The Formation of Binary Stars
IAU Symposium, Vol. 200, 2001
H. Zinnecker and R. D. Mathieu, eds.

Comparison between Extrasolar Planets and Low-Mass Secondaries

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Abstract. This paper compares the statistical features of the sample of discovered extrasolar planets with those of the secondaries in nearby spectroscopic binaries, in order to enable us to distinguish between the two populations. Based on 32 planet candidates discovered until March 2000, we find that their eccentricity and period distribution are surprisingly similar to those of the binary population, while their mass distribution is remarkably different. The mass distributions definitely support the idea of two distinct populations, suggesting the planet candidates are indeed extrasolar planets. The transition between the two populations probably occurs at 10–30 Jupiter masses. We point out a possible negative correlation between the orbital period of the planets and the metallicity of their parent stars, which holds only for periods less than about 100 days. These short-period systems are characterized by circular or almost circular orbits.

1. Introduction

In the last few years we are witnessing a burst of discoveries of candidates for extrasolar planets (for a recent review see Marcy, Cochran, & Mayor 2000, hereafter MCM). 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 minimum masses, which are of the order of a Jupiter mass ($=M_{Jup}$).

This identification is based on the commonly accepted notion that planet masses are substantially smaller than those of stars. Some works go even further and *define* a planet as an object with mass smaller than 13 M_{Jup}— the minimum mass needed to ignite deuterium in its core. This definition goes hand in hand with the definition of a brown dwarf as an object that does not burn hydrogen in its core, and therefore has a mass less than about 80 M_{Jup}. The mass-based definition of a planet became so popular, that some astronomers used it without requiring a planet to orbit another star. This is reflected, for example, in the title of a recent paper *A Population of Very Young Brown Dwarfs and Free-Floating Planets in Orion* by Lucas & Roche (2000).

Obviously, we can arbitrarily adopt any definition for any term. However, we usually expect a good definition to carry along any previous understandings

https://doi.org/10.1017/S0074180900225631 Published online by Cambridge University Press

of the term. Planets were conceived in the past as objects orbiting the Sun — a feature completely missing from the mass definition of a planet. Actually, one of the first works to suggest this distinction was that of Burrows et al. (1997), who emphasized that this distinction was arbitrary for "parsing by eye the information in the(ir detailed) figures", and they did not "advocate abandoning the definition based on origin".

We therefore suggest a somewhat hypothetical, open-ended definition, which is based on two notions. The first one is indeed that planets must orbit their parent stars. This immediately raises the question of how to distinguish between planets and low-mass secondaries in binary systems. We therefore suggest that the definition includes a second notion, based on the seemingly accepted paradigm that planets, including giant planets like Jupiter, were formed differently than stars. The present picture is that planets were probably formed by coagulation of smaller, possibly rocky, bodies, while stars were probably formed by some kind of fragmentation of larger bodies. In other words, planets were formed by small bodies that grew larger, while stars, binary included, were formed by fragmentation of large bodies into smaller objects. Therefore, according to the proposed definition, a planet is a low-mass object formed differently than a star, orbiting a much larger star. Note that this definition does not include *a priory* the planet mass, a specific mass limit in particular.

The formation notion, if true, probably allows us to differentiate *statistically* between giant planets and low-mass secondaries. A population of planets might show some statistical features different than the ones found in low-mass binaries, reflecting the difference in formation history. Finding such differences in observed samples can verify the formation aspect of the definition, which, at this stage of the research of extrasolar planets, is still only an assumption. Therefore, this paper adopts a purely observational approach and checks whether such distinguishing characteristics can be found, refraining from any theoretical discussion of their origin.

We could expect, for example, that the distribution of orbital eccentricities of giant planets and low-mass binaries will be substantially different, because all the solar planets have nearly circular orbits, while binaries do not (e.g., Mazeh, Mayor, & Latham 1996). Or, we could expect the periods of planets to be longer than 10 years, like the giant planets in the solar system. Many studies of the newly discovered planets showed that this is not the case (e.g., MCM). Moreover, following Heacox (1999) who based his analysis only upon 15 binaries and a handful of planet candidates, we will show that within some reasonable restrictions, the eccentricity and period distributions of the two samples are surprisingly similar. On the other hand, the mass distributions of the planet candidates and the low-mass secondaries are well separated (e.g., Marcy & Butler 1998), definitely suggesting the existence of two populations. At the same time the very different mass distributions validate the original notion of mass difference. The border zone between the two populations could be demarcated in the near future when more data are available.

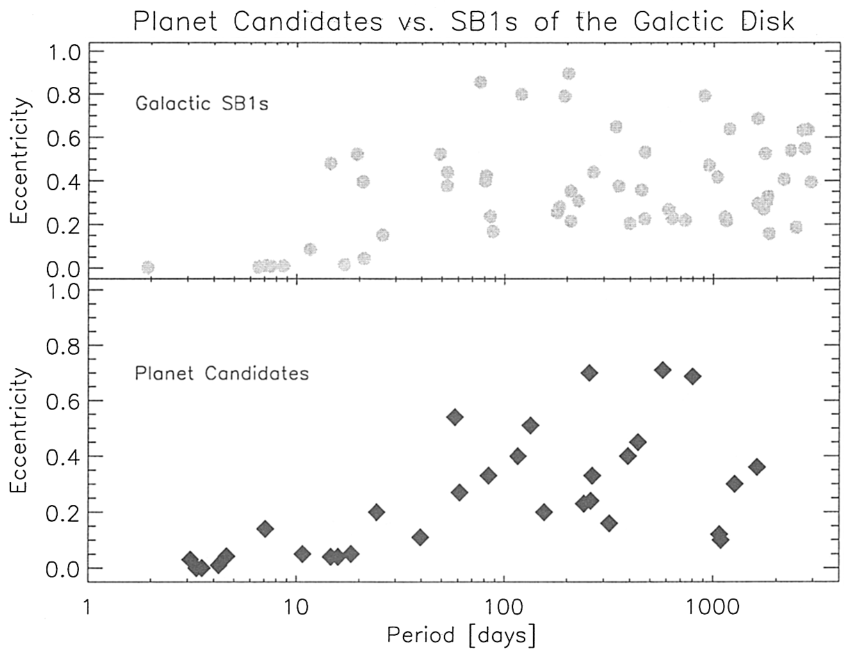

Figure 1. The eccentricity as a function of the orbital period for the Galactic disk SB1s and the planet candidates.

2. Eccentricity and Period Distribution

We consider here the 32 planet candidates that were discovered until March 2000 (Schneider 2000), comparing their orbital characteristics with those of spectroscopic binaries. For the latter we use the results of a very large radial-velocity study of the Carney & Latham (1987) high-proper-motion sample, which yielded 200 spectroscopic binaries (Latham et al. 2000; Goldberg et al. 2000). Goldberg (2000) succeeded to separate statistically between the binaries of the Galactic halo and those coming from the disk. We consider in this section only the 59 single-lined spectroscopic binaries (=SB1s) of the Galactic disk.

In Figure 1 we present the eccentricity-period relation for the two samples. In both samples all the short-period binaries have circular or almost circular orbits. Nevertheless, it seems as if there is some subtle difference in the way this effect is revealed in the two samples. At the upper panel there is a clear division; all binaries with periods shorter than 10 days are practically circular, while binaries with longer periods show considerable eccentricities. In the planet candidate sample we find high eccentricities, above 0.2, only with periods longer than 50 days. Orbits with shorter periods do not have high eccentricities, although some of the orbits are not completely circular. The difference between the two samples is certainly not well established statistically, and we need many more planet candidates to assess its reality.

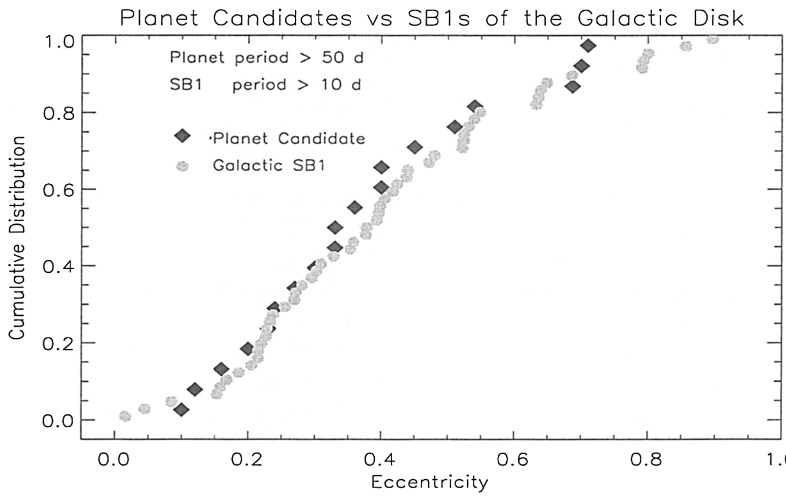

Figure 2. The eccentricity cumulative distribution of the planet candidates and the Galactic disk SB1s.

Apparently, some tidal interaction circularized or nearly circularized the orbits of the short period systems in both samples. Although the exact mechanism is not yet clear (e.g., Zahn & Bouchet 1989, Goldman & Mazeh 1991, Goodman & Oh 1997), the cutoff shape of the SB1s is well explained. The eccentricity distribution of the planet candidates, if different from that of the SB1s, is more difficult to interpret, and has probably to do with the orbital evolution that these systems have gone through (e.g., Wiedenschilling & Marzari 1996; Lin et al. 2000; Trilling 2000)

Next, we consider the eccentricity distribution of the uncircularized orbits of the two samples. To do so we plot in Figure 2 the eccentricity cumulative distribution of the two samples, with periods longer than 10 days for the SB1 sample and with periods longer than 50 days for the planet candidates. The result, first noted by Heacox (1999) who based his analysis only upon 15 binaries, is astounding. The two populations have practically the same distribution, at least for most of the eccentricity range. Stepinski & Black (2000, a poster paper in this meeting) who used Heacox small sample of binaries, and Mayor & Udry (2000) came to similar conclusions.

In the upper panel of Figure 3 we compare the *period* distribution of the two samples. The two distributions run parallel for most of the period span, which indicates the same density distribution. To emphasize this point we exclude binaries with period shorter than 7 days or longer than 1650 days from both samples and plot in the lower panel the two restricted distributions, which turn out to be the same. Moreover, as noted already by Heacox (1999), the figure shows that the two distributions, when plotted here on a logarithmic scale follow strictly a straight line, which indicates flat density distributions on a logarithmic scale. Stepinski & Black (2000) came to similar conclusion.

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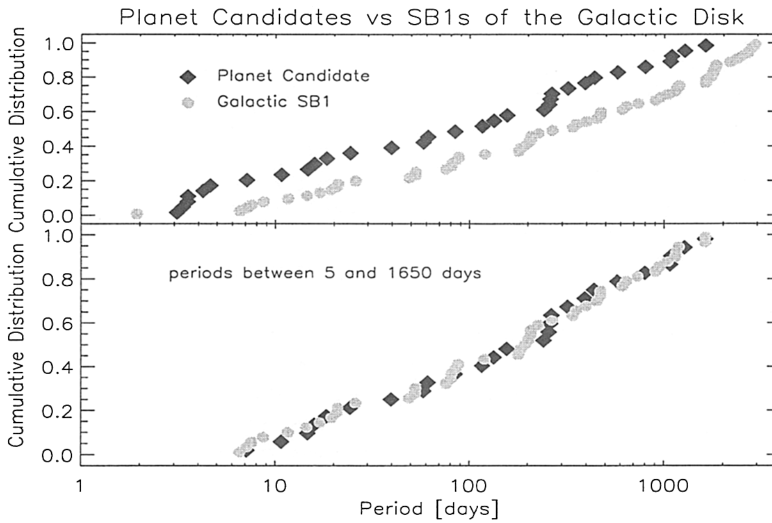

Figure 3. The period cumulative distribution of the planet candidates and the Galactic disk SB1s. See text for the two panels.

Any paradigm that assumes the two populations were formed differently has to explain why their eccentricity as well as period distributions are so much alike. One might wonder are they really two separate populations. However, any such doubt can be put to rest by considering the mass distribution, as is done in the next section.

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

In Figure 4 we present two separate mass histograms, one of the SB1s and the other of the planet candidates. We follow, with some slight modifications, the derivations of Mazeh, Goldberg, & Latham (1998, hereafter MGL) and of Mazeh (1999a,b), which were done with a substantially smaller sample of planet candidates. The detailed derivation is explained in those papers. In short, the *observed* histograms are modified so they take into account two effects. The first has to do with the unknown inclination angles of most of the systems, which allow the observer to derive only the minimum masses of the unseen companions. The second effect reflects the fact that the observers cannot detect radial-velocity modulation with a too small amplitude, either because of the low orbital inclination or because of the smallness of the secondary mass. To be able to compare the two distributions, which are spread over more than three orders of magnitudes, it is important to present the data on a logarithmic scale.

The last two bins of the SB1s histogram, with masses larger than 100 M_{Jup}, were derived from a subsample of the high-proper-motion binaries drawn from a sample of 420 primaries with masses higher than 0.7 $M_\odot$ (Latham et al. 2000; Goldberg et al. 2000). The other two bins, between 10 and 100 M_{Jup}, could not be derived from that radial-velocity survey, because of lack of sensitivity. The

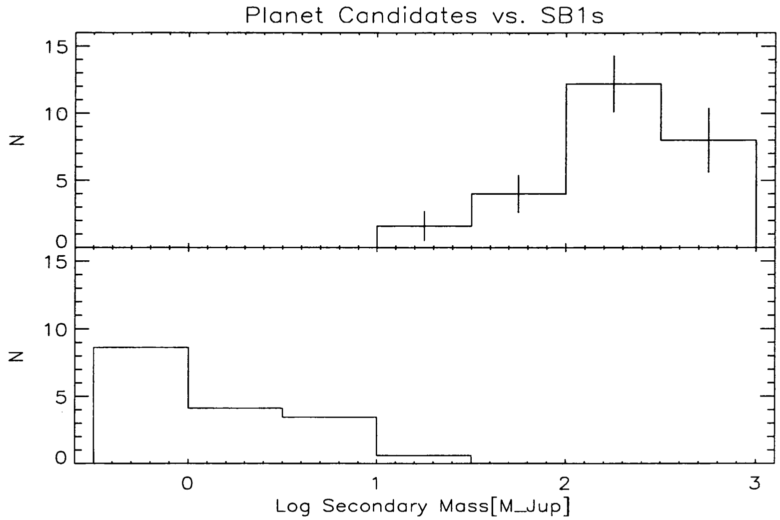

Figure 4. Corrected histograms of the extrasolar planet candidates and the low-mass secondaries of spectroscopic binaries. Upper panel for the SB1s. Lower panel for the planet candidates. Both scaled for a sample of 200 stars

histogram is based, instead, on the work of Mayor et al. (1997), who studied a sample of 570 nearby K stars (see also Halbwachs, Mayor & Udry 1998). Mayor et al. were kind enough to let MGL know that they have found 5 additional binaries in that range. The two sets of binaries were drawn from samples of different sizes. We therefore scaled both pairs of bins to a sample size of 200 systems, the number of stars included in the first phase of the planet search.

Note that the numbers of stars in the 10–30 M_{Jup} bin, and even in the 30–100 M_{Jup} one, are *statistically indistinguishable from zero*, consistent with the idea of a "brown-dwarf desert" (e.g., Halbwachs et al. 2000). They used Hipparcos data and concluded that some of the systems in these bins might have masses larger than 0.08 $M_{\odot}$ — the stellar border line, turning these 'brown-dwarf candidates' into stellar companions. In any event, the secondary frequency, which rises when moving from, say, 1000 $M_{Jup}(\simeq 1M_{\odot})$, to 300 M_{Jup}, drops down very sharply and gets to very low values at the range of 30–100 M_{Jup}.

The other histogram includes all the published and announced planet candidates, until March 2000. This sample is obviously incomplete, as no research group exhausted the planet discoveries in the sample they are following. In particular, the stars with low-amplitude variations are still being monitored so their periodic modulation can be verified. This complicates the correction of the two observational effects that we apply to the observed histogram. In order to proceed we choose to *assume* that the samples of the announced planet candidates are complete up to 40 m s^{-1}. Although we have no doubt that this assumption does not represent accurately the present status of the various studies, it nevertheless enables us to *estimate* the selection effect and correct for it. Obviously, we excluded from the sample HD 177830, which has an amplitude smaller than this arbitrary threshold.

We further assume that there are two phases of the planet candidate surveys. At the first phase the research groups of Marcy et al. and Mayor et al. monitored about 200 stars, out of which 8 planet candidates were found. We assumed this phase is close to completion. The other phase includes about 1000 additional stars, but, on the other hand, many more planets are expected to be found in these samples, so the scaling factor of this phase is not well known. We therefore *assumed arbitrarily* that the new planet candidates came from a sample of 400 stars and averaged and scaled the results of the two phases accordingly. The results of the calculation are presented in the lower panel of the figure.

Obviously, all these approximations cannot but obscure the frequency of the planet candidates and the exact shape of their mass distribution. This is why we choose not to assign any error bars to the various bins. The only two goals of the derivation of the histogram are to estimate the mass distribution *slope*, or rather the *direction* of the slope, and the mass distribution boundaries. Although there are still many unknown factors, we suggest that these two features of the distribution are already clear. As concluded by many studies (e.g., Mayor & Udry 2000) the planet candidates are not part of the low-mass tail of the secondary mass. They compose a different population, well separated on the mass axis, and therefore can be related to as proper planets. We find that the planet mass distribution starts with very low values at the 30–100 M_{Jup} region, and rises steeply, even on a logarithmic scale, towards Jupiter and sub-Jupiter mass range. Stepinski & Black (2000) got a different slope for the planet mass distribution, probably because they took a conservative stand and did not correct for the undetected systems.

4. Metallicity

In this section we turn our attention to the metallicity of the stars around which the planets have been discovered. Most of these stars exhibit metallicity higher than that found in the solar neighbourhood (Gonzalez 1997; Marcy & Butler 1998; Queloz et al. 2000; Gonzalez 2000; Butler et al. 2000). Queloz et al. (2000) and Butler et al. (2000) further pointed out that the host stars to the "51 peg like" planets are particularly metal-rich. In this section we further study the dependence of the metallicity on their orbital period, a dependence plotted in Figure 5.

Whenever available we have used metallicity derived from spectral analysis of the stars, mostly from the seminal work of Gonzalez (2000). Mazeh et al. (2000) derived the metallicity of HD 209458. Whenever such an analysis was not available, we have used photometric metallicity derived by Giménez (2000). The metallicities of the stars not considered by Giménez was derived by us following his prescription, based on the photometry of Hauck & Mermilliod (1998) and the calibrations calculated by Crawford (1975) and Olsen (1984). Following Giménez (2000), we did not include in the plot GJ876 and HD177830, for lack of data. Like in Giménez (2000), HD114762 was excluded because of its extremely low metallicity, and 55 Cnc and 14 Her because of their extremely high δc_1. Actually, inclusion of the last three stars would only enhance the effect suggested here.

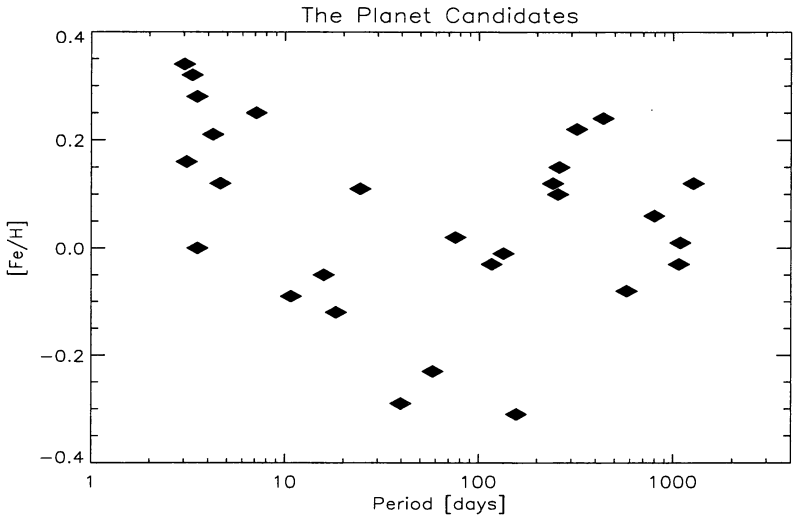

Figure 5. The metallicity of the parent stars of the extrasolar planets as a function of their orbital period

The figure suggests that the planet candidates with periods shorter than about 100 days show negative correlation between the metallicity of their host stars and their orbital period. This correlation disappears when we consider the planet candidates with longer periods. Although the effect is still not established to high statistical significance, we find this conjecture intriguing, as Section 2 finds a division between the almost circular planets and the eccentric ones at about the same period.

5. Conclusion

The logarithmic mass distribution derived here shows that the planet candidates are indeed a separate population, probably formed in a different way than the secondaries in spectroscopic binaries. Surprisingly the eccentricity and period distribution, with some restriction, are very much the same.

Furthermore, the two period distributions follow strictly a straight line. This indicates flat density distributions on a logarithmic scale, inconsistent with the Duquennoy and Mayor (1991) log-Gaussian distribution. Interestingly, flat logarithmic distribution is the only scale-free distribution, and could be argued to be the most simple distribution. Maybe the two populations were formed by two different mechanisms that still have this free-scale feature in common (Heacox 1999).

In the last section we present some evidence that the orbital period of the planets anti-correlates with the metallicity of their host stars. The aim of this section is to draw the community attention to this *possible* intriguing division, in order to fertilize further discussion. One interpretation of this *possible* effect is that the planets polluted the stellar atmospheres with heavy atoms from the early-phase accretion disks when they migrated towards the star. Another interpretation is that the stars with higher metallicities tend to form planets

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more easily. The metallicity can further influence the distance at which the planet is formed or the distance into which the planet migrates. In any case, if this effect is confirmed, it is interesting that it holds only for the close-in planets, for which we do not find orbits with large eccentricities.

Obviously, we need many more planet detections to confirm *each* of the features suggested here . Hopefully, the new high-precision surveys now in high gear will supply many more planets in the near future, unraveling the still hidden characteristics of the extrasolar planets.

Acknowledgments. We wish to thank D. Goldberg, D. W. Latham, M. Lecar and R. Noyes for many helpful discussions, and G. Torres for very illuminating comments on the manuscript. This research was supported by grant no. 97-00460 from the United States-Israel Binational Science Foundation (BSF), Jerusalem, Israel.

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