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# ON THE MASS-RATIO DISTRIBUTION OF SPECTROSCOPIC BINARIES WITH SOLAR-TYPE PRIMARIES

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## ABSTRACT

We use the radial-velocity complete study of the nearby G-type stars of Duquennoy & Mayor to derive the mass-ratio distribution of the short-period binaries. We include in the analysis only binaries with periods less than 3000 days and are left, therefore, with 23 systems. To analyze the data, we apply the recently published algorithm of Mazeh & Goldberg. The result seems to fit with a uniform distribution, while the linear fit rises moderately toward high mass ratio. The analysis ignores any possible local features because of the small number of binaries in the sample. This work suggests that the mass-ratio distribution of the short-period binaries is substantially different from the distribution of the long-period binaries. Moreover, the mass distribution of the secondaries of the present sample is very different from the mass distribution of the single stars.

*Subject headings:* binaries: spectroscopic — stars: fundamental parameters

## 1. INTRODUCTION

Duquennoy & Mayor (1991) have recently published a thorough radial-velocity study of the nearby G-type dwarfs. The high precision, long-time coverage, and completeness of this systematic search for spectroscopic binaries provide a unique opportunity to find the true characteristics of the nearby binary population. In particular, the new data can now solve the long-standing controversy over the mass-ratio distribution of short-period binaries (e.g., Abt & Levy 1976; Halbwachs 1987; Trimble 1990). To do so we take advantage of a new algorithm suggested very recently (Mazeh & Goldberg 1992a, b), which shows promising potential to derive the true mass-ratio distribution. This short paper briefly describes the binary sample (§ 2), outlines the procedure used, and presents the results (§ 3). The paper concludes with a discussion of the significance of our finding.

## 2. BINARY SAMPLE

The complete sample of Duquennoy & Mayor (1991) includes 164 primary stars of spectral types F7 to G9, luminosity classes IV–V, V, and VI, declination above $-15°$, and trigonometric parallax greater than $0''.045$ (or distance $r \leq 22$ pc). A typical time span of the observations per star is $\sim 3000$ days, with precision of 0.3 km $s^{-1}$ per measurement (Duquennoy, Mayor, & Halbwachs 1991).

Duquennoy & Mayor (1991) found 37 spectroscopic binaries in their complete sample. Some of these systems have relatively long periods, of the order of tens of years. This work focuses on the study of short-period binaries, so we include in the analysis only systems with periods shorter than 3000 days, the typical time span of the survey. In order to avoid binaries which have undergone through extensive mass-transfer phase we exclude HD 133640, a W UMA star with a period of 0.27 days. We are left with 23 binaries, which are listed in Table 1.

For each single-line binary, Table 1 lists the period, the amplitude $K_1$, the derived mass function of Duquennoy & Mayor (1991), the MK classification of the primary star, and the primary mass estimation. The estimation of the mass comes from the standard mass spectral-type relation of Schmidt-Kaler (1965). All of the stars have luminosity class V or IV–V according to Gliese (1969) or Bright Star (Hoffleit & Jaschek 1982) catalogs (except HD 153631, which is not classified, but whose colors, however, are those of a dwarf). For double-line binaries, the observed mass ratio is listed instead of the mass function, and no primary-mass estimation is given.

Admittedly, the number of binaries in the present sample is small, and therefore the derived distribution is vulnerable to statistical errors. On the other hand, the completeness of the Duquennoy & Mayor survey and the uniformity of the data render this sample rather unique, almost without any observational selection effects. Therefore, this sample can help to find the unbiased mass-ratio distribution of the short-period binaries.

## 3. ANALYSIS AND RESULTS

To analyze the present sample we used the recently suggested algorithm of Mazeh & Goldberg (1992a, b). Those papers detailed the algorithm philosophy, basic assumptions, and methodology. In short, the algorithm includes an iterative procedure in which each binary of unknown inclination is replaced by an ensemble of virtual systems with a distribution of inclinations. Contrary to a widely held assumption, the orientations of each virtual ensemble are not distributed randomly in space. The mass ratio of each *virtual* system is then derived by using the mass function, the estimation of the primary mass, and the orbital inclination assigned to that system. Consequently, each single-line binary is replaced by an ensemble of systems with different mass ratios. A few iterations are performed to reach the best estimate for the true mass-ratio distribution. This procedure is not applied to the double-line spectroscopic binaries; for these systems the algorithm uses the observed mass ratio.

The results of the analysis are presented in Figure 1. We chose to divide the mass ratio range into six equal bins, because of the small sample. Such a division enabled us to find only the general trend of the mass-ratio distribution. Even with

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TABLE 1

THE BINARY SAMPLE

| Star | $P$ (days) | $K_1$ (km s$^{-1}$) | $f(m)$[a] ($M_\odot$) | MK Type | $M_1$ ($M_\odot$) |
|---|---|---|---|---|---|
| HD 3196Aa | 2.081891 | 43.98 | 0.01844 | F8V | 1.2 |
| HD 3196A-B | 2527 | 10.90 | 0.663[a] | F8V | ... |
| HD 4676 | 13.8318 | 57.31 | 0.9588[a] | F8V | ... |
| HD 13974 | 10.02008 | 10.49 | 0.88[a] | G0Ve | ... |
| HD 16620A-B | 969.4 | 5.86 | 0.68[a] | F8V | ... |
| HD 16739 | 330.935 | 21.03 | 0.918[a] | F9V | ... |
| HD 17433 | 13.19828 | 30.35 | 0.0380 | G9Ve | 0.8 |
| HD 61994 | 553.51 | 10.69 | 0.715[a] | G6V | ... |
| HD 64606 | 447.32 | 5.85 | 0.00756 | G8V | 0.8 |
| HD 79028 | 16.2397 | 35.3 | 0.073 | F9V | 1.1 |
| HD 98231Aa | 669.18 | 8.0 | 0.00214 | G0Ve | 1.0 |
| HD 98231Ba | 3.9805 | 5.0 | 0.000053 | G0Ve | 1.0 |
| HD 101177Ba | 23.5409 | 24.31 | 0.0267 | K2V | 1.0 |
| HD 108754 | 25.9347 | 8.08 | 0.0013 | G8V | 0.8 |
| HD 144284 | 3.07084 | 24.7 | 0.0048 | F8IV–V | 1.2 |
| HD 146361 Aa-b | 1.139788 | 63.01 | 0.99[a] | F8V | ... |
| HD 149414Aa | 133.13 | 16.11 | 0.0514 | G5Ve | 0.9 |
| HD 153631 | 386.72 | 6.14 | 0.0088 | G3 | 1.0 |
| HD 170153 | 280.547 | 18.22 | 0.701[a] | F7V | ... |
| HD 178428 | 21.95536 | 13.42 | 0.00546 | G5V | 0.9 |
| HD 195987 | 57.3240 | 28.73 | 0.1219 | G9V | 0.8 |
| HD 202275A-B | 2082.90 | 12.26 | 1[a] | F8V | ... |
| HD 213429 | 632.54 | 11.44 | 0.549[a] | F7V | ... |

[a] Mass ratio for double-line binaries.

six bins, there were only a few binaries in each bin, and consequently the uncertainty in every bin was relatively large. To estimate the uncertainty of the resulting distribution, we have run a series of numerical simulations, generating random samples with the size of the real sample, and analyzing them with the same algorithm. A typical standard error of each bin was found to be 1.5 binaries, provided the mass-ratio distribution used was uniform. As the distribution actually found is not far from the uniform one, we have adopted this uncertainty estimation for all bins except the first one, where the observational effects (discussed below) made the possible error larger.

The estimated relative error of the primary masses is ~15% (Andersen 1991). This error contributes a relative error of the order of $15\%/(n_{\rm bin})^{1/2}$ to the error of each bin, where $n_{\rm bin}$ is the number of systems found in the bin. This error is much smaller than the statistical error caused by the small number of systems analyzed and therefore is neglected here.

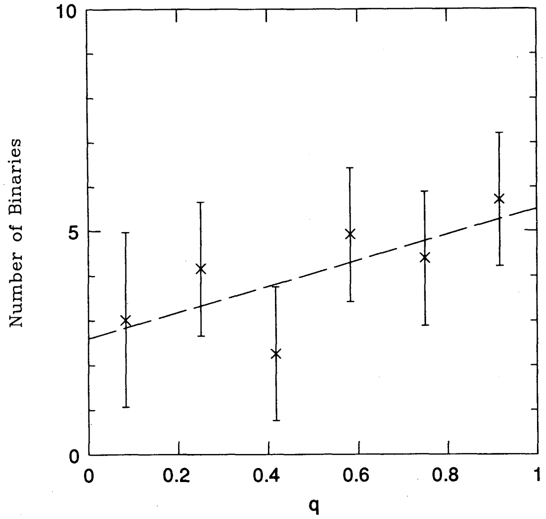

FIG. 1.—The number of binaries, $\mathcal{N}$, as a function of the mass ratio for the G-dwarf sample.

One observational limit which affected the present sample is the inability to detect radial-velocity periodic modulations with small amplitude. To correct for this effect we assumed a constant detection threshold of 2 km s$^{-1}$ and ignored its actual dependence on the binary period and eccentricity. The correction was found to be significantly effective only for the first bin, where the mass ratio is between 0.0 and 0.17. Using the observed period distribution of the sample and the scheme outlined by Mazeh & Goldberg (1992a, b), our best estimate for the correction factor for the first mass-ratio bin was 1.7. The first point of Figure 1 was plotted after this correction factor was applied. We have found, based on our simulation, that this correction increases the error of the first bin by about a factor of $(1.7)^{1/2} = 1.3$. We adopt this estimate, although some possible systematic errors, like the dependence of the threshold on the period, could have also distort the value of the first bin. The error bar of the first point of Figure 1 was plotted accordingly.

The histogram of Figure 1 is a realization of $n(q)$—the continuous mass-ratio distribution density of the G-dwarf binaries. For a large sample with $N$ binaries the *expected* number of binaries, $\mathcal{N}$, with mass ratio between $q$ and $q + dq$ is

$$\mathcal{N}(q, dq, N) = n(q) dq N \ . \tag{1}$$

The six bins of Figure 1 represent six values of $\mathcal{N}(q, dq, N)$, all with the same value of $dq(=0.167)$ and $N(=164)$. Figure 1 suggests a uniform mass-ratio distribution, or perhaps a slightly rising distribution. A formal linear fit to the data yields

$$\mathcal{N}(q) = (2.6 \pm 1.4) + (2.9 \pm 2.3) q \ . \tag{2}$$

The best linear fit is also plotted in Figure 1. Note that the uniform distribution, which is a linear function with a slope equal to zero, is only 1.25 $\sigma$ away from the best fit and therefore is still possible.

### 4. DISCUSSION

One of the basic assumptions of the algorithm is that the analyzed sample does not include binaries with mass ratio larger than unity, implying that the observed component of all binaries in the sample is the more massive star. This is certainly true for any binary with two main-sequence components. Consider now the other possibility, namely that the less-luminous component is not any more on the main sequence. In the present sample, the secondary (faint) star can be more massive only if its mass is larger than 1 $M_\odot$ because all primaries are dwarfs with spectral type between F7 and G9. Therefore, the hypothetical more massive fainter component can be either a very massive white dwarf or a neutron star. Both cases are very rare. Therefore, the assumption that the mass ratio is smaller than unity seems well justified for the present sample.

The binary systems of the present sample were all discovered by a systematic long-term radial-velocity survey, performed all along by the same team and the same instrument, out of a preselected volume-limited sample of stars. Therefore, we are not aware of any observational effect which could distort the derived distribution, except for the inability to detect low-amplitude binaries. This observational limit has reduced the number of detected binaries only in the first bin, and this bin was corrected to obtain the true distribution. The inability to detect double-line binaries with very small inclination introduces small errors in the bins of large mass ratio and therefore was neglected here. We therefore suggest that Figure 1 presents the gross features of the true mass-ratio distribution of the nearby short-period binaries with G-type primaries.

The obtained histogram can be fitted very well with a linear function, one of the most simple fits available. Previous studies have invoked exponential, power-law, low-end cutoff, or double-peak functions (see Trimble 1990 for a thorough review) to fit their data. We find no need to use these interesting functions. Note, however, that any possible local feature could not have been detected by the present work, because of the small sample and consequently the small number of bins. Nevertheless, the simple shape of the distribution, obtained with a modern algorithm by using one of the best complete samples of binaries, is intriguing. Maybe nature is simple after all!

The mass-ratio distribution of the short-period binaries obtained here is significantly different from the corresponding distribution of the long-period binaries found in the same sample (Duquennoy & Mayor 1990, 1991). While the long-period distribution rises toward small mass ratio, with a possible drop off at $q$ equals 0.1 or less, the short-period distribution is uniform and might even rise toward large mass ratio. Abt & Levy (1976) have noticed a very similar difference between the short- and the long-period binaries.

The difference between the short- and the long-period binaries might arise either from different formation processes for close and wide binaries (Trimble & Cheung 1976), or from some evolutionary processes that can change the mass ratio and acts differently in the two populations of binaries. One such process is the substantial mass loss which takes place at the giant or supergiant phase. In close binaries, this process can modify the mass ratio of the system differently than in the wide binaries, because of the proximity of the second component.

Mass loss could happen in our sample only for binaries for which the present G dwarf was not the primordial primary; the original primary lost a substantial fraction of its mass and is now a secondary white dwarf. The fraction of evolved secondaries in the present sample is therefore the fraction of the original sample for which the G dwarf was the secondary. If both components were formed with the Salpeter (1955) mass distribution, the fraction of new-born stars with mass larger than 1 $M_\odot$ is ~10%. Of course, the Salpeter function describes the mass distribution of the single stars, which might be different from that of the primaries of binary systems. However, if the two distributions are not substantially different, the fraction of evolved stars in our sample is also 10%. Thus, the small number of evolved systems could not have change the general features of the original distribution. It seems therefore that the short- and the long-period binaries of this sample were formed with different mass-ratio distributions.

We move now to compare the secondary mass distribution of the present sample with that of single stars. Note that in many samples of binaries the obtained mass-ratio distribution is not necessarily equal to the secondary mass distribution. This is so because the mass ratio and the secondary mass are two different variables, and it is not clear a priori which one is chosen by nature to be independent of, say, the primary mass. Therefore, one should be careful when comparing the mass-ratio distribution of a given sample with some secondary mass distribution (Tout 1991) or with the results of a different sample. Luckily, the primaries of the present sample all have about the same mass, close to 1 $M_\odot$. Therefore, the obtained mass-ratio distribution represents also the mass distribution of the secondaries.

The linear, possibly uniform, distribution obtained here for the secondary mass is very different from the mass distribution of single stars. All the functions suggested to describe the mass distribution of single stars (e.g., Kroupa, Tout, & Gilmore 1991) include a substantial drop when the stellar mass changes from, say, 0.3, to 1 $M_\odot$. The result of the present sample, despite its smallness, is not consistent with any of these functions. We find a uniform and even possibly rising distribution in this range. Apparently, some mechanism which acts during the formation of short-period binaries affects the secondary mass.

Finally, we cannot resist the temptation to speculate about the frequency of low-mass secondaries in our sample. Careful estimation of this frequency can shed some light on the presently intensive search for brown dwarfs in close binary systems (Latham et al. 1989; Mazeh et al. 1990; Duquennoy & Mayor 1991). The linear fit of Figure 1 implies that the number of binaries with mass-ratio smaller than 0.1 is

$$\mathcal{N}(q \leq 0.1) = 1.7 \pm 0.8 \,, \tag{3}$$

out of 164 primaries. Therefore, our best guess for the frequency of *short-period* low-mass secondaries comes out to be (1 ± 0.5)%.

This is a very preliminary result, because of the small size of our sample and the observational limits which affect the number of binaries detected in this range of small mass ratio. The procedure we applied to correct for the observational effects is only a zero-order approximation, and the actual error in this bin might be larger. Moreover, equation (3) uses the linear fit of the distribution, which ignores any possible local feature of the mass-ratio distribution. Nevertheless, this very preliminary result, when extended over the whole range of periods considered by Duquennoy & Mayor (1991), is consistent with their conclusion. It is also consistent with the negative results of Marcy & Benitz (1989), who could not find strong evidence for a low-mass companion with a period less than ~3 yr in a sample of 65 M dwarfs.

The distribution obtained here is based on a relatively small sample of binaries. Enlarging the *complete* sample of binaries with additional G-type primaries will refine our knowledge of the mass ratio distribution and therefore would be of special importance. Unfortunately, such an extension is not expected in the near future. On the other hand, the CORAVEL team is completing these days two samples of nearby binaries with K- and M-type primaries. Analysis of these coming samples will enable us to compare the mass-ratio distribution of different samples, and to decide whether the mass ratio is indeed independent of the primary mass. In addition, two surveys for spectroscopic binaries in large samples of halo stars are being performed in the last several years (Latham et al. 1988; Ardeberg, Lindgren, & Lundstrom 1991). The analysis of the two samples of binaries, when completed, would be of special interest. We might even be able to find out whether the different conditions which prevailed in the early phase of the Galaxy affected the mass-ratio distribution to become different from that of the nearby disk binaries.

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