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Distinction between Extra-solar Planets and Low-mass Secondaries

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Abstract.
This paper discusses the distinction between extra-solar planets and low-mass secondaries, in principle as well as in practice. Adopting a distinction based on the presumed different processes of formation, the paper compares the characteristic features of the giant planets in our solar system with those of the low-mass secondaries in spectroscopic binaries. The discussion reveals that there is no *a priori* obvious feature that can identify planets. Instead, this work considers the extremely small emerging population of discovered extra-solar planets. Based on the nine "planet-candidates" discovered as of mid-1998, it was found that their mass distribution is remarkably different from the distribution of low-mass secondaries. The transition between the two populations probably occurs at 10–30 Jupiter masses. This transition could reflect the borderline between planet and brown dwarf secondary masses.

1. Introduction

In the last two years we have been witnessing a burst of discoveries of candidates for extra-solar planets (e.g. Mayor & Queloz 1995; Marcy & Butler 1996). These "planet candidates" were discovered by detecting small periodic radial-velocity modulations of their parent stars, which indicate the existence of unseen companions. The identification of the companions as planet candidates is based solely on their inferred masses, which are of the order of a Jupiter mass.

This paper addresses the question of how we can distinguish between an extra-solar planet and a very small secondary. After all, most stars dwell in binary systems, with secondaries of different masses. We expect the mass distribution of these secondaries to have a low-mass tail that could extend down to the planet-mass range. Therefore, the mass of the unseen companion is not necessarily an obvious criterion to distinguish between a planet and a low-mass secondary.

To find such a criterion we must have first a clear notion of the defining difference between a planet and a low-mass secondary. I will adopt here a defining distinction which lies in the realm of formation (e.g. Boss 1996; Black 1997) although other distinctions have been put forward (e.g. Oppenheimer, Kulkarni & Stauffer 1999). The present paradigm assumes that, at least in our solar system, the first stage of the formation of the giant planets was the generation of planetesimals from the gas and dust of the cold, relaxed, circumsolar disk.

Accumulation of planetesimals formed sufficiently massive planetary cores that could gravitationally capture large amount of gas to form the present envelopes of the giant planets (e.g. Lissauer 1993). Secondaries in binary systems were formed differently, perhaps by double or multiple fragmentation of collapsing protostellar clouds (e.g. Burkert & Bodenheimer 1996).

Actually, we do not fully understand how close binaries, and low-mass secondaries in particular, were formed. In addition to the fragmentation during the isothermal collapse (Boss 1986) a few other ideas, like fragmentation of an accretion disk (e.g. Adams, Ruden & Shu 1989) or capture of a secondary with the dissipative effect of a circumstellar disk (Clark & Pringle 1991; McDonald & Clark 1995), have been put forward. Even the planetary formation planetesimal paradigm has been challenged (Boss 1998). In any event, to preserve the formation-based distinction between planets and low-mass secondaries I *assume* that planets were formed out of a cold, relaxed disk, while low-mass secondaries were formed differently, like any other binaries.

One drawback of the formation-based distinction between planets and low-mass secondaries is that for any specific system we do not know how exactly the unseen companion has been formed. What we can do, instead, is to look for expected characteristic observable features of extra-solar planets as opposed to low-mass secondaries.

In search for genuine features of planets, the next section considers the characteristics of the giant planets in our own solar system. The discussion of the differences between the solar system and the low-mass secondaries suggests that none of the known differences can serve *a priori* as a safe criterion to identify extra-solar giant planets. Instead, one can study the characteristics of the emerging small population of planet candidates, looking for any salient feature that can distinguish between real planets and small-mass secondaries. This work concentrates on one particular feature — the mass distribution.

The mass distribution of the planet candidates has been already discussed by previous studies (Basri & Marcy 1997; Mayor, Queloz & Udry 1998; Mayor, Udry & Queloz 1998; Marcy & Butler 1998), but in those papers the mass distribution was binned linearly. Here we choose to use a logarithmic scale because of the large range of masses involved. The logarithmic scale has also been used by Tokovinin (1992) to study the secondary mass distribution in spectroscopic binaries, and was suggested by Black (1998) to study the mass distribution of the planetary-mass companions. The present study suggests that the mass distributions of the planet candidates and the low-mass secondaries are quite different, and therefore the companion mass might indeed serve as a signature of extra-solar planets.

Early versions of the logarithmic mass distribution were presented at the meeting "Physical Processes in Astrophysical Fluids", in Haifa, January 1998 (Mazeh 1999) and in an ApJL paper (Mazeh, Goldberg & Latham 1998a).

2. Comparison Between the Giant Planets of our Solar System and Low-Mass Secondaries

Comparison between the giant planets of our solar system and the secondaries of short-period binaries suggests a few distinctive characteristics:

1. Planetary mass is relatively small, up to a Jupiter mass, while typical secondaries have stellar mass.
2. The solar giant planets reside at large distances from the Sun, of the order of a few AUs, while secondaries are found at various distances, including radii smaller than a tenth of an AU.
3. Planets have circular orbits, while binaries have eccentric or circular orbits (Duquennoy & Mayor 1991).
4. A few planets orbit together around the same central star, while binaries have only one secondary per system (e.g. Black 1997).
5. Planets have high metallicities, while secondaries have regular stellar abundances (Lunine 1986).

All these features are well explained by the formation paradigm:

1. The relatively small mass reservoir in the protoplanetary disk limited the planets' masses.
2. At close distances to the central star, the temperature of the disk was too high to allow the growth of giant planets.
3. Planets were formed from particles in a relaxed disk, where all particles were in circular Keplerian orbits, so the planetary orbits are circular.
4. A few planets could be formed simultaneously in different places in the disk.
5. The solid material from which the planet cores were formed had high metal abundance, so the planets accumulated a higher frequency of metals during their early stages of formation (Saumon 1996).

Naively, one could suggest any of these features to distinguish between giant planets and low-mass secondaries. However, we should be careful not to project automatically any feature of our own solar system onto other possible systems. The scientific community made this mistake too many times in the history of astronomy, including the idea that giant planets can not reside close to their parent stars. In fact, quite a few planet candidates were found recently at very small radii (e.g. Mayor & Queloz 1995), contrary to feature #2. Only after these planet candidates were found, a few ingenious ideas were suggested to explain how some of the giant planets migrated to their present locations (e.g. Murray et al. 1998; Trilling et al. 1998). In any event, we have lost one of the possible distinctions between planets and low-mass secondaries.

It is not clear that the orbital eccentricity (feature #3) can be used to distinguish between planets and stellar companions. Mazeh, Mayor & Latham (1996) pointed out that the planet-disk interaction (e.g. Goldreich & Tremaine 1980) is a possible mechanism for generating a strong eccentricity-mass dependence for planets (Artymowicz 1992; Lubow & Artymowicz 1996). Furthermore, Black (1997) analyzed the eccentricity as a function of *period* and concluded that the eccentricities observed are consistent with the assumption that all the planet candidates are actually low-mass brown dwarfs formed like binary stars. It seems therefore that it might be premature to distinguish between low-mass secondaries and planets solely on the basis of their orbital eccentricity.

Even the multiple number of planets as opposed to only one secondary per system is not a safe way to separate the two types of objects. We do find multiple stellar systems, some with more than one low-mass component. The difference between a planetary system with a few planets and the known multiple stellar systems is the hierarchical structure. Triple stellar systems, for example, are found only in hierarchical configurations, where two components are close together in a relatively tight binary, while the tertiary is far away, orbiting around the close binary (Tokovinin 1997). In planetary systems, on the other hand, a few planets orbit around the same central object in orbits with similar radii. However, this distinction is not necessarily rooted in different formation processes. Multiple stellar systems with similar orbits are dynamically unstable (e.g. Marchal 1990). Planetary systems, on the other hand, are stable even in cases where the different planets have similar orbital radii, because of the very large mass ratio between the planets and the central object. Therefore, the multiplicity of the solar system is not an independent feature of planets, but is anchored in the mass difference between the two types of objects. A few extremely low-mass secondaries could have existed in similar radii around a stellar object (Anosova 1996).

Feature #5 is presently not observable, because we cannot resolve the images of the planet and that of its parent star. We therefore cannot secure the planet spectrum and cannot study its metal abundance.

So, from the five features enumerated above we are left with the original concept, that only the mass of the companion can be used for the definition of a planet. However, even this is not clear, because we do not have yet an upper limit for the possible mass of a planet. Nor do we know the lower limit for the mass of a low-mass secondary companion. It is true that stellar theory tells us that objects below 0.08 $M_{\odot}$ cannot ignite hydrogen in their cores, and the present nomenclature calls such objects 'brown dwarfs' and not stars. Nevertheless, in the context of the planet formation-based definition, brown dwarfs found as companions to normal stars are still considered by the astronomical community as low-mass secondaries. Therefore, there is no obvious *a priori* mass borderline between the population of planets and secondaries. Moreover, it is possible, in principle, that the two populations overlap in their mass ranges. If this is indeed the case, the last criterion to distinguish between the two populations is also put into doubt.

The next section therefore discusses in details the mass distributions of the planet candidates and that of the low-mass secondaries. The comparison of the two is enlightening.

3. The Mass Distribution of the Planet Candidates and the Low-Mass Secondaries

Between October 1995 and mid-1998, eight candidates for extrasolar planets were announced (e.g. Marcy & Butler 1998). We do not consider the planet candidates found after mid-1998 (see Mayor and Marcy papers, this volume) because the very recent discoveries are the first results of large new surveys, and therefore are severely incomplete. The minimum possible masses for the eight candidates, corresponding to an inclination angle of 90°, are in the range 0.5 to 8 Jupiter masses ($M_{\rm Jup}$). These findings render the eight companions to be giant planets or at least 'planet candidates'.

The detections of these eight companions were announced seven to nine years after a companion of HD 114762 was discovered (Latham et al. 1989), based on measurements with a lower precision (Latham 1985). Mazeh, Latham, & Stefanik (1996) have shown that the minimum mass for the companion of HD 114762 is 9.4 $M_{\rm Jup}$. Therefore, when considering the emerging population of planet candidates, HD 114762 should be considered together with the eight new candidates. Table 1 lists the minimum possible mass, period and discovery date of the nine objects.

Table 1. The Planet Candidates

Name	$M_{2,\rm min}$ ($M_{\rm Jup}$)	P (days)	Discovery Date	Ref.
HD 114762	9.4	84	1989	1,2
51 Peg	0.5	4.2	1995	3
47 UMa	2.5	1090	1996	4
70 Vir	7.4	117	1996	5
55 Cnc	0.8	14.7	1996	6
τ Boo	3.9	3.3	1996	6
υ And	0.7	4.6	1996	6
16 Cyg B	1.6	804	1996	7
ρ CrB	1.1	39.6	1997	8

[1]Latham et al. 1989; [2]Mazeh, Latham & Stefanik 1996; [3]Mayor & Queloz 1995; [4]Butler & Marcy 1996; [5]Marcy & Butler 1996; [6]Butler et al. 1997; [7]Cochran et al. 1997; [8]Noyes et al. 1997.

The mass distribution of low-mass secondaries in spectroscopic binaries derived here is based on the results of the very large radial-velocity study of the Carney & Latham (1987) high-proper-motion sample (Latham et al. 1998, 1999; Goldberg et al. 1999). First analysis of the secondary-mass distribution of this large sample was presented in a conference paper (Mazeh, Goldberg and Latham 1998b, hereinafter MGLb). The results of this analysis are used here to estimate the secondary mass distribution in the range of 100–1000 $M_{\rm Jup}$.

Another source for the secondary mass distribution is the work of Mayor et al. (1997), who studied a sample of 570 nearby K stars (see also Halbwachs, Mayor & Udry 1998). Their results are used to estimate the mass distribution of the low-mass secondaries in the range of 10–100 $M_{\rm Jup}$. The range of masses considered here, for the population of the planet candidates and the low-mass secondaries *together*, is from 0.5 to 1000 $M_{\rm Jup}$. This is the reason that Mazeh, Goldberg & Latham (1998a, hereinafter MGLa) chose a logarithmic scale to consider simultaneously the two populations. The present work follows their approach.

MGLb divided the high-proper-motion (H-P-M) sample into two subsamples, with high- and low-mass primaries. Only the high-mass primary subsample of 420 stars, with primary masses between 0.7 and 0.85 $M_\odot$, will be used here. From Figure 1 of MGLb one can estimate the number of systems with secondary masses in the range of 100–316 $M_{\rm Jup}$, or 0.1–0.3 $M_\odot$, which is half a logarithmic unit. The number of binaries in this range is found to be 19.

The number of binaries with secondaries in the range of 316–1000 $M_{\rm Jup}$ (0.3–0.96 $M_\odot$) cannot be deduced directly from MGLb figure, because that figure is limited to masses up to 0.7 $M_\odot$. This is so because all primaries of that sample have masses smaller than 1 $M_\odot$, and therefore their secondaries could not possibly have mass of 1 $M_\odot$. Nevertheless, one can read from the figure that between 0.3 and 0.7 $M_\odot$ there are 19 systems, and scaling it linearly up to 0.96 $M_\odot$ brings us to 32 systems.

Mayor et al. (1997) listed 2 spectroscopic binaries with minimum mass in the range 10–32 $M_{\rm Jup}$ and 8 systems in the range 32–63 $M_{\rm Jup}$. Mayor (this volume) reported ingenious work done with the Hipparcos data that indicated that the 8 systems have masses larger than the 0.08 $M_\odot$ stellar border line, turning these "brown-dwarf candidates" back into stellar companions. For the present work, in which I am interested in plotting a binned histogram, the exact mass of the 8 secondaries is irrelevant, as long as they fall in the bin of 32–100 $M_{\rm Jup}$. I therefore still consider the minimum masses of these 8 systems, derived from the radial-velocity data, to be the relevant information. Mayor et al. were kind enough to let MGLa know that they have found 5 additional binaries in the range of 63–100 $M_{\rm Jup}$.

The number of detected spectroscopic binaries has to be scaled to the size of the sample out of which the nine planet candidates were found. The scaling is not simple because the nine planets were discovered by different research groups, with different time coverage and slightly different precision (e.g. Marcy & Butler 1998). MGLa assumed that the total number of observed stars was two hundred, and ignored the differences between the various studies. The number of detected binaries in each bin, scaled to a sample of 200, denoted by $N_{\rm scl}$, is given in Table 2.

One still needs to correct the scaled number of binaries for two effects. The first one has to do with the fact that the masses given in Table 1 and in Mayor et al. (1997) list are only *minimum* masses, and therefore the actual mass of each companion is most probably larger, depending on the unknown orbital inclination. The correction for this effect tends to shift the distribution towards larger masses. The second effect reflects the fact that binaries with too small an amplitude could not have been detected, because their period is too large, or their inclination angle is too small. The correction of this effect tends to increase the number of companions in bins with small masses. Both effects were taken into account in the work of MGLb, so we need to correct only the counts of the two other samples.

To correct for the first effect, MGLa calculated the probability of every system to fall in each bin of Table 2, assuming random orientation in space. To derive a modified distribution, MGLa added up the probabilities of every binary to fall in each bin, the resulting counts denoted by $N_{\rm mod}$.

To correct for the second effect MGLa assumed that the search detects all stars with radial-velocity modulation with semi-amplitude K larger than or equal to the search threshold $K_{\rm min}$ (see Mazeh, Latham & Stefanik (1996) for

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details). $K_{\min}$ strongly depends on the precision per measurement, but also on the number of measurements per star and their temporal distribution. Therefore, the exact values of $K_{\min}$ for each of the samples discussed here are still not well known. For the planet searches MGLb assumed $K_{\min}$ to be 20 m s^{-1}. For the K-star sample they assumed $K_{\min}$ of 1 km s^{-1}.

To calculate the correction factor for each bin, MGLa considered a population of binaries with secondary mass range coinciding with the bin mass range, with a Duquennoy & Mayor (1991) period distribution between 1 and 1500 days. The probability of not detecting a binary was then used to correct for the actual counts of each bin, the results of which are denoted by $N_{\rm cor}$.

The estimated error of the first three bins is the square root of the modified number of systems in that bin, multiplied by the correction factor. For the K-star and the H-P-M samples one has to take into account the scaling factors too. The 'corrected' histogram is given in Table 2 and plotted in Figure 1.

Table 2. The 'Corrected' Mass Distribution

Mass Range ($M_{\rm Jup}$)	# of systems	$N_{\rm scl}$	$N_{\rm mod}$	Corr. factor	$N_{\rm cor}$
Planet candidates:					
$-0.5 \le \log M \le 0.$	3	3.0	1.6	2.2	3.6 ± 2.8
$0. \le \log M \le 0.5$	3	3.0	2.7	1.1	2.9 ± 1.8
$0.5 \le \log M \le 1.$	3	3.0	2.6	1	2.6 ± 1.6
$1. \le \log M \le 1.5$			1.5	1	1.5 ± 1.2
K-star sample:					
$1. \le \log M \le 1.5$	2	0.7	0.4	3.9	1.6 ± 1.5
$1.5 \le \log M \le 2.$	8+5	4.6	3.1	1.3	4.0 ± 1.4
H-P-M sample:					
$2. \le \log M \le 2.5$	19	9.1			9.1 ± 2.1
$2.5 \le \log M \le 3.$	32	15.2			15.2 ± 3.4

Note that two samples cover the range 10–30 $M_{\rm Jup}$, and both yield very similar estimates. I combined the two estimates together, and plotted 1.5 ± 1.0 at this bin.

4. Two Populations

The corrected combined histogram suggests that we see here two populations. At the high-mass end of the figure we see a steep drop as we move from 1000 to 30 $M_{\rm Jup}$. At the planetary range of masses we see a flat distribution, which might even rise very mildly when we move from, say, 30 to 0.3 $M_{\rm Jup}$. Unfortunately, the number of systems in each bin is extremely small. However, the two different slopes in the two parts of the diagram seem real, as each of the two slopes is spread over three bins, and both slopes are monotonic over their three bins.

The gross features of the combined histogram are independent of the value of $K_{\min}$. For example, changing $K_{\min}$ from 20 to 50 m s^{-1} only made the slope

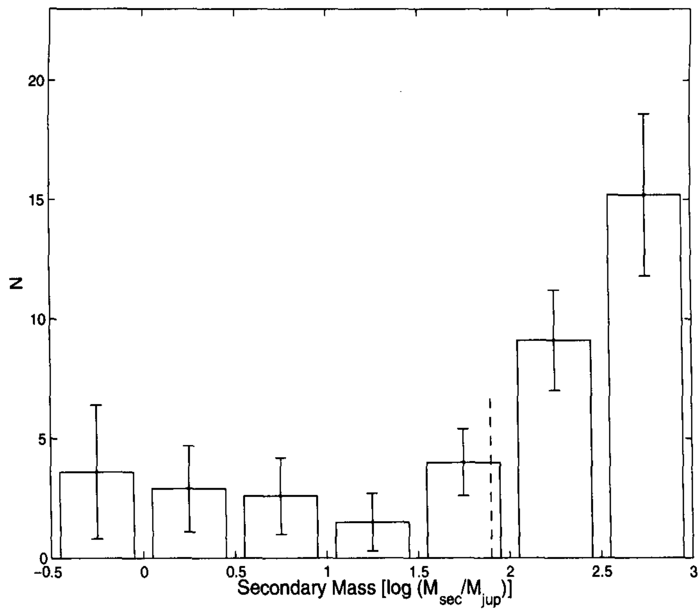

Figure 1. Corrected histogram of the extrasolar planet-candidates and the low-mass secondaries of spectroscopic binaries. The dashed line is the stellar/substellar limit.

at the left hand side of the diagram steeper, but kept the minimum at the same bin, and retained the monotonic nature of both slopes.

The transition region between the two populations is at the bin with minimum counts, at 10–30 $M_{\rm Jup}$. Unfortunately, the relative error of this bin is very large. However, the very low-count estimate in this bin is supported by the fact that the very sensitive searches for planets, which yielded the discovery of the eight new planet candidates, did not find *any* companions with minimum masses between 10 and 30 $M_{\rm Jup}$. With $K_{\rm min}$ of about 20 m s^{-1} these searches could detect more than 99% of the binaries in this bin.

The drop of the secondary mass distribution when moving from 1 to 0.1 $M_\odot$ is consistent with the finding of Halbwachs, Mayor & Udry (1998), who studied the mass *ratio* distribution of spectroscopic binaries in the samples of G and K stars of Mayor et al. (1997). However, the transition region between the two slopes found here is somewhat different from the findings of Mayor, Queloz & Udry (1998) and Mayor, Udry & Queloz (1998). They find a borderline at 7 $M_{\rm Jup}$, while this work suggests a transition at the range of 10–30 $M_{\rm Jup}$. Another difference is the shape of the distribution within the planetary mass range. They find a very steep rising distribution when moving down towards the range of 1–5 $M_{\rm Jup}$. This work finds an almost flat logarithmic distribution, with perhaps a mild rise towards lower masses, depending on the exact value of $K_{\rm min}$.

Let us *assume* that Figure 1 shows indeed two distinctive slopes, corresponding to two different populations, one below and one above 10–30 $M_{\rm Jup}$.

One possible interpretation of the diagram is that the lower-mass population is composed of planets, while the higher-mass population is the low-mass secondaries.

The probable transition region is of astrophysical significance, because it tells us about the lower and upper mass limits of brown-dwarf secondaries and extra-solar planets. These limits, if confirmed, can be confronted with the corresponding formation theories. According to the commonly believed paradigm, the last stage of giant planet formation involves an extensive gas accretion from the disk. Therefore, the upper limit of the planetary masses is set by the interaction between the planets and the gas in the disk (e.g. Artymowicz & Lubow 1994), depending on the disk parameters, like mass, density profile, temperature and viscosity. The lower limit for brown-dwarf secondary masses is set by the binary formation mechanism, whatever that mechanism might be. In the cloud fragmentation scenario, for example, the typical mass of a fragment depends on the Jeans mass of the protocloud. Boss (1988) already noted that the theory of cloud fragmentation predicts the minimum mass for a companion to be about 10 $M_{\rm Jup}$. In fact, Low & Lynden-Bell (1976) estimated already twenty years ago that the minimum Jeans mass for fragmentation of a molecular cloud is 7 $M_{\rm Jup}$. Given the uncertainties in molecular cloud parameters and the challenging computation involved, these figures are consistent with the transition region, at 10–30 $M_{\rm Jup}$, suggested here.

Obviously, we need many more planet candidate detections to confirm the two slope diagram suggested here. Hopefully, the new high-precision surveys now in high gear will supply many more planet candidates in the near future. If the transition found here is confirmed, mass is indeed a reliable parameter to distinguish between brown-dwarf secondaries and extra-solar planets.

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Discussion

Mayor: We observe a mass function clearly indicative of two different populations (planets versus stars). But taking into account the astrometric orbital plane angles derived from Hipparcos data, what we now observe is a much clearer separation between these two populations with an almost complete absence of objects in the range of 10 to 40 $M_{\rm Jup}$.

Queloz: What is the metallicity effect on the mass distribution diagram? Might it be a second hidden player (on the right side, metal poor, on the left side metal rich)?

Mazeh: The high-proper-motion sample includes many solar metallicity stars. We checked to see if the secondary mass distribution depends on metallicity and found that it does not.

Scarfe: At the colloquium in Atlanta in 1992 you discussed the mass ratio distribution in spectroscopic binaries. Have the discoveries since then affected the conclusions you drew in that paper?

Mazeh: We have now many more binaries. The secondary mass distribution seems now very similar to that of single stars in the field.

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