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THE MASS DISTRIBUTION OF EXTRASOLAR PLANET CANDIDATES AND SPECTROSCOPIC BINARY LOW-MASS COMPANIONS

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ABSTRACT

Spectroscopic orbits have been reported for nine unseen companions orbiting solar-type stars with minimum possible masses in the range 0.5–10 Jupiter masses. We compare the mass distribution of these nine planet candidates with the distribution of low-mass secondaries in spectroscopic binaries. Although we still have only a very small number of systems, the two distributions suggest two distinctive populations. The transition region between the two populations might be at the range of 10–30 Jupiter masses.

Subject headings: binaries: spectroscopic — planetary systems

1. INTRODUCTION

Eight candidates for extrasolar planets have been announced over the past two years (e.g., Marcy & Butler 1998). In each case, very precise stellar radial velocity measurements, with a precision of about 10 m s^{-1} or better, indicated the presence of a low-mass unseen companion orbiting a nearby solar-type star. The individual masses of the eight companions are not known, because the inclination angles of their orbital planes relative to our line of sight could not have been measured. The minimum masses for the eight candidates, attained for an inclination angle of 90°, are in the range 0.5–7.4 Jupiter masses (M_J). These findings render the eight companions to be giant planets or at least "planet candidates."

The detections of these eight companions were announced 7–9 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 (1996a) have shown that the minimum mass for the companion of HD 114762 is 9.4 M_J. 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 mass, period, and discovery date of the nine objects. For random orbital orientations, the expectation value for sin i is 0.76, so the actual masses of the nine companions are expected to be in the range of 0.6–12 M_J.

The nature of the newly discovered low-mass companions is not yet clear. They could be planets, as suggested by various authors (e.g., Marcy & Butler 1998), or many could just be brown-dwarf secondaries, formed in binary stars (Black 1997). With the small but not insignificant number of spectroscopic orbits implying planetary minimum masses, we can now begin to study the distribution of their orbital parameters in order to address this very basic question.

In this Letter we discuss the emerging difference between the *mass* distribution of planet candidates and the low-mass end of the distribution of binary secondaries. This point has been already discussed by previous studies (Basri & Marcy 1997; Mayor, Queloz, & Udry 1998a; Mayor, Udry, & Queloz 1998b; Marcy & Butler 1998), but in those papers the mass distribution was binned linearly. Here we choose to use a logarithmic scale to study the mass distribution, because of the large range of masses, 0.5–300 M_J, 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.

This work is based on an extremely small sample, and the validity of our results will need to be verified by many more detections. However, if verified, the difference in mass distributions that we find might provide an important clue for how to distinguish between planets and low-mass stellar companions.

A preliminary version of this work was presented at the meeting "Physical Processes in Astrophysical Fluids," in Haifa, 1998 January (Mazeh 1998).

2. COMBINED MASS DISTRIBUTION

We wish to consider the mass distribution of the planet candidates and compare it with that of the low-mass secondaries in spectroscopic binaries. To do so we use the results of two very large radial velocity studies of spectroscopic binaries recently completed, for which partial results have been published. One sample is composed of G and K stars studied by Mayor et al. (1997), and the other is the Carney & Latham (1987, hereafter CL) high proper motion sample. We will use the first sample to estimate the mass distribution in the mass range $1 \leq \log(M/M_J) \leq 2$, and the latter sample to estimate the value of the distribution in the range $2 \leq \log(M/M_J) \leq 2.5$.

Mayor et al. (1997) listed 10 spectroscopic binaries with minimum secondary masses in the range 10–63 M_J. Their list includes only two systems in the range $1 \leq \log(M/M_J) \leq 1.5$ and eight systems in the range $1.5 \leq \log(M/M_J) \leq 2$. We note that their list does not cover the second range completely, because the table of Mayor et al. does not include binaries with minimum secondary masses between 63 and 100 M_J. Mayor et al. were kind enough to let us know that they have found five additional binaries in the range of 63–100 M_J (J.-L. Halbwachs 1997, private communication).

Detailed results for the CL sample are not yet published, but partial results were presented in two conference papers (Latham et al. 1998; Mazeh, Goldberg, & Latham 1998). Mazeh, Goldberg, & Latham divided the sample into two subsamples, with

TABLE 1

The Planet Candidates

Name	$M_2 \sin i$ (M_J)	P (days)	Discovery Date	Reference
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

References.—(1) Latham et al. 1989; (2) Mazeh et al. 1996a; (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.

TABLE 2

The Scaled Mass Distribution

Mass Range (M_J)	Number of Observed Systems	Scaling Factor	N_{scl}
$-0.5 \le \log(M) \le 0.$	3		3
$0. \le \log(M) \le 0.5$	3		3
$0.5 \le \log(M) \le 1.$	3		3
$1. \le \log(M) \le 1.5$	2	200/570	0.7
$1.5 \le \log(M) \le 2.$	8 + 5[a]	200/570	4.6
$2. \le \log(M) \le 2.5$	20	200/420	9.5

[a] Unpublished data (J.-L. Halbwachs 1997, private communication).

high- and low-mass primaries. We use here only the high-mass primary subsample, with primary masses between 0.7 and 0.85 $M_\odot$, because they are more similar to the primaries in the other samples considered here. From Figure 1 of Mazeh, Goldberg, & Latham we can estimate the number of systems with secondary masses in the range $2 \le \log(M/M_J) \le 2.5$ to be 20.

The results of the two samples of spectroscopic binaries have 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 parent samples in which the planets were found are not well defined. The nine planets were discovered by different research groups, with different time coverage and slightly different precision (e.g., Marcy & Butler 1998). For the present discussion we will *assume* that the total number of stars searched was 200. This has to be compared to the 570 stars of Mayor et al. (1997) and 420 stars of the subsample of high-mass primaries of the CL sample (Mazeh et al. 1998). The results are summarized in Table 2, where N_{scl} is the number of binaries, scaled to a sample of 200 systems. The combined scaled histogram is plotted in Figure 1.

3. ESTIMATE OF THE CORRECTED DISTRIBUTION

Before considering the possible interpretation of the combined histogram, we have to correct the histogram 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 secondary is most probably larger. The correction of this effect tends to shift the distribution toward the right side of Figure 1. The second effect reflects the fact that binaries with too small amplitudes 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 detected in bins with small masses, while the effect is negligible for bins with large masses. Both effects were taken into account in the work of Mazeh et al. (1998), so we need to correct only the counts of the two other samples.

To correct for the first effect we calculated the probability of each system to fall in each bin of the histogram, assuming random orientation in space. To derive a modified histogram we added up the contributions of each binary to each bin of the histogram, denoting the resulting counts by N_{mod}.

To correct for the second effect we consider the probability of *not* detecting a binary or a planet in a systematic radial velocity search (see Mazeh et al. 1996a for details). Suppose that the search detects all stars with radial velocity modulation with a period P between P_{min} and P_{max}, and with semiamplitude K larger than or equal to the search threshold K_{min}. For given primary and secondary masses, and for a given orbital period, all systems with an inclination smaller than some threshold inclination *cannot* be detected, because K is smaller than K_{min}. We can therefore calculate $U[K_{min}](P, M_1, M_2)$—the probability of *not* detecting a binary by a search with a given threshold K_{min}, assuming random orientation in space (e.g., Mazeh & Goldberg 1992).

To get the probability of *not* detecting a binary taken at random from a population of binaries, with given *range* of secondary masses and periods, we have to integrate $U[K_{min}](P, M_1, M_2)$ over the given parameters of the population. We will then get $U[K_{min}](M_1)$, which presents the probability of not detecting a binary, averaged over the secondary masses and period domains.

To correct for the undetected binaries, we have to multiply the number of systems in each bin by the corresponding

$$C = \left(1 - U[K_{min}]\right)^{-1}, \tag{1}$$

where we have dropped the dependence on M_1.

The main parameter here is K_{min}, which in turn 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 we will assume that K_{min} is twice the precision per

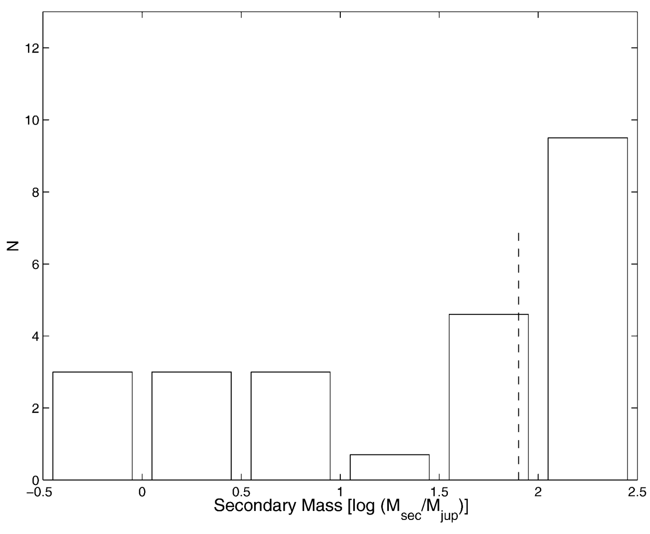

Fig. 1.—Scaled histogram of the extrasolar planet candidates and the low-mass secondaries of spectroscopic binaries. The dashed line is the stellar/substellar limit.

TABLE 3

ESTIMATED CORRECTED MASS DISTRIBUTION

Mass Range (M_J)	N_{mod}	Correction Factor	N_{cor}
Planet Search			
$-0.5 \leq \log(M) \leq 0.$ ……	1.6	2.2	3.6 ± 2.8
$0. \leq \log(M) \leq 0.5$ ……..	2.7	1.1	2.9 ± 1.8
$0.5 \leq \log(M) \leq 1.$ ……..	2.6	1	2.6 ± 1.6
$1. \leq \log(M) \leq 1.5$ ……..	1.5	1	1.5 ± 1.2
Mayor et al. Sample			
$1. \leq \log(M) \leq 1.5$ ……..	0.4	3.9	1.6 ± 1.5
$1.5 \leq \log(M) \leq 2.$ ……..	3.1	1.3	4.0 ± 1.4
Carney & Latham Sample			
$2. \leq \log(M) \leq 2.5$ ……..	…		9.5 ± 2.1

measurement. This means that any binary with a peak-to-peak variation larger than $2K_{\mathrm{min}}$, or 4 times larger than the error per measurement of the survey, was detected. We therefore assume K_{min} to be 20 m s^{-1} for the planet search. For the Mayor et al. sample the detection threshold is larger than twice the precision per measurements (J.-L. Halbwachs 1997, private communication), so we will assume, somewhat arbitrarily, K_{min} of 1 km s^{-1}.

To calculate the correction factor for each bin of the histogram, we 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. We then applied the correction derived to the modified counts in each bin to get N_{cor}. We estimated the error in each of the first three bins by the square root of the modified number of systems in each bin, multiplied by the correction factor. For the Mayor et al. sample we took into account the fact that the original sample was larger by 570/200, so the *relative* errors for these two bins are smaller by the square root of this scaling factor. The "corrected" histogram is given in Table 3.

Note that both samples cover the range $1. \leq \log(M/M_J) \leq 1.5$, both of which yielded very similar estimates. When plotting the corrected histogram in Figure 2 we combined the two estimates together and got 1.5 ± 1.0 for this bin.

4. DISCUSSION

The corrected combined histogram might suggest that we see here two populations. At the high-mass end of the histogram we see a distribution that drops steeply when we move from 200 to 20 M_J. At the planetary range of masses we see a flat distribution, which might even rise very mildly when we move from, say, 20 to 0.6 M_J. Unfortunately, the number of systems in each bin is small. However, the two different slopes in the two parts of the diagram seem real, since they are based on more than one bin.

The derived diagram depends on two parameters—K_{min} and the number of bins of the histogram. We got the same gross features—namely, two opposite slopes in the two parts of the diagram—when we changed the values of these two parameters. Dividing the total range of the diagram into five or four bins instead of six bins shifted the transition region between the two slopes somewhat to the right. Changing K_{min} from 20 to 50 m s^{-1} made the slope at the left-hand side of the diagram steeper. We conclude, therefore, that the overall shape of the diagram does not depend strongly on the specific values of the parameters of the derivation.

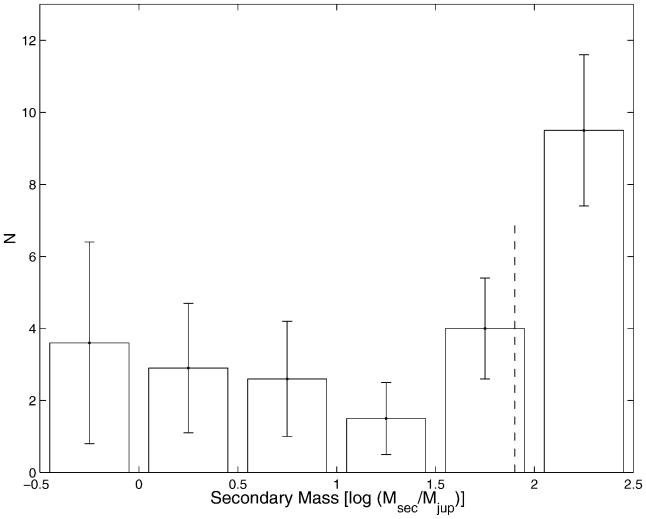

FIG. 2.—Corrected histogram of the extrasolar planet candidates and the low-mass secondaries of spectroscopic binaries. The dashed line is the stellar/substellar limit.

The transition region between the two populations is at about 10–30 M_J. Unfortunately, the relative error of this bin is very large. Nevertheless, it seems that this is the bin with the smallest number of systems. 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_J. With K_{min} of 20 m s^{-1} these searches could detect more than 99% of the binaries in this bin. The fact that no precise search discovered any binary in this bin indicates that the number of systems with secondary masses between 10 and 30 M_J is very small.

The drop of the secondary mass distribution we find when moving from 200 to 20 M_J 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). Halbwachs, Mayor, & Udry found a flat histogram of the mass ratio, although they could not exclude increasing or decreasing power laws of the form q^{α}, where q is the mass ratio and $-0.82 \leq \alpha \leq 0.87$. The flat distribution of q yields constant dN/dm_2, if all primary masses are similar. This corresponds to $dN/d\log(m_2) \propto m_2$, consistent with our findings. The drop we find is also consistent with the findings of Mayor et al. (1998a; see also Mayor et al. 1998b), who found that $dN/dm_2 \propto m_2^{-0.4}$. Their result corresponds to $dN/d\log(m_2) \propto m_2^{+0.6}$. Figure 2 of this work suggests a steeper drop, but the difference is within the errors.

The transition region between the two populations, or between the two slopes, that we find here is, however, different from the findings of Mayor et al. (1998a, 1998b). They find a borderline at 7 M_J, while our logarithmic treatment of the data suggests a transition region at the range of 10–30 M_J. Another difference is the shape of the distribution in the planetary mass range. They find a very steep rising distribution when moving down toward the range of 1–5 M_J. We find an almost flat logarithmic distribution, with perhaps a mild rise toward lower masses, depending on the exact value of K_{min}.

Let us *assume* that Figure 2 indeed shows two distinctive slopes in the two parts of the diagram. Let us further *assume* that this reflects the fact that we see here two different populations, one below 10–30 M_J, and one with masses larger than this transition region. One possible interpretation of the diagram, if indeed we see here two different populations, is that the two populations were formed differently. Maybe the lower mass population was formed like planets, out of an accretion disk, while the higher mass population was formed like binary stars, in a mechanism that probably involves large-scale gravitational collapse (e.g. Boss 1996; Black 1986). If this is the case, then the binary secondaries include stars and brown dwarfs together.

Figure 2 suggests that the transition region between the two populations is at about 10–30 M_J. This is of astrophysical significance, if indeed the lower mass population is composed of planets, since it might tell us about the lower limit and upper limit of the formation of secondaries and planets, respectively (Marcy & Butler 1995, 1998; Mayor et al. 1998a, 1998b). The upper limit of the planetary masses is set by the conditions in the accretion disk, and most probably by the interaction between the planet and the gas and dust in the disk. Boss (1996) already noted that Lin & Papaloizou (1980) theoretically predicted that the maximum mass for the formation of a planet in the disk of the Solar nebula is about 1 M_J. As the maximum mass depends on the mass of the early nebula, we can get somewhat higher masses in different cases. The lower limit for secondary masses in binaries is set by the binary formation mechanism, whatever that mechanism might be. Boss (1988), for example, noted that the theory of opacity limited cloud fragmentation predicts that the minimum mass for a companion is about 10 M_J. In fact, Low & Lynden-Bell (1976) estimated 20 years ago that the minimum Jeans mass for fragmentation of a molecular cloud is 7 M_J. Silk (1977), in a contemporaneous study, came up with minimum masses between 10 and 100 M_J, depending on the shape of the collapse. If we indeed see the transition region between the two populations at about 10–30 M_J, this is not too far from the predictions of the theories.

Duquennoy & Mayor (1991; see also Mayor et al. 1998a) have suggested that the observed orbital eccentricities can be used to distinguish between planets and stellar companions. However, Mazeh, Mayor, & Latham (1996b), when discussing the eccentricity versus mass of the known planet candidates, pointed out that the planet-disk interaction (e.g., Goldreich & Tremaine 1980) is a possible mechanism for generating a strong dependence of eccentricity versus mass (Artymowicz 1992; Lubow & Artymowicz 1996), at least for moderate eccentricities. This possibility can undermine the potential of the eccentricity-mass dependence to distinguish between planets and secondaries. 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 too early to distinguish between brown dwarfs and planets solely on the basis of their orbital eccentricity.

Mazeh et al. (1996b) speculated that “The 10–40 M_J mass gap may prove to be critical for the interpretation of” the eccentricity-mass dependence. We confirm here that the transition region between the two populations could be at this range of masses.

Obviously, the left-hand side of the histogram and the transition region between the two slopes derived in this Letter are based on a very small number of objects all together, and these features need to be verified by many more detections. Further, one still needs to make sure that the different slope in the planetary-mass range is not caused by some selection effects. For example, there might be a correlation between the orbital period and the secondary mass, which might make the small-mass secondaries easier to detect. Such an effect could cause the histogram to appear to rise toward smaller mass. However, if the shape of the histogram can be verified, and if the planetary-mass objects prove to be extrasolar planets, the shape of the histogram might give us the long-sought clue for how to distinguish planets from low-mass stellar companions.

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