Microlensing 2000: A New Era of Microlensing Astrophysics
ASP Conference Series, Vol. 000, 2000
J.W. Menzies and P.D. Sackett, eds.

From low-mass star binaries down to planetary systems

S. Udry[1], M. Mayor[1], J.-L. Halbwachs[2], F. Arenou[3]

[1] *Observatoire de Genève, CH-1290 Sauverny, Switzerland*
[2] *Observatoire de Strasbourg UMR 7550, F-67000 Strasbourg, France*
[3] *DASGAL, Observatoire de Meudon, F-92195 Meudon, France*

Abstract. In the context of progress possibly brought by large microlensing surveys in the field of binaries with low-mass stars, long-term radial-velocity surveys of G, K and M dwarfs of the solar neighbourhood are presented. The inferred orbital elements are discussed focusing on the $(e, \log P)$ diagram, the mass-ratio and secondary mass distributions and on the binary frequency of the studied samples. For G and K dwarfs, most of the characteristics pointed out in previous studies are confirmed. The proportion of companions to M dwarfs is not found to be significantly different from the binary frequency among G- and K-dwarf primaries.

The orbital-element distributions and mass function of stellar companions to solar-type stars compared to the equivalent distributions for extra-solar giant planets strongly suggest different formation and evolution mechanisms for the two populations. In particular, the secondary minimum-mass function shows the paucity of companions in the brown-dwarf domain whereas there is a large peak of giant-planet candidates. Other characteristics of the period and eccentricity distributions also point out the different origins of stellar+brown-dwarf and planetary companions to solar-type stars.

1. Introduction

Binary stars are so widespread that we can expect a significant fraction of microlensing events to be affected by stellar duplicity. On the long term, if the number of microlensings of multiple stars is large enough, we have a chance to get new insights into the statistical properties of multiple systems. However, it represents a quite complex effort to derive distribution functions depending on orbital eccentricities, separations, mass ratios, percentages of multiple systems, primary masses, and so on. Probably at the beginning it will be easier to use existing orbital distributions $f(m_1, m_2, e, P, ...)$ derived from classical approaches like spectroscopy, astrometry, imagery, common proper motion or interferometry to help understand the data provided by the microlensing events.

Multiple-star lensing events will most frequently appear when the system components are not too far apart. The statistical properties of binaries with semi-major axes less than a few AU ($P \leq 10$ years) are most relevant for microlensing. Moreover, most of the lensing events will result from stars at the lower end of the main sequence or from substellar objects. This paper will thus mainly discuss the orbital distributions derived from spectroscopic binaries at the bottom of the main sequence, and below.

Since about 20 years, systematic searches have been made to determine the distribution of orbital elements of companions to dwarf stars between F7 and M5. The working horses of these RV searches have been the CORAVEL spectrometers (Baranne et al. 1979) in both hemispheres monitoring at a moderate precision ($\sim 250\,\mathrm{ms}^{-1}$) the radial velocities of more than 1000 stars of the solar vicinity. In particular, they have provided an almost complete census of spectroscopic binaries (SB) part of a volume-limited sample of some 570 F7 to K9 dwarf stars (Duquennoy & Mayor 1991; Halbwachs et al. 2000a). The M part of the survey is also bringing new results (Udry et al. 2000a) to be compared with what is obtained for the G-K stars. Improvements of our knowledge on M-dwarf binaries are expected from on-going high-precision RV surveys with ELODIE and FEROS of M dwarfs of the solar close vicinity (Delfosse et al. 1999a).

The surveys will be briefly presented in Sect. 2 and their comparative results discussed in Sect. 3. Binaries detected in systematic long-term searches among the members of open clusters can also provide useful additional information for the mass-ratio distribution, improving the available statistics by combining the data accumulated in clusters and from the field. They are included in the discussion as well. Section 4 discusses the mass function of substellar companions. Giant planets more massive than 0.3 Jupiter masses ($\mathrm{M_{Jup}}$) and with periods shorter than 3 years have been found around $\sim 5\,\%$ of solar-type stars. In the same domain of periods ($P \leq 1000\,\mathrm{d}$), spectroscopic binaries are detected only around 8-9 % of low-mass stars. We will present in Sect. 5 the present status of distributions of orbital elements for giant planets. Finally, Sect. 6 will be devoted to the future developments expected in the field of multiple stars.

2. Large radial-velocity monitoring of well-defined dwarf samples

The definition of the survey samples is of prime importance for obtaining unbiased estimates of the binary frequency and the distribution of mass ratios. For field stars, a volume-limited sample is a mandatory condition to avoid the well known over-representation in the mass-ratio distribution of binaries with Δm close to zero. Precise parallaxes provided by the Hipparcos astrometric mission (ESA 1997) have been of fundamental importance in the last years to more carefully redefine the stellar samples.

In the early eighties, systematic RV monitorings were initiated with the two CORAVEL spectrographs (Baranne et al. 1979) for different populations of nearby stars in both hemispheres. The two CORAVEL spectrographs were mounted on the 1-m Swiss telescope at Haute-Provence Observatory (France) and on the 1.54-m Danish telescope at La Silla Observatory (Chile). The modest precision of these instruments of about $0.25\,\mathrm{kms}^{-1}$ have already permitted a binarity study of close dwarf stars, namely the G, K and M dwarfs of the solar neighbourhood. Originally the stars were taken from the *Catalogue of Nearby Stars* (CNS2, Gliese 1969) and from its supplement (Gliese & Jahreiss 1979). They were selected using trigonometric parallaxes derived from on-ground observations, expected to give unbiased volume-limited samples. The results are summarized in following subsections.

2.1. The CORAVEL G- and K-dwarf surveys

The G-dwarf sample. The statistical study of the G-dwarf part of the sample was initially presented in Duquennoy & Mayor (1991, DM91). Thanks to the rich data collected for the nearby stars (visual and astrometric companions, common proper motion stars) this survey is rather complete, at least for the detection of stellar companions. Part of the 269 stars of that sample, a smaller volume-limited subset of 164 stars has allowed DM91 to derive:

1) The distribution of periods on a broad domain. The mode of the distribution $f(\log P)$ appears around 180 years (Fig. 7 of DM91).

2) The distribution of orbital eccentricities as a function of the orbital periods (Fig. 5 of DM91). The main characteristics of the $(e, \log P)$ distribution still hold with additional recent data (see Sect. 3).

3) The distribution of mass ratios $f(q) \equiv f(m_2/m_1)$ for the complete sample (all periods; Fig. 10 of DM91) whose most important characteristics were: a maximum value of the distribution for $q \sim 0.2$ and a declining distribution up to $m_2/m_1 = 1$ (no peak close to $q = 1$). A rediscussion of that material but restricted to SB with periods $P \leq 3000$ days revealed a flat distribution ($f(q) =$ cst; Mazeh et al. 1992). Note that in 1991, the mass distribution for substellar companions was completely unknown.

4) The global percentage of binaries (or multiple stars) in the solar vicinity is close to 2/3.

The combined G+K-dwarf sample. Significant steps towards improved orbital-element distributions for companions to solar-type stars have been brought by the extension of the sample to K dwarfs (Halbwachs et al. 1998), a better definition of the volume-limited sample thanks to the precise Hipparcos parallaxes, the determination of the companion real masses by using Hipparcos astrometric data (Halbwachs et al. 2000b) and the enlargement of the survey span. The final analysis of the combined G-K sample is about to be published (Halbwachs et al. in prep). Some aspects are already presented in Halbwachs et al. (2000a) and the distributions of masses and periods will be further discussed in Sect. 3.

2.2. Spectroscopic binary surveys of M-dwarf stars

Despite the quoted importance of information on very low-mass star duplicity, systematic spectroscopic studies of the binarity of M dwarfs have been very sparse. Few orbital parameters have been derived so far and the binarity frequency was generally estimated from a statistical treatment of the RV variations (Young, Sadjadi & Harlan 1987; Marcy & Benitz 1989). The existing studies suffer from small number statistics and large, uncertain, incompleteness corrections. A broad discussion of binaries with M-dwarf primaries within 20 pc may also be found in Fischer & Marcy (1992).

The CORAVEL M-dwarf surveys. Preliminary results of a long-term RV search for companions of nearby M dwarfs in both hemispheres, with the 2 CORAVEL, have been reported in Udry et al. (2000a). The CORAVEL M-dwarf samples consist of about 450 stars of the solar vicinity. Although not complete yet these surveys are already drastically improving the amount of data available for M-dwarf SB by providing a first set of orbital elements for 31 binaries (among which 23 were previously unknown).

The high-precision M-dwarf surveys. The situation is also improving with the results of a high-precision RV survey initiated by Delfosse et al. (1998a, 1999a) in 1995 with the ELODIE spectrograph (Baranne et al. 1996) at the Haute-Provence Observatory. A systematic RV monitoring of all northern M dwarfs closer than $\sim 10\,\mathrm{pc}$ is in progress. The first unbiased view of the low-mass star duplicity is expected soon. For the moment only a first estimate of the occurrence frequency of short-period M-dwarf binaries is available and can be compared with more massive primaries (see Sect. 3). This survey has nevertheless already been very fruitful by revealing previous unknown companions to our closest neighbours (Delfosse et al. 1999a) and a first planet orbiting the low-mass M4 dwarf Gl 876 (Delfosse et al. 1998b; also found by Marcy et al. 1998). Adding new SB orbits from the high-precision RV surveys (Delfosse et al. 1999abc, Forveille et al. 1999) and from the literature to the CORAVEL data, we have 48 M-dwarf orbits that permit a first qualitative comparison of their orbital properties ((e, $\log P$) diagram) with solar-type star characteristics (see Sect. 3).

A high-precision planet search around M dwarfs in the south has recently been started with FEROS on the 1.5-m ESO telescope at La Silla by the same team, under the leadership of Thierry Forveille. This programme will also provide, as a by-product, useful information on M-dwarf binary characteristics.

2.3. Other on-going large programmes

We can anticipate further significant progresses in the distributions of orbital elements for companions to solar-type stars thanks to other large programmes. For example, a volume-limited survey of $\sim$ 1650 late F to early M dwarfs is on-going at La Silla with the CORALIE spectrograph on the 1.2-m Euler Swiss telescope, at a 5-7 ms^{-1} precision level (Udry et al. 2000b). Already now, a few long-term drifts of RV in the programme have revealed SB of long periods and small amplitudes not detected by previous surveys.

Another very-large RV monitoring of about 3400 G dwarfs has also been initiated a few years ago in order to obtain an unequaled set of orbital parameters for solar-type stars and thus provide a significant improvement on the classical systematic study by DM91. The observational part of the survey has been carried out in the context of a collaboration between the Geneva Observatory, CfA and Tel Aviv University. Preliminary results, mainly on the (e, $\log P$) diagram, are presented in Udry et al. (1998).

Systematic adaptive optics searches for distant companions are also promising progress in the definition of the long-period part of the period distribution.

3. Orbital-elements distributions of companions to solar-type stars

3.1. The (e, $\log P$) diagram

The distribution of orbital eccentricities as a function of periods brings information on formation mechanisms of binaries and their dynamical evolution. The comparison of (e, $\log P$) diagrams of spectroscopic binaries for G-K primaries in

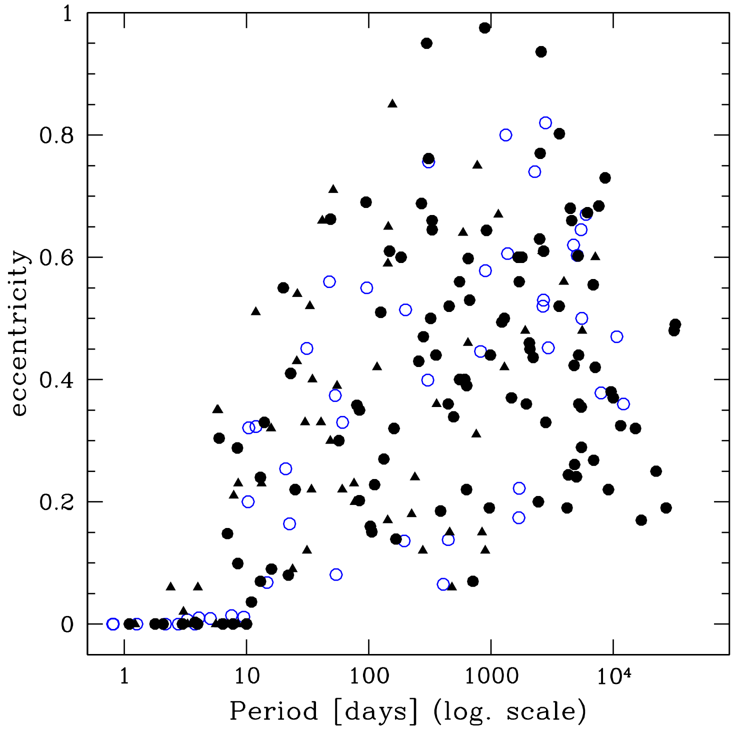

Figure 1. Comparative $(e, \log P)$ diagrams between M dwarfs (open symbols; Udry et al. 2000a) and G+K dwarfs in the field (filled circles; Halbwachs et al. 2000a) and in open clusters (triangles; Mermilliod et al. 1992; Stefanik & Latham 1992; Mermilliod & Mayor 1999)

the field (DM91, Halbwachs et al. 2000a) and in open clusters (Mermilliod et al. 1992; Stefanik & Latham 1992; Mermilliod & Mayor 1999) with the equivalent distribution for M dwarfs (Udry et al. 2000a) is given in Fig. 1. Qualitatively, no fundamental differences are found between the different star populations. The $(e, \log P)$ diagram seems independent from the primary masses. It presents essentially the usual features already pointed out in DM91.

– The short-period SB with $P \leq P_{\rm circ} \simeq 10$ d are circularized by tidal interactions. For stars with convective envelopes, turbulent viscosity retarding the equilibrium tides is the most efficient mechanism for spin-orbit synchronism and circularization through tidal friction (Zahn 1992). The limit is well marked for M dwarfs: the highest period with $e \leq 0.05$ is 9.5 d whereas the smallest period for eccentric orbits is 10.3 d. $P_{\rm circ}$ is equivalent for G and K dwarfs but with a few "eccentric" stars at smaller periods, possibly experiencing partial circularization (Duquennoy, Mayor & Mermilliod 1992).

– "Longer"-period systems with small eccentricities are missing. Above $P_{\rm circ}$ imposed by the tidal circularization, all SB are eccentric. A lower envelope at about $e = 0.1$ is observed. Explanations invoke eccentricity pumping mechanism acting at an early phase when stars have disks (e.g. Lubow & Artymowicz 1992).

– The eccentricity scatter increases with period attesting for a correlation between e and P. An upper envelope to the distribution is easily recognized. It probably results from the Roche lobe limitation at the pre-main sequence time.

3.2. The mass-ratio distribution: $f(q)$

Systematic RV surveys carried out over the last 20 years have allowed the detection of numerous stellar companions for the stars in the solar vicinity. Distributions of orbital elements for these SB are reasonably well determined, at least down to the substellar regime ($m_2 \sin i \geq 0.075\,\mathrm{M}_\odot$). However, the mass function of secondaries is much more sensitive to biases of "badly"-defined samples: non volume-limited samples, volume-limited samples incomplete or based on unprecise parallaxes will all be affected by biases. Unfortunately, the price to pay for the strict definition of a volume-limited sample, complete and based on precise parallaxes, is a drastic reduction of the number of useful SB.

Among our ~ 570 stars of the G+K-dwarf sample, 57 SB have been found with periods less than 10 years. This group of SB is called our *extended sample* and will serve to derive the lower part of $f(q \leq 0.5)$, not affected by the possible excess of binaries with comparable magnitudes. The CNS2 + complement are almost complete for $\pi \geq 65\,\mathrm{mas}$ ($\delta \geq -15°$) and are almost unbiased for $\pi \geq 46\,\mathrm{mas}$ (Halbwachs et al. 2000a). This latter *unbiased sample* consists of 249 stars among which only 26 SB with periods smaller than 10 years. That sample has to be used to define the frequency of binary stars with $q > 0.5$.

For double-line spectroscopic binaries (SB2), the measured ratio of RV amplitudes directly provides the mass ratio: $q = m_2/m_1 = K_1/K_2$. For single-line binaries (SB1), from the radial velocities, we only have access to

$$Y \equiv f(m)/m_1 = \frac{q^3 \sin^3 i}{(1+q)^2}.$$

For limited-size samples the deconvolution of the distribution from the unknown $\sin i$ is hazardous. However, if the periods are not too short, the orbital-plane inclination can be derived from the Hipparcos astrometric data taking into account the precise orbital elements derived from the RV curve (Halbwachs et al. 2000ab, Arenou et al. 2000). In our 57-SB sample we have 25 SB2. For 22 among the remaining 32 SB1, the astrometric orbit has been solved. Only 10 SB1 are left without additional constraints on their mass-ratios. Finally, an iterative inversion technique is applied (Boffin, Paulus & Cerf 1992; Mazeh & Goldberg 1992).

Stars members of open clusters also provide stellar samples convenient to study the mass-ratio distribution. Complete samples of late F to G dwarfs members of the Pleiades and Praesepe have been monitored in RV with CORAVEL at the Haute-Provence Observatory during more than 10 years. A set of 11 SB (9 SB1 + 2 SB2) have been found in the Pleiades with periods inferior to 10 years (Mermilliod et al. 1992) and 16 (13 SB1 + 3 SB2) in Praesepe[1] (Mermilliod &

[1] The SB2 percentage is smaller than for the field due to the relative faintness of cluster stars

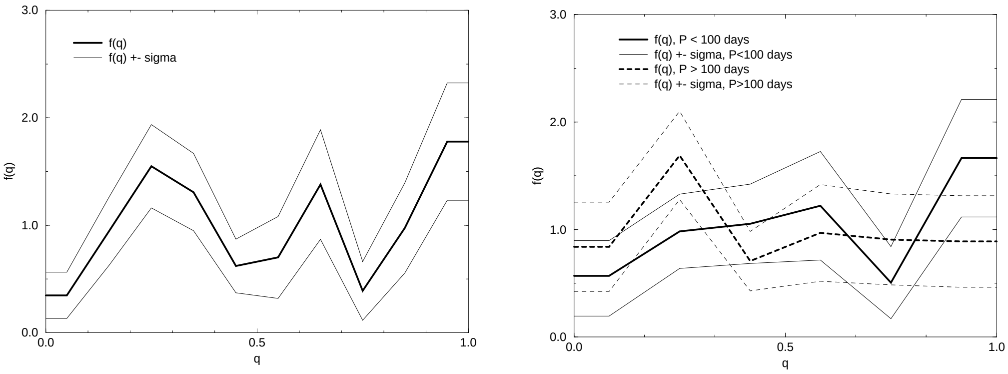

Figure 2. Mass-ratio distributions for: *Left:* the whole sample (field + open clusters); *Right:* 2 domains of periods, $P \leq 100\,\mathrm{d}$ and $P > 100\,\mathrm{d}$

Mayor 1999). However, for open clusters, photometry is sufficient to set in most cases a fair estimate of the companion masses or at least to set an upper bound (the RV curve gives a lower limit for the secondary mass).

Comparing the binaries in the field and in these clusters, we have a 26% probability that these two samples are issued from the same parent population. We thus merge the two samples to derive the mass-ratio distribution (Halbwachs et al. in prep). The global sample is then composed of 84 SB among which only 10 are SB1 without additional constraints. The *unbiased part*, limited to 46 mas for the field stars and used to analyse the $f(q > 0.5)$ side of the distribution, restricts the sample to 50 SB of which only 6 SB1 without constraints.

Figure 2 (left) presents the mass-ratio distribution for the whole sample ($P \leq 10\,\mathrm{y}$). We see 3 peaks in the distribution, at $q = 0.25$, 0.6 and 1. We also observe the significant decrease of the distribution for $q < 0.2$. The peak at $q = 0.6$ possibly results from binaries with white-dwarf companions. By estimating the statistical significance of the peak at $q = 1$, we only can reject a constant distribution at a 11% level, a percentage not really significant. If we now separately analyse SB with periods smaller and larger than 100 days (but with $P \leq 10$ y), we see that the possible peak of the mass-ratio distribution at $q = 1$, if real, comes from the "shorter-period" binaries ($P \leq 100\,\mathrm{d}$; Fig. 2 right).

The preliminary mass-ratio distribution derived by Fischer & Marcy (1992) for M dwarfs is in agreement with a flat distribution above $q = 0.4$. This distribution has to be improved in a near future based on the extended M-dwarf samples currently observed.

3.3. The period distribution and binary frequency

From the enlarged G+K sample we observe a rise of $f(\log P)$ up to $P \sim 10$ years. The full analysis including visual binaries and common proper-motion stars has still to be finalized to improve the $f(\log P)$ distribution of DM91.

We have found 26 SB in the *unbiased sample* ($\pi \leq 46\,\mathrm{mas}$) composed of 249 F7-K9 main-sequence primaries. A statistical correction of 0.8 ± 0.5 "star" has been estimated for the undetected-binary selection effect. In conclusion, for

$q > 0.02$ and $P \leq 10$ years, we observe $11 \pm 2\,\%$ of double stars among G-K stars. The rate is $9 \pm 2\,\%$ for $P < 1000$ days.

For comparison, the percentage of SB detected among close M dwarfs is $8{\pm}3\,\%$ for $P \leq 1000$ days (Delfosse & Forveille 2000). **We thus do not observe a significant smaller percentage of SB among M stars compared to solar-type stars,** at least for the unbiased domain of periods ($P \leq 1000$ d).

4. The mass function below the main sequence

The moderate precision programmes have already revealed a few companions with $m_2 \sin i$ small enough to be brown-dwarf candidates (Latham et al. 1989; DM91; Mayor et al. 1997). At the present time, the spectrographs with higher-precision capabilities have brought much further insight into orbital-element distributions and mass function of secondaries with minimum masses below $0.1\,M_\odot$. In particular, more than 50 companions have been detected with $m_2 \sin i$ smaller than $20\,M_{\rm Jup}$, most of them having minimum masses lower than $5\,M_{\rm Jup}$ (Marcy, Cochran & Mayor 2000; Vogt et al. 2000; ESO 2000; Fischer et al. 2000; Udry, Mayor & Queloz 2000c) . The information collected so far on SB, combined with the most recent detection of very low-mass companions (planets and brown-dwarf candidates), give us a synthetic view on companions to solar-type stars from $q = m_2/m_1 = 1$ to $q < 0.001$ (Fig. 3).

The histogram of minimum masses for the companions of solar-type stars with $m_2 \sin i$ less than 0.1 $M_\odot$ is drawn in Fig. 4. The impressive peak for $m_2 \sin i \leq 8\,M_{\rm Jup}$ is certainly not part of the very flat tail of stellar and brown-dwarf secondaries. Despite the huge observational bias against the detection of small mass companions we observe an increasing number of low mass gaseous planets. In the same time, brown-dwarf candidates easier to detect are rare. If we consider the still limited span of precise RV surveys as well as the sometimes still limited number of measurements per star, the correction of observational biases is premature. In this sense the dotted line in Fig. 3 in only indicative of a potential estimate of the bias-corrected distribution.

Radial velocities only give access to the minimum mass $m_2 \sin i$ of low-mass companions. In addition to RV data, we have collected information constraining the orbital-plane inclinations of brown-dwarf and planetary candidates from different sources (see Mayor & Udry 2000 for a review): Hipparcos astrometric data (Halbwachs et al. 2000a, Zucker & Mazeh 2000), planetary transit (Charbonneau et al. 2000, Henry et al. 2000, Mazeh et al. 2000), dust disks around stars (Trilling, Brown & Rivkin 2000) or synchronization properties for short-period systems (Fuhrmann, Pfeiffer & Bernkopf 1998). For these companions we obtain real masses. It is very impressive to see that most of the $\sin i$ of the brown-dwarf candidates are found to be small leading to masses of the secondaries above the H-burning limit, at the bottom of the main sequence. They possibly represent the tail of the binary $\sin i$ distribution of the peak at $f(q = 0.2)$. Only 4 objects with $\sin i$ determination have real-mass estimates in the brown-dwarf domain (3 from Halbwachs et al. 2000b and 1 from Zucker & Mazeh 2000).

Taking into account available orbital inclinations a composite histogram is built up for masses m_2 or $m_2 \sin i$ (if $\sin i$ not known) (Figs. 3 and 4, bottom). The gap between SB and planets is remarkable, emphasizing the paucity of

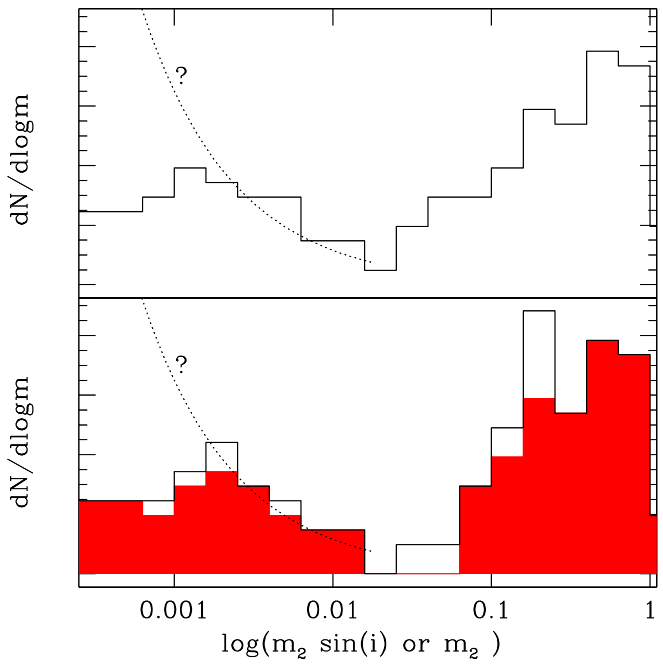

Figure 3. Mass function of companions to solar-type stars. Log scale. The dotted line is indicative of a potential bias-corrected distribution. *Top:* $m_2 \sin i$. *Bottom:* composite histogram of m_2 (open part) and $m_2 \sin i$ (if $\sin i$ not known; colored part)

brown-dwarf companions. It clearly suggests different formation and evolution processes for the two populations. Further indications for such differences have been pointed out in the period and eccentricity distributions (see Sect. 5).

The sharp drop of the mass function observed below $\sim 8\,\mathrm{M_{Jup}}$ strongly suggests a maximum mass for giant planets close to $10\,\mathrm{M_{Jup}}$, without any relation with the D-burning limit around $13\,\mathrm{M_{Jup}}$ (Fig. 4). The latter has very probably nothing to do with the maximum mass of objects initially formed from dust/ice particles in an accretion disk. At the opposite, present samples cannot provide any real estimate of the minimum mass for brown dwarfs orbiting solar-type stars. The D-burning limit seems neither related to the minimum mass of brown dwarfs formed by fragmentation in a cloud. Free-floating "planets" (i.e. brown dwarfs) with masses probably below $10\,\mathrm{M_{Jup}}$ have been reported in σ-Orionis (Zapatero Osorio et al. 2000). **The D-burning mass is clearly of no help to understand the observed mass distribution.**

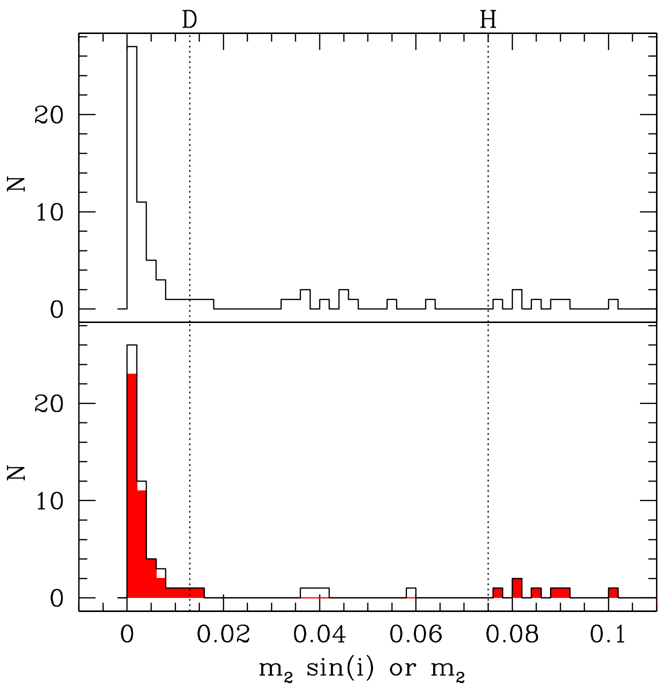

Figure 4. Mass function of companions to solar-type stars. Linear scale. The dotted lines indicate the H- ($75\,\mathrm{M_{Jup}}$) and the D- ($13\,\mathrm{M_{Jup}}$) burning limits. *Top:* $m_2 \sin i$. *Bottom:* composite histogram of m_2 (open part) and $m_2 \sin i$ (if $\sin i$ not known; colored part)

5. Orbital-element distribution of giant planets

The observed gap in the mass distribution between giant planets and stellar secondaries strongly suggests the existence of two distinct companion populations for solar-type stars. Giant planets and stellar binaries are believed to have different formation mechanisms whose fossil traces should be revealed by a comparison of their orbital properties.

5.1. The distribution of periods

Clearly, due to the still strong bias affecting the detection of long-period planets, a significant comparison of the period distributions of planetary candidates ($m_2 \sin i \leq 10\,\mathrm{M_{Jup}}$) and spectroscopic binaries ($m_2 \sin i \geq 10\,\mathrm{M_{Jup}}$) is only possible for relatively short-period systems ($P \leq 100\,\mathrm{d}$), for which the detection bias is vanishing. On the domain of very-short periods ($P \leq 10\,\mathrm{d}$), the distribution of periods of giant planets is steeply rising for decreasing periods down to about 3 days. A cut-off is observed around that period. The shortest period observed to date is $P = 2.986$ days for HD 83443 b (ESO 2000, Mayor et al. 2000). It is

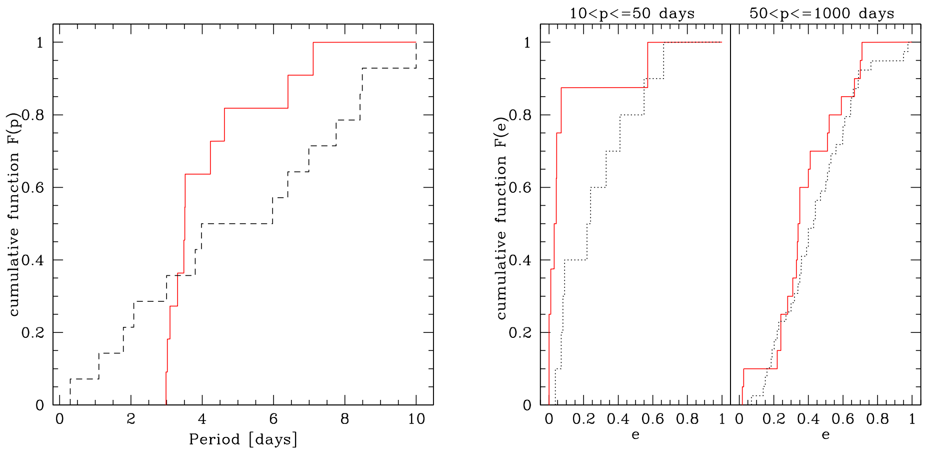

Figure 5. *Left:* Cumulative distributions of periods smaller than 10 days for planetary (solid line) and stellar companions (dashed line) to solar-type stars. *Right:* Cumulative distributions of eccentricities for planets (solid line) and stellar binaries (dotted line) for 2 domains of periods: $10 \leq P \leq 50\,\mathrm{d}$ and $50 \leq P \leq 1000\,\mathrm{d}$

clearly emphasized in Fig. 5 (left) comparing the cumulative distributions of periods smaller than 10 days for giant planets and spectroscopic binaries. Several reasons may be invoked to set this limit like e.g. magnetospheric central cavity of the accretion disk, tidal interaction (Lin et al. 1996), Roche lobe overflow (Trilling et al. 1998) or evaporation (Mayor & Udry 2000).

5.2. The distribution of eccentricities

The comparison of orbital eccentricities of spectroscopic binaries for G, K and M primaries (DM91, Halbwachs et al. 2000a; Udry et al. 2000a) with the equivalent distribution for giant planets is remarkable. In Fig. 6 we have plotted the orbital eccentricities as a function of $\log P$ both for double stars and giant planets. At the first glance we do not observe significant differences of orbital elements between planets and SB. If the formation mechanisms for planets and double star are different, why do we observe so similar (e, $\log P$) distributions? In fact some differences may be emphasized in particular domains of periods.

For planets with very short periods, most of the orbits are quasi-circular as for double stars. Planets having suffered a strong orbital migration are probably circularized by the tidal interaction with the accretion disk. We observe quite a number of quasi-circular planetary orbits with $P \leq 40$ days. It is however also true that two short-period planets present eccentric orbits: around HD 108147 ($P = 10.9\,\mathrm{d}$, $e = 0.56$) and HD 217107 ($P = 7.11\,\mathrm{d}$, $e = 0.14$). Such configurations could be explained by the presence of an additional companion revealed by a drift observed in the systematic velocity of those stars or by gravitational interaction between giant planets formed in the outer regions of the system (Weidenschilling & Marzari 1996; Lin & Ida 1997).

We have seen that most of the orbits of double stars with long periods ($P \geq 50\,\mathrm{d}$) are fairly eccentric. Quasi-circular ($e < 0.01$) long-period orbits are

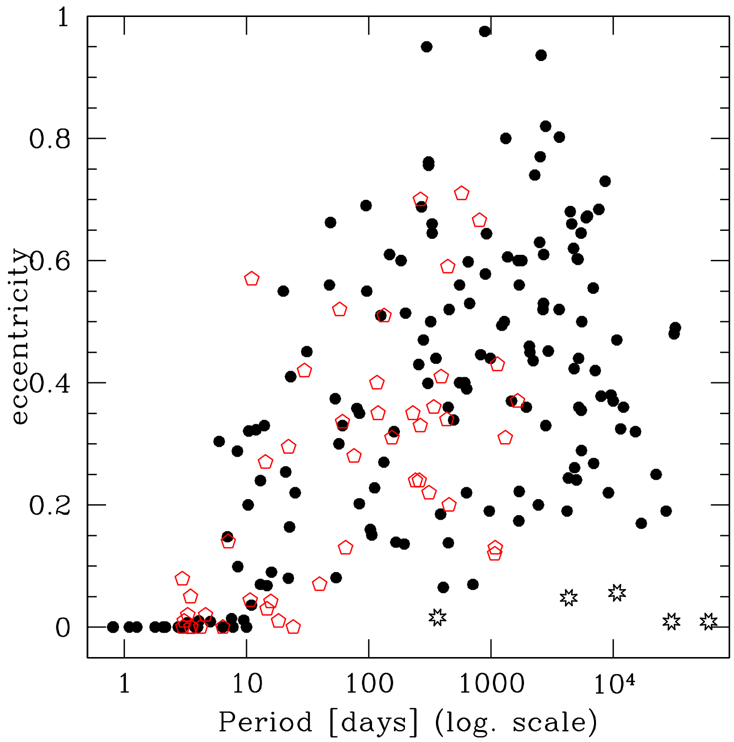

Figure 6. Comparative (e, $\log p$) diagram for planetary (open pentagons) and stellar companions to G+K+M solar-type stars of the field (filled circles). Starred symbols indicate planets of the solar system

very rare. A similar situation exists for extra-solar giant planets (with $e = 0.13$, 47 UMa is just at the border), although they are still strongly observationally biased in that period range. We of course know one planetary system with long-period giant planets on quasi-circular orbits, namely our own Solar system.

The origin of the eccentricity of extra-solar giant planets has been searched in the gravitational interaction between multiple giant planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Lin & Ida 1997) or between the planets and the planetesimals in the early stages of the system formation (Levison, Lissauer & Duncan 1998). Among the giant planet candidates several eccentric orbits show a drift of their mean velocity indicating the presence of a long-period companion (probably stellar) whose gravitational perturbation can also be suspected to be responsible for the observed (high) planetary eccentricity as e.g. for the planet orbiting 16 Cyg B (Mazeh, Krymolowski & Rosenfeld 1997).

In summary, for periods larger than about 50 days, the comparison of double star and planet eccentricities is really surprising. With the limited-size samples presently available, we cannot see any significant distinctions between both populations. This is shown in Fig. 5 (right) which gives the cumulative function of eccentricities for periods between 50 and 1000 days, for the two populations. If the orbital eccentricity of binaries finds its origin in the disruption of small N-body systems, maybe the generated distribution of eccentricities is close to the distribution generated by the gravitational interactions between giant planets.

Nevertheless, a clear difference may be noticed between the two populations for periods between 10 and 50 days. This is illustrated by the corresponding cumulative functions given in Fig. 5 (right). In this range of periods, outside the circularization domain, planetary systems have smaller eccentricities than stellar binaries indicating different formations or evolutions.

In conclusion, the differences observed between planetary systems and double stars in the shape of the secondary mass functions and in the period and eccentricity distributions argue for the two populations being formed by distinct processes. More observations are however still needed to bring clear constraints on the possible formation and evolution scenarios.

6. Future prospects in the domain of multiple stars

Most of our knowledge of the orbital-element distributions of short-period binaries ($P \leq 10\,\mathrm{y}$) is derived from spectroscopic surveys done in the 80's-90's with a moderate precision of about $0.25\,\mathrm{km s^{-1}}$. New precise RV surveys ($\varepsilon \simeq 10\,\mathrm{m s^{-1}}$) carried out on F-K stars (e.g. the CORALIE survey, Udry et al. 2000b) or for M dwarfs (Delfosse et al. 1999a) will have an almost 100 % completeness from jovian-type objects to normal spectroscopic binaries.

If we want to explore the domain of longer periods, drastic improvements are expected both from imagery and astrometry. Follow-up studies with adaptive optics of stars with giant planets or brown-dwarf companions quite frequently reveal distant visual additional companions, not previously identified, and clearly show the incompleteness still existing in surveys searching for distant, very faint, stellar secondaries: e.g. the companions to τ Boo and HD 114762 (Lloyd et al. 2000) or the companion to HD 174457 (Naef et al. 2000). Systematic adaptive optics surveys of all stars in a volume-limited sample have to be done.

Ground-based interferometry will prove to be very fruitful for binary star research (Davis 1996). In dual-beam mode (Shao & Colavita 1992), foreseen for the VLT and Keck telescopes, a higher precision is achieved. For the VLTI the astrometric reflex motion of a primary star will be detected with a precision of 10-50 μas. This precision will be sufficient to determine the orbital orientations (and real masses) of most of the detected giant planets and brown-dwarf candidates. Space missions like SIM, FAME or GAIA will still further improve our knowledge of orbital distributions with unprecedented astrometric precision (down to 4 μas for GAIA for a huge stellar sample and maybe 1 μas for SIM for some specific high-priority targets). Figure 7 illustrates the domain in the ($\log a$, $\log m_2$) plane where astrometry and Doppler spectroscopy are sensitive.

We can now ask ourselves what are the domains where the microlensing technique can provide unique results. Several brown dwarfs have been found to be double (PPL 15, Basri & Martin 1999; DENIS-PJ1228.2-1547, Delfosse et al. 1997, Martin, Brandner & Basri 1999). Some results on the duplicity of young brown dwarfs could be expected from adaptive optics and in a few cases from spectroscopy. However, most of old brown dwarfs in the field will only be revealed (as well as their duplicity) through microlensing surveys.

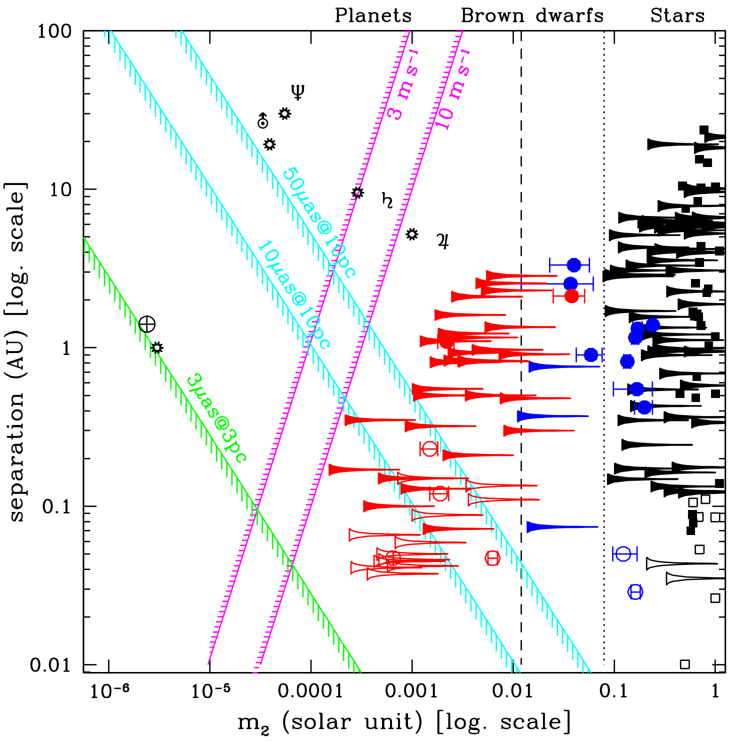

Figure 7. Separation-mass diagram for companions to solar-type stars from binaries to planetary systems. Elongated symbols represent the $\sin i$ probability. Open symbols are for low-e orbits. Limits of the Doppler spectroscopic and astrometric techniques are indicated

At the present time our knowledge on giant planets is restricted to objects with masses from just below the mass of Saturn to a few times the mass of Jupiter. The minimum mass detected so far is for HD 83443 c with $m_2 \sin i = 0.5\,M_{Saturn}$ (Mayor et al. 2000). An increase of the number of measurements per star and of the precision of spectrograph will maybe allow us to detect planets just at the border of the Neptune mass, but only for very short orbital periods. Before the arrival of space interferometers, microlensing surveys should have the possibility to explore the still unknown domain of very low-mass planets.

References

Arenou F., Halbwachs J.-L., Udry S., Mayor M. 2000, in *Birth and Evolution of Binary Stars*, IAU Symp. 200P, Eds. B. Reipurth & H. Zinnecker, p. 135

Baranne A., Mayor M., Poncet J.-L. 1979, Vistas in Astron. 23, 279

Baranne A., Queloz D., Mayor M., et al. 1996, A&AS 119, 373

Basri G., Martin E. 1999, AJ 118, 2460

Boffin H., Paulus G, Cerf N. 1992, in *Binaries as Tracers of Stellar Formation*, Eds. Duquennoy A. & Mayor M., Cambridge University Press, p.26

Charbonneau D., Brown T., Latham D., Mayor M. 2000, ApJ 529, L45

Davis J. 1996, in "Science with the VLT Interferometer", ESO Astrophys. Symp., Ed. Paresce F., p.143

Delfosse X., Forveille T. 2000, in "Very-low mass stars and brown dwarfs in stellar clusters and associations", Eds. Rebolo R., Zapatero Osorio M.R.& Béjar V., Cambridge University Press

Delfosse X., Tinney C., Forveille T. 1997, A&A 327, L25

Delfosse X., Forveille T., Perrier C., Mayor M. 1998a, A&A 331, 581

Delfosse X., Forveille T., Mayor M., et al. 1998b, A&A 338, L67

Delfosse X., Forveille T., Beuzit J.-L., et al. 1999a, A&A 344, 897

Delfosse X., Forveille T., Udry S., et al. 1999b, A&A 350, L39

Delfosse X., Forveille T., Mayor M., Burnet M., Perrier C. 1999c, A&A 341, L63

Duquennoy A., Mayor M. 1991, A&A 248, 485

Duquennoy A., Mayor M., Mermilliod J.-C. 1992, in *Binaries as Tracers of Stellar Formation*, Eds. Duquennoy A. & Mayor M., Cambridge University Press, p.52

ESA 1997, *The Hipparcos and Tycho Catalogue*, ESA-SP 1200

ESO 2000, http://www.eso.org/outreach/press-rel/pr-2000/pr-13-00.html

Fischer D., Marcy G. 1992, ApJ 396, 178

Fischer D., Marcy G., Butler P., et al. 2000, ApJ submitted

Forveille T., Beuzit J.-L., Delfosse X., et al. 1999, A&A 351, 619

Fuhrmann K., Pfeiffer M.J., Bernkopf J. 1998, A&A 336, 942

Gliese W. 1969, Ver Astron Rechen Inst Heidelberg, 22

Gliese W., Jahreiss H. 1979, A&AS 38, 423

Halbwachs J.-L., Mayor M., Udry S. 1998, in "Brown Dwarfs and Extrasolar Planets", Eds. Rebolo R., Martin E. & Zapatero Osorio M.R., ASP Conf. Ser. 134, 308

Halbwachs J.-L., Arenou F., Mayor M., Udry S. 2000a, in "Birth and Evolution of Binary Stars", IAU Symp. 200P, Eds. Reipurth B. & Zinnecker H., p.132

Halbwachs J.-L., Arenou F., Mayor M., Udry S., Queloz D. 2000b, A&A 355, 581

Henry G., Marcy G., Butler P., Vogt S. 2000, ApJ 529, L41

Latham D., Mazeh T., Stefanik R., Mayor M., Burki G. 1989, Nature 339, 38

Levison H.F., Lissauer J., Duncan M.J. 1998, AJ 116, 1998

Lin D., Ida S. 1997, ApJ 477, 781

Lin D., Bodenheimer P., Richardson D.C. 1996, Nature 380, 606

Lloyd J., Patience J., Liu M., et al. 2000, in "Planetary Systems in the Universe", IAU Symp. 202, Eds. Penny A., et al., PASP Conf. Ser., in press

Lubow S.H., Artymowicz P. 1992, in *Binaries as Tracers of Stellar Formation*, Eds. Duquennoy A. & Mayor M., Cambridge University Press, p.145

Marcy G.W., Benitz K.J. 1989, ApJ 344, 441

Marcy G., Butler P., Vogt S., Fischer D., Lissauer J. 1998, ApJ 505, L147

Marcy G., Cochran W., Mayor M. 2000, in "Protostars and Planets IV", Eds. Mannings V., Boss A., Russel S., The University of Arizona Press, p.1285

Martin E., Brandner W., Basri G. 1999, Science 283, 1718

Mayor M., Udry S. 2000, in "Disks, Planetesimals and Planets", Eds. Garzón F., Eiroa C., de Winter D. & Mahoney T., ASP Conf. Ser., in press

Mayor M., Queloz D., Udry S., Halbwachs J.-L. 1997, in "Astronomical and Biochemical Origins of Life in the Universe", Eds. Cosmovici C., Browyer S. & Werthimer D., IAU Coll. 161, Editrice Compositori, p.313

Mayor M., Naef D., Pepe F., et al. 2000, in "Planetary Systems in the Universe", IAU Symp. 202, Eds. Penny A., et al., PASP Conf. Ser., in press

Mazeh T., Goldberg D. 1992, ApJ 394, 592

Mazeh T., Goldberg D., Duquennoy A., Mayor M. 1992, ApJ 401, 265

Mazeh T., Krymolowski Y., Rosenfeld G. 1997, ApJ 477, 403

Mazeh T., Naef D., Torres G. et al. 2000, ApJ 532, L55

Mermilliod J.-C., Rosvick J., Duquennoy A., Mayor M. 1992, A&A 265, 513

Mermilliod J.-C., Mayor M. 1999, A&A 352, 479

Naef D., Mayor M., Arenou F., et al. 2000, in "Planetary Systems in the Universe", IAU Symp. 202, Eds. Penny A., et al., PASP Conf. Ser., in press

Rasio F., Ford E. 1996, Science 274, 954

Shao M., Colavita M. 1992, A&A 262, 353

Stefanik R., Latham D. 1992, in "Complementary Approaches to Double and Multiple Star Research", IAU Coll. 135, Eds. McAlister H.A. & Hartkopf W.I., ASP Conf. Ser. 173, 32

Trilling D.E., Benz W., Guillot T. et al. 1998, ApJ 500, 428

Trilling D.E., Brown R.H., Rivkin A.S. 2000, ApJ 529, 499

Udry S., Mayor M., Latham D., et al. 1998, in "Cools Stars, Stellar Systems and the Sun", Eds. Donahue R. & Bookbinder J., ASP Conf. Ser. 154

Udry S., Mayor M., Delfosse X., et al. 2000a, in "Birth and Evolution of Binary Stars", IAU Symp. 200P, Eds. Reipurth B. & Zinnecker H., p.158

Udry S., Mayor M., Naef D., et al. 2000b, A&A 356, 590

Udry S., Mayor M., Queloz D. 2000c, in "Planetary Systems in the Universe", IAU Symp. 202, Eds. Penny A., et al., PASP Conf. Ser., in press

Vogt S., Marcy G., Butler P., Apps K. 2000, ApJ 536, 902

Weidenschilling S.J., Marzari F. 1996, Nature 384, 619

Young A., Sadjadi S., Harlan E. 1987, ApJ 314, 272

Zahn J.-P. 1992, in *Binaries as Tracers of Stellar Formation*, Eds. Duquennoy A. & Mayor M., Cambridge University Press, p.253

Zapatero Osorio M.-R., Béjar V., Martin E., et al. 2000, Science, in press

Zucker S., Mazeh T. 2000, ApJ 531, L67