Part I

Discovery and study of extrasolar planets - current

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Statistical Properties of Extrasolar Planets

R. Paul Butler

Dept. of Terrestrial Magnetism, Carnegie Inst. of Washington, 5241 Broad Branch Rd, NW, Washington DC, 20015-1305 USA

Geoffrey W. Marcy and Debra A. Fischer

Astronomy Dept., University of California, Berkeley, CA 94720 USA

Steven S. Vogt

UCO/Lick Observatories, University of California, Santa Cruz, CA 95064 USA

C. G. Tinney

Anglo–Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia

Hugh R. A. Jones

Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead CH41 1LD, UK

Alan J. Penny

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK

Kevin Apps

Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QJ, UK

Abstract. The emerging statistical properties from the first 50 extrasolar planets are startlingly different from the picture that was imagined prior to 1995. About 0.75% of nearby solar type stars harbor jovian planets in 3 to 5 day circular orbits. Another ~7% of stars have jupiter–mass companions orbiting in eccentric orbits within 3.5 AU. The mass distribution of substellar companions rises abruptly near 5 M_{JUP} and continues increasing down to the detection limit near 1 M_{JUP}. Orbital eccentricities correlate positively with semimajor axes, even for planets beyond the tidal circularization zone within 0.1 AU, distinguishing planets from binary stars. The planet bearing stars are metal–rich relative to both nearby stars and to the Sun. Analogs of Solar System planets have not been detected to date as they require precision of 3 m s^{-1} maintained for more than a decade.

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1. Introduction

The first half dozen extrasolar planets, discovered between late 1995 and mid 1996, were both exciting and shocking. After more than a century of determined effort, astronomers finally had a technique capable of detecting planets orbiting nearby stars. But the planets that were turning up were not at all what was expected. Instead of Solar System analogs with planets orbiting in concentric circular orbits at several AU, the initial batch of planets included 51 Peg and τ Boo in 4 day circular orbits, and 70 Vir and 16 Cyg B in radically eccentric orbits beyond 0.3 AU.

It was not clear if these seemingly bizarre objects were related to Solar System planets, the tail of the brown dwarf distribution, or something else altogether. Over the succeeding five years, precision Doppler surveys have revealed about 50 substellar mass companions orbiting nearby Sun–like stars. All 50 of these have $M \sin i < 10$ M_{JUP} and are either "51 Peg–like" or eccentric. Before the statistical properties of this ensemble of planets can be considered, the selection effects of the precision velocity surveys must be considered.

The fundamental detection limits for Doppler surveys are set by measurement precision and time baseline. Since 1995 the number of stars under survey has increased from about 200 to roughly 2,000. Most of the stars under survey have been observed for 4 years or less. As the discovery of a planet from a precision Doppler survey requires observation of more than one orbit, we are only now sensitive to planets orbiting within ~2 AU. Surveys that achieve a precision of 10 m s^{-1} can reliably detect planets of 2 M_{JUP} or larger out to 2 AU, while surveys that achieve 3 m s^{-1} are sensitive to planets down to 0.5 M_{JUP} at 2 AU.

The Keck, Lick, and Anglo–Australian surveys are unique in achieving measurement precision of 3 m s^{-1}, as demonstrated both by stable stars (Butler et al. 1996; Butler & Marcy 1997; Vogt et al. 2000; Butler, Tinney et al. 2000), and by residuals to Keplerian fits (Vogt et al. 2000; Marcy et al. 2000; Butler, Vogt et al. 2000; Butler, Tinney et al. 2000). Thirty-four planets have been announced from 31 stars that were placed on these surveys without *a priori* knowledge of substellar companions. This sample represents about 70% of the known extrasolar planets. All but three of these planets were first published by the Keck, Lick, and Anglo–Australian teams.

Here, we consider the Keck, Lick, and Anglo–Australian surveys only in a new statistical analysis of planet characteristics. All of the planets announced from these surveys have been published in refereed journals (cf. Butler et al. 2000).

2. Statistical Properties of Planets

2.1. Substellar Companion Mass Function

The substellar companion mass function for all 34 planets detected by the Keck, Lick, and AAT surveys is shown in Figure 1. This mass function abruptly begins to rise below 10 M_{JUP}, and continues to rise down to the detection limit. These surveys would have easily detected any companions with $M \sin i \gtrsim 3$ M_{JUP}

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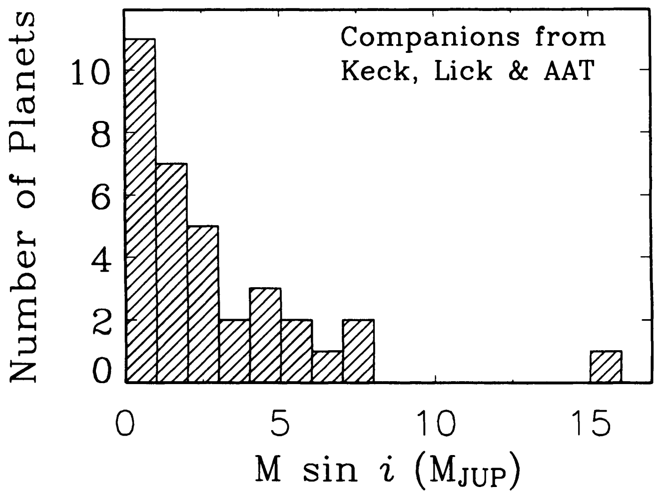

Figure 1. Substellar mass function found from the Keck, Lick, and AAT precision Doppler surveys. These are the only surveys sensitive to 1 M_{JUP} planets orbiting beyond 2 AU. Out to 2 AU these surveys are complete for companions of more than 3 M_{JUP}. Incompleteness is greatest for the smallest mass bin. The discontinuous and abrupt rise in the mass function below 10 M_{JUP} empirically motivates setting the upper mass limit of planets at 10 M_{JUP}.

orbiting within 2 AU. However these surveys still carry great incompleteness for companions having $M \sin i$ less than 1 M_{JUP}.

The Keck, Lick, and AAT surveys have no bias against brown dwarf companions. The stars in these surveys were chosen without knowledge or regard to substellar companions. The extreme paucity of companions having $M \sin i$ > 10 M_{JUP} is stunning given the extreme ease with which such companions would be detected. Less than 0.3% of stars in the mass range 0.3 to 1.1 M_{JUP} have companions between 10 and 80 M_{JUP} orbiting within 3 AU. The 1,100 stars in the Keck, Lick, and AAT surveys have turned up only one lone companion to populate this brown dwarf desert.

Despite the incompleteness for companions with $M \sin i < 1$ M_{JUP} our precision of 3 m s^{-1} reveals saturn–mass planets only within 1 AU, and neptune–mass planets within 0.1 AU. As a result, the true mass function probably rises even more steeply toward lower masses than the observed mass function.

2.2. Orbital Eccentricities

Of the 34 planets to emerge from the Keck, Lick, and AAT surveys, only 10 reside in nearly circular orbits ($e < 0.07$), and all 10 of these orbit within 0.15 AU. Of the 21 planets orbiting beyond 0.15 AU, all 21 have $e > 0.1$.

The time scale for tidal circularization of planets in 4 day orbits may be as short as 1 Gyr (Lin, Bodenheimer & Richardson 1996; Rasio & Ford 1996; Marcy et al. 1997), possibly explaining the circular orbits of the planets with the shortest periods. These systems may not preserve information about the primordial eccentricities.

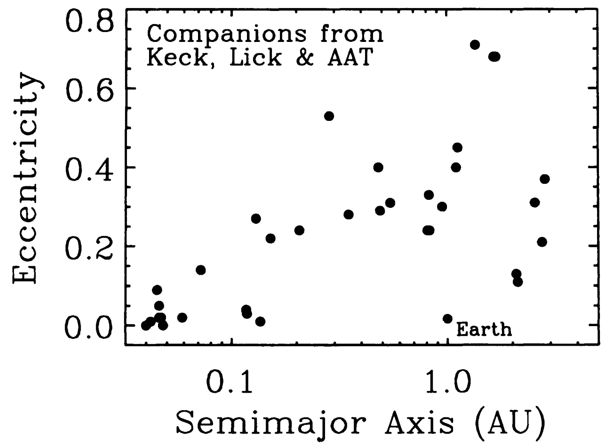

Figure 2. Eccentricity vs Semimajor Axis. All of the extrasolar planets found orbiting beyond 0.15 AU are in eccentric ($e > 0.1$) orbits. The Earth is shown for comparison. The circularity of planets in the smallest orbits ($\sim$ 0.05 AU) is expected due to the strong tidal effects of the host stars. For planets orbiting between 0.15 and 3 AU, eccentric orbits are the rule, not the exception.

Figure 2 shows that the orbital eccentricities are correlated with semimajor axis. Even excluding those within 0.1 AU that are possibly subject to tidal circularization, the trend in eccentricities persists. Both the upper envelope and the lower envelope shows a trend in eccentricity vs semimajor axis. The slope is approximately, $de/dloga = 0.2\ AU^{-1}$. This eccentricity trend seems to be a unique characteristic of extrasolar planets, not found in binary stars. The trend presumably stems from the formation or subsequent dynamics of the planets.

A number of theories have been suggested to explain the ubiquity of eccentric orbits for planets with semimajor axes greater than 0.15 AU, including gravitational interactions between planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Levison et al. 1998), gravitational interactions with a companion star or a passing star (Holman et al. 1997; de la Fuente Marcos & de la Fuente Marcos 1997; Laughlin & Adams 1998), tidal interactions between the protoplanet and the disk (Artymowicz 1993), and protoplanetary disk instabilities (Boss 2000). As all observed planets beyond 0.15 AU are in eccentric orbits, mechanisms that generate eccentric orbits must be common and robust.

2.3. Orbital Semimajor Axes

Figure 3 shows the observed distribution of semimajor axes from the Keck, Lick, and AAT surveys. The precision Doppler technique is strongly biased toward the discovery of planets in small orbits. Many orbits can be observed in a few weeks or months, and the gravitational tug of the planet on the star is maximized, yielding larger Doppler velocity amplitudes relative to more distant orbits.

While this selection effect could explain the excess of planets found within 0.2 AU relative to planets orbiting beyond 2 AU, it does not explain why orbits

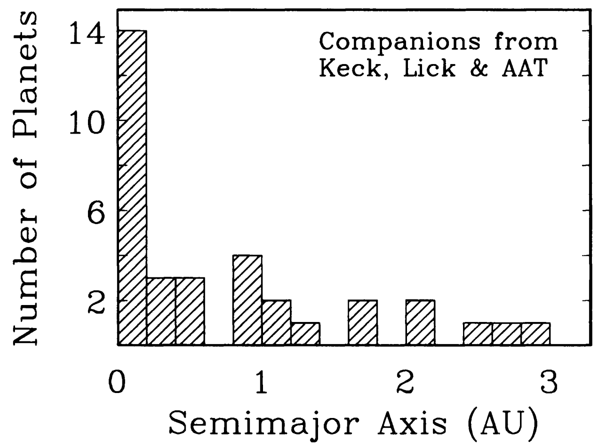

Figure 3. Histogram of semimajor axes. There is a strong bias toward discovering planets in the smallest orbits. Many orbits can be observed in just a few weeks, and the stronger gravitational tug of the planet on the star creates a larger Doppler velocity signal. The discovery of planets in 5 AU orbits will require an additional decade of monitoring.

within 0.2 AU are so greatly preferred relative to orbits between 0.2 and 0.6 AU. With orbital periods of less than half a year, most jupiter–mass planets within 0.6 AU are found with less than 3 years of precision velocity data.

In the standard paradigm, giant planets form outside 4 AU (Boss 1995; Lissauer 1995). Inward orbital migration (Lin et al. 1996) within the gaseous protoplanetary disk could explain the small orbits detected to date among extrasolar planets. As the orbital migration time scale is proportional to the orbital period, with rapid orbital decay for successively smaller orbits, it would be expected that more planets should be observed at greater orbital distances. The piling up of planets at 0.05 AU may be due to a halting mechanism which stabilizes the orbit of a protoplanet until the disk evaporates (Lin et al. 1996). Over the interval of 0.2 to 3 AU the observed distribution of orbital semimajor axes is roughly flat. No migration halting mechanism is known for these intermediate orbits, nor are their orbital eccentricities understood.

3. Statistical Properties of Planet Bearing Stars

3.1. HR Diagram

The precision Doppler technique puts a premium on stars with many sharp spectral features. Stars earlier than F7 have relatively few absorption lines, and they tend to be broadened by rapid stellar rotation. It has been empirically shown that slowly rotating main sequence stars later than G0 are intrinsically stable to at least the 3 m s^{-1} level (Saar et al. 1998). This is the minimum precision necessary to detect a jupiter-analog orbiting a solar–type star.

Figure 4 shows the HR diagram centered on the main sequence stars ranging from F0 through M7. The small dots are all the stars within 20 pc from the

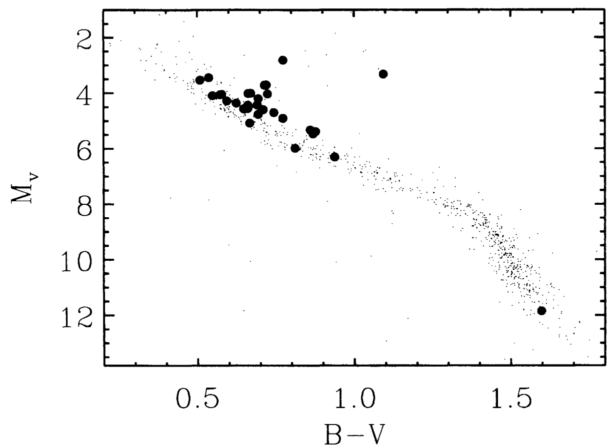

Figure 4. HR diagram centered on the Main Sequence spanning spectral types F0 through M7. The small dots are Hipparcos catalog stars within 20 parsecs, while the large dots are the Keck, Lick, and AAT stars that have yielded planets.

Hipparcos catalog (Perryman et al. 1997) that fall within this range of absolute magnitude and color. The main sequence is well defined. The large dots are the planet bearing stars from the Keck, Lick, and AAT surveys. Nearly all the planet bearing stars lie on the main sequence with $B-V$ values between 0.5 and 1.0. Most of the planet bearing stars in this range of $B-V$ are nearly naked eye stars, and as such they represent the first generation of planet bearing stars from these surveys.

GL 876 (Marcy et al. 1998), the only M dwarf known to harbor a planet, is also among the very brightest M dwarfs. A total of 120 M dwarfs are included in the Keck survey, but most of these have been added in just the last year. They will require an additional 2 years to begin yielding planets.

Relatively few K dwarfs have yielded planets, and none later than about K2. This is due in part to the relative dearth of stars ranging from K2 through K7. This sparseness is obvious in the Hipparcos stars shown in Figure 4. $B-V$ changes quickly with mass in this range, leaving relatively few stars in each $B-V$ bin.

Slowly rotating class IV and V stars from G0 through M4 have been empirically shown to be stable at the 3 m s^{-1} level. Giant stars and stars transitioning to giant status near $M_V = 3$ are intrinsically unstable at the level of a few tens of m s^{-1} .

3.2. Stellar Metallicities

Figure 5 shows a histogram of the metallicities of the planet bearing stars (solid line), and a comparison set of field stars (cross–hatched region). The comparison field stars are the volume limited sample of 77 single G dwarfs within 20 pc, as determined by Hipparcos. The metallicities of these stars were determined by uvby photometry as described in Butler, Vogt et al. (2000).

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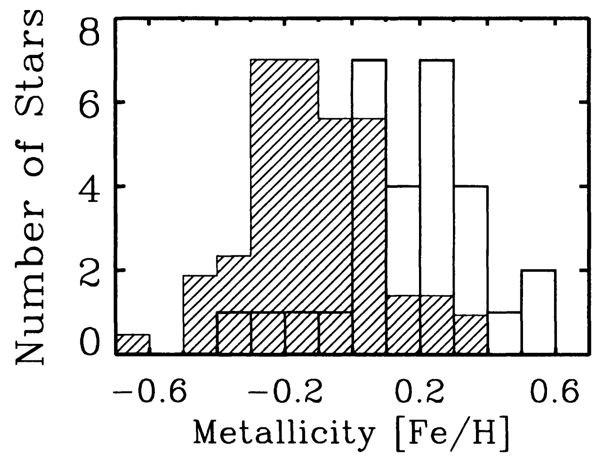

Figure 5. Histogram of metallicities of planet bearing stars from Keck, Lick, and AAT (solid line), compared to the nearest field stars (cross–hatched region). The majority of the planet bearing stars are metal–rich relative to the Sun, which is itself metal–rich relative to nearby field stars.

As Figure 5 shows, the planet bearing stars are metal–rich relative both to the field stars and to the Sun. In particular, planets have been detected around three stars that are more metal–rich than any single G dwarf within 20 pc. As most of the stars in the Keck, Lick, and AAT surveys are within 50 pc, these three stars suggest that super metal–rich stars may commonly have detectable planets orbiting within 3 AU. At the other extreme, stars with [Fe/H] < 0 have yielded only 4 planets, $\sim$12% of the planets from these surveys, yet such stars make up about 65% of all field stars.

There are several competing hypotheses to explain the metal–rich nature of the observed planet bearing stars. Most obviously, planets may form more readily in metal–rich environments. It is important to consider selection effects in making such arguments. Precision Doppler surveys are most sensitive to massive planets in small orbits. Since jupiter–mass planets presumably form beyond the ice boundary in a protoplanetary disk, the planets that have been found to date have presumably migrated from beyond 4 AU to less than 3 AU. Migration may occur more readily in a metal–rich disk, thus jupiter–mass planets around metal–poor stars would be found in more distant orbits. Another possibility is that metal–poor stars may preferentially form sub–saturn–mass planets, making them harder to detect with current technology.

Choosing between these competing metallicity hypotheses will require the detection of saturn–mass planets in the inner few AU and jupiter–mass planets beyond 4 AU. With measurement errors of 3 m s^{-1} , the Keck, Lick, and AAT planet surveys are sensitive to jupiter-mass companions out to 5 AU, though another 10 years of data will be required to cover an entire orbital period. The first two sub–saturn–mass candidates (Marcy et al. 2000) have just recently been reported from the Keck survey. Both of these planets orbit metal–rich stars.

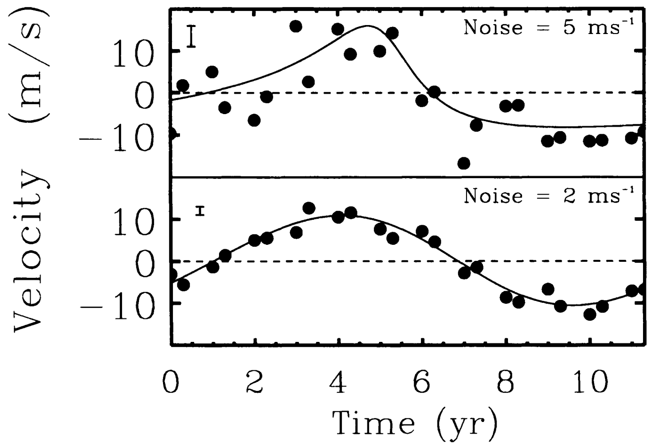

Figure 6. Simulated Jupiter signal observed with a precision of 5 and 2 m s^{-1} . Solid lines are best–fit Keplerians to the simulated data sets. With measurement precision of 5 m s^{-1} , an unreliable 2σ detection is obtained with no information on the orbital eccentricity. With precision of 2 m s^{-1} , a solid 5σ detection is made, and the eccentricity is determined to within ± 0.05.

4. Precision and Solar System Analogs

With Doppler precision of 10 m s^{-1} , the smallest velocity semiamplitude that can be reliably detected is 40 m s^{-1} in long–period orbits. Nearly all the announced planets have semiamplitudes greater than or equal to this. Detection of *bona fide* Solar System analogs, jupiter–mass companions orbiting beyond 4 AU, requires measurement precision of 3 m s^{-1} , as does the detection of saturn–mass companions within 1 AU, and neptune–mass companions within 0.1 AU.

True Solar System analogs must reside in circular orbits. Figure 6 shows a simulated data set for a 1 M_{JUP} companion orbiting at 5 AU. The top panel has measurement errors of 5 m s^{-1} , while the bottom panel shows the same data with errors of 2 m s^{-1} . At 5 m s^{-1} precision, a 2σ marginal detection is possible. With 3 m s^{-1} precision, a minimal 3σ detection is obtained with uncertainties in the eccentricity of ± 0.2. At 2 m s^{-1} precision, a solid 5σ detection is obtained and the eccentricity is determined to ± 0.05.

Our group currently achieves long term precision of 3 m s^{-1} at Keck, Lick, and the AAT, and short term precision of 2 m s^{-1} (Bedding et al. 2000). We are working to improve our long term precision to 2 m s^{-1} and our short term precision to 1 m s^{-1} .

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