+12

Wolszczan & Frail(1992) detected two very low-mass ($M \sin i = 3.9$ and 4.3 $M_{\oplus}$) objects orbiting the pulsar PSR B1257+12 using pulse timing methods. Two years later, Wolszczan(1994) detected the planet-planet interactions from the planets' 3:2 MMR, as well as a smaller, 0.02 $M_{\oplus}$ object in the system.

2.5.2   HD 69830

Based on observations with HARPS, Lovis et al.(2006) announced a "triple-Neptune" system orbiting the K dwarf HD 69830, having periods of $\sim$ 9, 32, and 200 days. This system is especially interesting because Beichman et al.(2005) had used Spitzer photometry and spectroscopy to reveal an infrared excess characteristic of a large cloud of fine silicate dust within a few AU of the star, suggestive of a large asteroid belt or "super-comet".

2.5.3   GJ 581

Also using HARPS, Bonfils et al.(2005) announced a $M \sin i = 0.052 M_{\mathrm{Jup}}$ planet in a 5.366 d orbit around GJ 581, making that star only the third M dwarf known to host a planet. After collecting additional data, two years later Udry et al.(2007) announced the discovery of two additional planets in the system with minimum masses of 5 and 7.7 $M_{\oplus}$, with periods of 12.9 and 83.6 d. The outermost planet

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[4]A preliminary orbit for this system also appears in Udry et al.(2003).

in the system sits at 0.25 AU, a location Udry et al.(2007) and Selsis et al.(2007) identify as being near the "cold edge" of the star's Habitable Zone (Kasting et al.(1993)).

2.5.4   HD 40307

Mayor et al.(2008) announced a third triple "Super-Earth" system from HARPS around the K2, dwarf HD 40307, and noted a linear trend in the radial velocities suggestive of a fourth, outer companion, as well. The low metallicity of this star ([Fe/H] $= -0.31$) and others has led to the suggestion that the well known metallicity dependence of planet occurrence breaks down for low-mass stars.

2.6   Future Detections and the Multiplicty Rate

Many systems show strong evidence of second planets due to long-period companions whose orbits are too incomplete for strong constraints to be put on their masses. For instance, 14 Her clearly has a long period companion of some sort, probably planetary (Naef et al.(2004), Wittenmyer et al.(2007), Wright et al.(2007), and Goździewski et al.(2008)), as may GJ 317 (Johnson et al.(2007)).

Of the 200 planet-bearing stars within 200 pc, the 28 above (not counting PSR B1257+12 and OGLE-2006-BLG-109L) constitute 14% of the total. An additional 27 (including 14 Her and GJ 317) show clear evidence of trends in their residuals and no evidence of stellar duplicity, meaning that the true multiplicity rate is at least 28%.

3   Statistical Properties of the Multiple Planet Sample

Wright et al.(2009) contains a catalog of the above multi-planet systems including updated latest orbital parameters for 10 of the systems. From this catalog, several intriguing patterns emerge; these features represent an opportunity to test models of planet formation, migration, and the origin of eccentricities:

- Planets in multiple-planet systems have eccentricities no higher than single planets (see Figure 1).

- The distribution of orbital distances of planets in multi-planet systems and single planets are inconsistent: single-planet systems show a pile-up at $P \sim 3$ days and a jump near 1 AU, while multi-planet systems show a more uniform distribution in log-period (see Figure 2).

In addition, among all planetary systems:

- There may be an emerging, positive correlation between stellar mass and giant-planet semi-major axis (see, e.g., Johnson et al.(2007)).
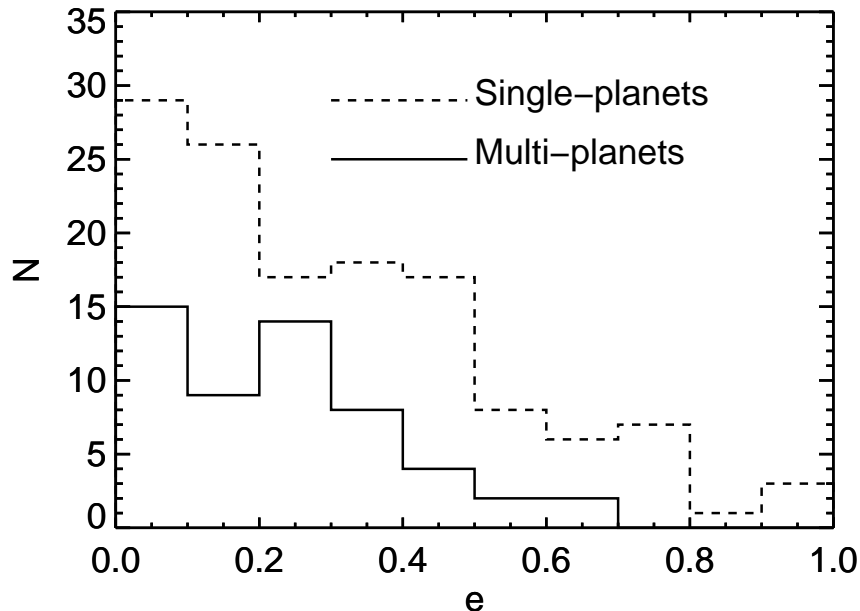
Fig. 1. Distribution of eccentricities of exoplanets for known multiple planet systems (solid) and apparently single planet systems (dashed). Note the high eccentricity orbits, $e > 0.6$ occur predominantly in single planets.

- Exoplanets more massive than Jupiter have eccentricities broadly distributed across $0 < e < 0.5$, while lower-mass exoplanets exhibit a distribution peaked near $e = 0$ (see Figure 3).

From Figure 2 it is clear that the orbital distances of planets in systems currently known to be multiple are not drawn from the apparently single-planet distribution, indicating that the migration mechanisms operate differently in these populations. Yet the eccentricity distributions of these two populations are nearly identical (Figure 1), suggesting that the mechanisms of eccentricity excitation are similar. Figure 3 shows that whatever those mechanisms are, they are ultimately more effective in pumping the eccentricities of planets with $M \sin i > 1\mathrm{M}_{\mathrm{Jup}}$. Reproducing these distributions will be a good test for future models and simulations of planet formation and dynamical evolution.
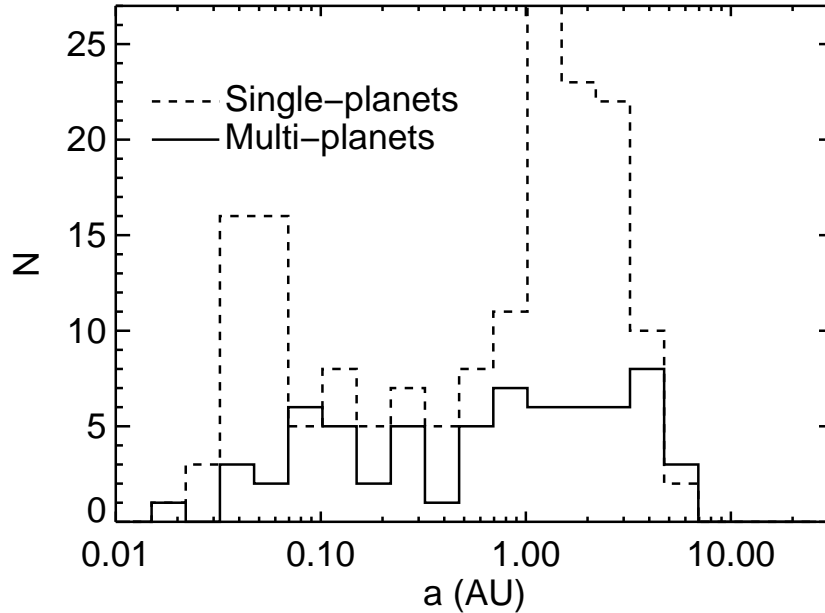
Fig. 2. Distribution of semimajor axes of exoplanets for multiple-planet systems (solid) and apparently single systems (dashed). Note the enhanced frequency of hot jupiters and the jump in abundance beyond 1 AU in the single-planet systems.

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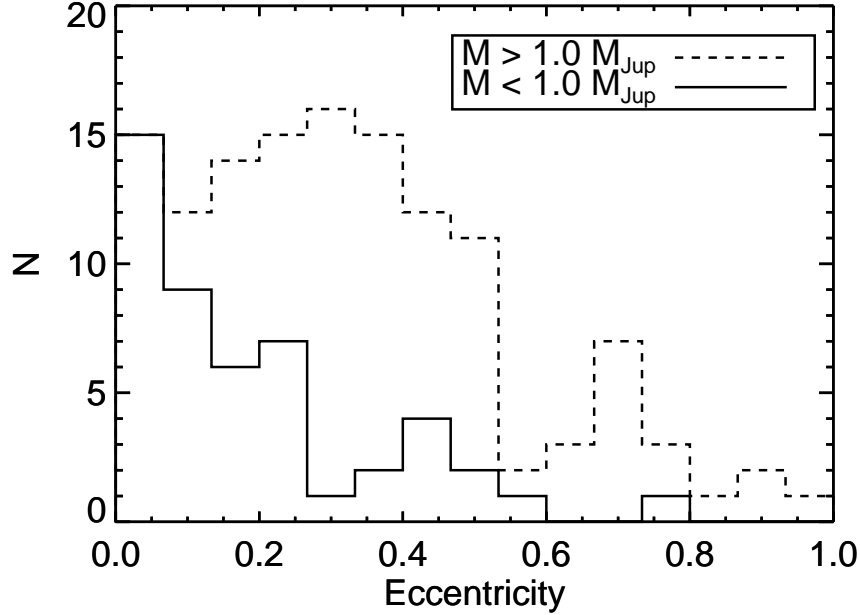
Fig. 3. Distribution of eccentricities of exoplanets with $M \sin i < 1.0 \mathrm{M_{Jup}}$ (solid) $M \sin i > 1.0 \mathrm{M_{Jup}}$ (dashed). The tidally circularized hot jupiters have been removed. Note that the eccentricity of planets of minimum mass $< 1.0 \mathrm{M_{Jup}}$ peaks at eccentricity < 0.2, while the eccentricities e of planets of minimum mass $> 1.0 \mathrm{M_{Jup}}$ are distributed broadly from $0.0 < e < 0.5$.

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