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MULTIPLICITY OF SOLAR-TYPE STARS*

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RESUMEN

Se describe una búsqueda sistemática de binarias en una muestra de 123 estrellas brillantes de campo, de tipos F3-G2 IV o V. Combinando los resultados de 25 nuevas binarias espectroscópicas con los de 21 binarias espectroscópicas, 23 binarias visuales y 25 pares de movimiento propio común, previamente conocidas, llega a 88 el número total de compañeras identificadas en esta muestra. La distribución de los 88 períodos muestra un máximo único. El periodo medio es de 14 años. Las frecuencias de estrellas solas, dobles, triples o cuádruples se ha encontrado que es 42, 46, 9 y 2 por lo tanto menos de la mitad de las estrellas son solas. Estimaciones de la completez de esta búsqueda condujeron a una determinación del número de los sistemas que no son detectados así como a una determinación de las masas de sus secundarias.

Un análisis de la distribución de masas secundarias observadas y predichas de las estimaciones de completez indica la existencia de dos tipos de binarias:

Para sistemas con periodos menores de aproximadamente 100 años, la distribución de las secundarias varía con la raíz cúbica de la masa de la secundaria. Estos sistemas deben ser resultado de fisión. Dos terceras partes de sus primarias tienen compañeras de masa estelar. La extrapolación de la relación de la raíz cúbica implica que el tercio restante de las primarias tienen secundarias de masa no estelar, i.e., compañeras cercanas cuyas masas son menores que 0.07 masas solares.

Para sistemas con periodos mayores de aproximadamente 100 años la distribución de las secundarias sigue la función dada por van Rhijn. Estos sistemas deben ser el resultado de condensaciones que se contrajeron separadamente pero que están amarradas gravitacionalmente. A grosso modo, tres cuartos de todas las primarias en la muestra tienen tales compañeras distantes, todas éstas a su vez pueden ser sistemas cerrados formados por fisión. Evidentemente las estrellas únicas son raras entre las enanas de tipo solar.

ABSTRACT

A systematic search for binaries in a sample of 123 bright field stars of types F3-G2 IV or V is described. Combination of the results for 25 newly discovered spectroscopic binaries with those of 21 spectroscopic, 23 visual, and 25 common-proper-motion pairs previously known brings to 88 the total number of companions identified in the sample. The distribution of the 88 periods shows a single maximum; the median period is 14 years.

The frequencies of singles: doubles: triples: quadruples are found to be 42: 46: 9: 2. Less than half of the stars are thus observed to be single. Estimates of the completeness of this search lead to a determination of the number of systems missed and to a determination of their secondary masses.

Analysis of the secondary-mass distributions, observed and predicted from completeness estimates, indicates the existence of two types of binaries.

For systems with periods less than about 100 years, the distribution of secondaries varies with the cube-root of the secondary mass. These systems must be the result of fission. Two-thirds of their primaries have companions of stellar mass. Extrapolation of the cube-root relation implies that the remaining one-third of the primaries have non-stellar secondaries, i.e., close companions whose masses are less than 0.07 solar masses.

For systems with periods larger than roughly 100 years the distribution of secondaries follows that given by the van Rhijn function. They must be the result of condensations that contracted separately but are bound gravitationally. Roughly three-fourths of all primaries in the sample have such distant companions, all of which are likely to be themselves close fission-systems. Evidently single stars are rare among solar-type dwarfs.

* Figures 1 and 2 have been reproduced from *Ap. J. Suppl. Ser.*, 1976, **30**, 273, published by the University of Chicago Press for the American Astronomical Society.

I. INTRODUCTION

This paper describes a systematic search for spectroscopic and visual binaries in a sample of 123 F3-G2 IV or V stars. The sample includes all such stars brighter than V = 5.5 mag and north of $\delta = -20°$. We obtained for each star 20 coudé spectra, mostly with a dispersion of 13 Å mm^{-1}; these were obtained with the Kitt Peak 2.1-m telescope. The resulting radial velocities were combined with published results and the wealth of data obtained by visual observers for these stars, which are mostly within 20 pc. The measurements were made by Saul Levy and the results have been published (Abt and Levy 1976).

The spectral range was selected with the following criteria:

1. To avoid the region of the Am and Ap stars, which have special binary characteristics (Abt 1961, Abt and Snowden 1973).
2. To include mostly narrow-lined stars for which good-quality radial velocities may be obtained.
3. To include the sun.
4. To stop at G2 because later stars become rare within our brightness limit.

II. BINARIES DETECTED

In the sample of 123 primaries there are 21 spectroscopic binaries with known orbital elements. For many of these we obtained improved orbital elements. We obtained first orbital elements for 25 additional stars. These tended to be the ones with small velocity amplitudes, so some of the results are marginal in quality. Visual observers have published orbital elements for 23 binaries in this sample. Finally, 25 stars have common proper motion (CPM) companions. For these we do not have known periods —only rough estimates based on the assumption that the current separations are measures of the mean separations. Since some of these binaries are observed by two methods, the total number of companions detected is 88.

Figure 1 shows the distribution of binaries by period. Please note that the distribution has a single maximum, rather than two as one would expect for stars of earlier type for which the spectroscopic and visual methods do not overlap well in period. The range in periods is a factor of 10^9.

The median period is 14 years, compared with values of 320 years by Luyten (1930) and 79 years by Kuiper (1935). The difference is probably due to the discovery of more spectroscopic binaries.

The observed frequency of doubles is such that there are seven companions for every ten primaries. This fraction does not show a systematic variation with spectral type within the F3-G2 range, or a systematic difference between stars near the zero-age main sequence and evolved stars near the upper boundary of the main-sequence band.

The observed ratios of single : double : triple : quadruple stars are 42 : 46 : 9 : 2 percent. Thus less than half of the stars are observed to be single.

III. INCOMPLETENESS ESTIMATES

We know that we are missing many of the actual binaries by our techniques, either due to low-mass companions, inclination aspects, or broad lines. However surprisingly, we can predict statistically many of the companions that we have overlooked. These

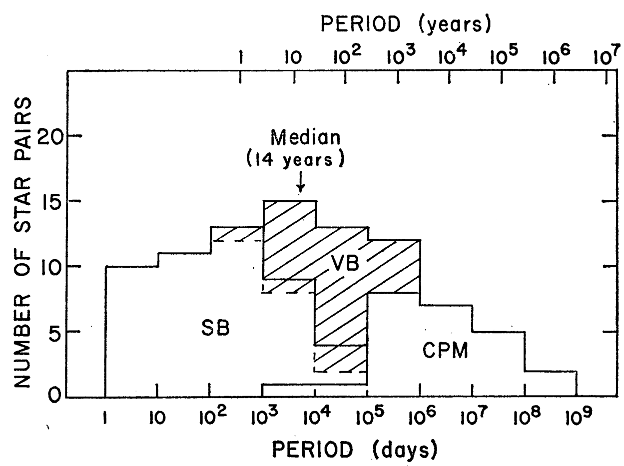

FIG. 1. The frequencies of observed binary orbital periods expressed on a logarithmic scale in days (*below*) and years (*above*). The cross-hatched area refers to systems with known visual orbital elements; this area overlaps the spectroscopic binary region (defined by solid lines). The periods for the CPM pairs are statistical and very uncertain. One CPM pair may coincide with a SB orbit; that overlap has not been indicated.

predictions are based on a set of seven assumptions, of which we give samples here:

1. Random orientation of orbital axes.
2. Failure to detect single-lined spectroscopic binaries (SB1) with $K_1 < 2.0$ km s^{-1}.
3. Failure to detect double-lined spectroscopic binaries (SB2) with $K_1 < 20$ km s^{-1}.
4. Failure to detect visual binaries with separation $a < 0.3$ arcsec and with a magnitude difference $\Delta V > 0.4$ mag.
5. Failure to detect CPM pairs with $a > 75$ arcsec.

Let us give examples of the incompleteness calculations.

Example 1: Six SB2's with periods $\sim 10^{-2}$ years were observed with $i > 21°$ and $K_1 > 20$ km s^{-1}. On the basis of assumption 1, we would expect 0.4 systems with $i < 21°$ and $K_1 < 20$ km s^{-1}.

Example 2: For each assumed $\mathcal{M}_2$ (in discrete steps) we can fit the observed systems with known mass functions to those with $K_1 > 2.0$ km s^{-1} and predict the ones of small inclination. In an iterative method we also derived the frequencies of various secondary masses. Of course we lose the identity of the predicted companions with specific primaries.

Example 3: Among the visual binaries we will assume that the secondaries are on the main sequence and that the mass-luminosity relation will give the secondary masses. We know of one exception (Procyon) but suspect that such exceptions are rare. Visual secondaries fainter tha $V = 10$ mag and especially those fainter than $V = 13$ mag are often not measured, so frequencies of such systems are indeterminate at this stage in the analysis.

IV. SECONDARY MASS DISTRIBUTIONS

The incompleteness analysis was done for various period ranges and secondary masses. The results for the cases where the incompleteness estimates could be made and the values were mostly less than observed values are shown in Figure 2. The frequencies of various secondary masses (in steps of factors of 2) are shown for periods less than 100 years on the left and for longer periods on the right.

We see from Figure 2 that the mass distributions for the shorter periods do not obey the van Rhijn distribution, but rather vary as $\mathcal{M}_2^{1/3}$. For the longer periods the data fit the van Rhijn function within the observational errors.

These data suggest that there may be two mechanisms of binary formation. Perhaps we can identify the short-period binaries with stars formed from a single protostar condensation that fissioned or bifurcated because of too much angular momentum to form a single stable star. In such a division of a protostar, there is probably a tendency for the members of a binary to have roughly equal masses, rather than the disparate masses that would result in a van Rhijn distribution. The long-period binaries then would be formed from pairs of condensations that contracted separately but were held together gravitationally. For separate condensations the van Rhijn distributions should hold for both the primaries and secondaries.

The period break between the two kinds of binaries occurs at about 100 years, which corresponds to a mean separation of about 28 AU between star centers. If 2 $\mathcal{M}_\odot$ were distributed uniformily over a sphere of this radius, the mean density would be 10^{-10} gm cm^{-3}; this value is roughly that expected (Goldreich and Ward 1973) to occur in the solar nebula at the time of planetary differentiation.

V. MULTIPLICITY

If we integrate the $N \propto \mathcal{M}^{1/3}$ relation for periods less than 100 years and masses greater than 0.07 $\mathcal{M}_\odot$, we find that there are 82 stellar companions for the 123 primaries, or an average of 0.67 close companions per primary. However, I see no obvious reason why the mass distribution should go to zero at 0.07 $\mathcal{M}_\odot$, although we do no know if the functional relation continues to be $\mathcal{M}_2^{1/3}$. If we extrapolate the distribution to zero mass with the same functional relationship, we can find by integration that one-third of the primaries have a companion with a mass between 0.07 $\mathcal{M}_\odot$ and zero mass. This range would include planets. This result would mean that *all* primaries have nearby companions.

It has been known for some time that the total angular momentum in an interstellar cloud contain-

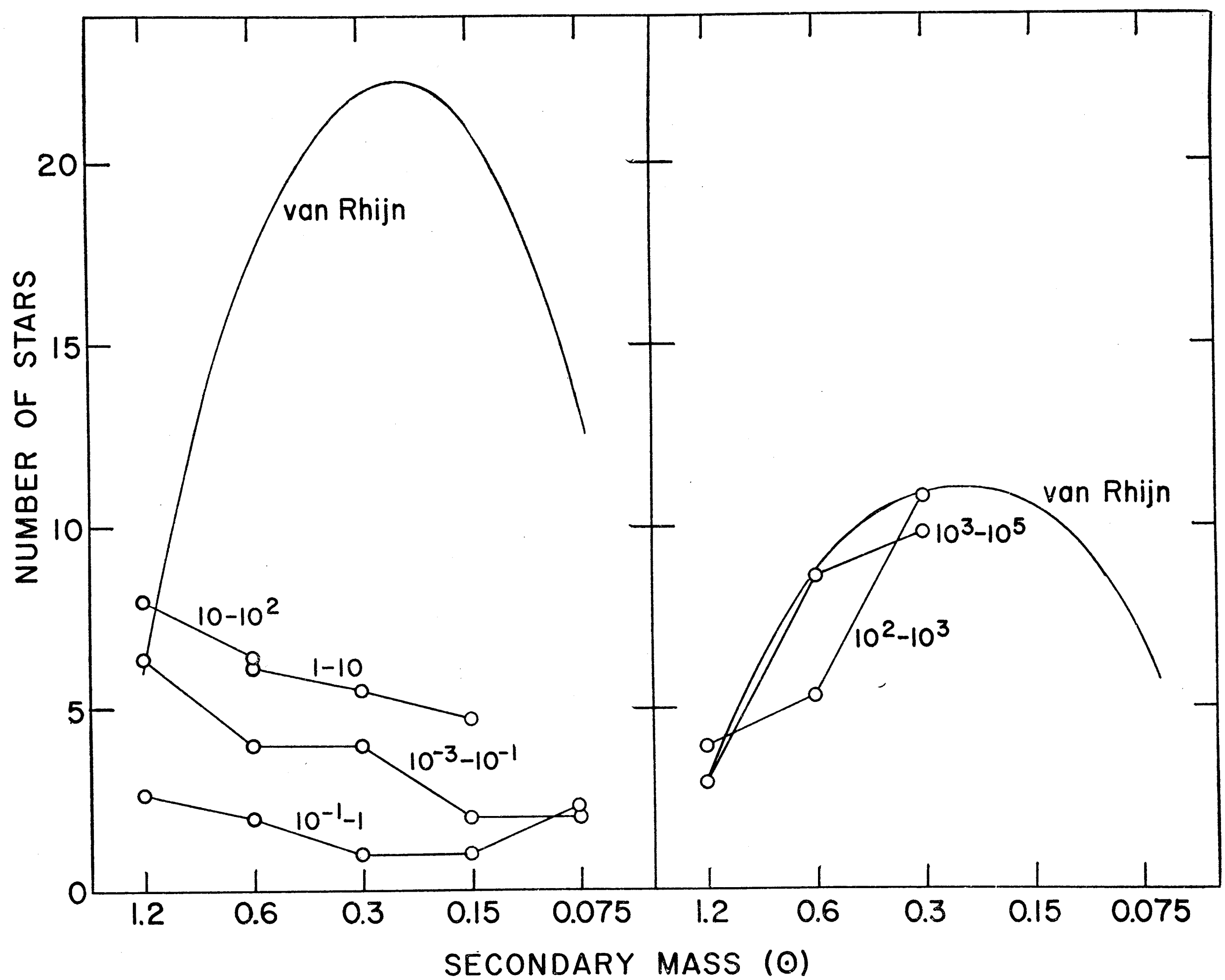

FIG. 2. The frequencies of binaries, both observed and predicted, having various secondary masses (grouped in bins) are plotted as circles. The segments connect points for various period ranges expressed in years. Data for binaries with periods less than 100 years are shown in the left panel and for binaries with larger periods in the right panel. The van Rhijn luminosity function, transformed to a mass scale, has been normalized at 6.0 stars of mass 1.2 $\mathfrak{M}_{\odot}$, in the left panel and at 3.0 stars of mass 1.2 $\mathfrak{M}_{\odot}$ in the right panel.

ing roughly 1 $\mathfrak{M}_{\odot}$ is far more than can be absorbed by a single stable star. However, if all protostars subdivided and most of the angular momentum went into orbital motion, the problem may disappear. Therefore the possibility that essentially all solar-type dwarfs are double (or multiple) makes quite a bit of sense.

If we now integrate the van Rhijn distribution for the long-period binaries from 1.2 to 0.7 $\mathfrak{M}_{\odot}$, we find that about 72 percent of the primaries have a distant companion (in addition to the close one). Of course this fraction is uncertain because of the uncertainties in the van Rhijn distribution at low masses, and we do not know how to extrapolate the van Rhijn distribution to planetary masses. In addition, the distant companion, presumably formed from a separate protostar, may itself be a closely-spaced double for the same reason —to use up excess angular momentum— that the primary is a close double.

We conclude from this discussion that perhaps every solar-type dwarf has a nearby companion that was formed from the same protostar condensation; two-thirds of the secondaries are stars while one-third are companions that are too low in mass to be stars producing energy by nuclear reactions in their cores. And roughly three-fourths of the primaries have distant companions (that may all be double) that were formed from separate protostar condensations. Evidently single stars are rare.

A straightforward integration tells us that the total mass of all the secondary stars is just half of the mass of all the primaries. Thus secondaries will not explain the hidden mass in galactic structure problems. The visual brightness of the multiple systems average 0.22 mag brighter than the primaries.

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DISCUSSION

Pişmiş: You have shown us the distribution of the secondary masses. Your material should enable you to obtain the distribution of the ratios of the masses. What is this distribution?
Abt: The distribution is the same because the primaries are all F3-G2 IV, V and therefore have masses of about 1.2 $\mathcal{M}_\odot$.
Worley: That all stars are at least double confirms my happiest expectations. But I would question your assumption that incompleteness in discovery of orbits for visual pairs of $\rho < 0.3$ arcsec begins at $\Delta m = 0.4$. I would expect $\Delta m \sim 1.0$.
Abt: Actually, the incompleteness is a steadily decreasing function of increasing magnitude difference. I just made an abrupt cutoff to make the analysis simpler. The position of the cutoff (in magnitude difference) was determined from a lack of systems with larger differences.
Poveda: Why is it that you have only one maximum in the distribution of periods when there are two types of binaries?
Abt: This is perhaps surprising, unless the two types of binaries overlap in semi-major separations. I believe that Dr. Huang is going to discuss this matter.
King: Is your limit of 75 arcsec for common proper motion pairs realistic? Should they not have been picked up out to a much greater distance?
Abt: For a 4th-magnitude star there is a 50-50 chance that there is a 13th or 14th-magnitude field star within 60 arcsec. Observers have known this and have suspected that faint stars 60 arcsec or more from bright ones are usually field stars and therefore have not bothered to measure their motions. But a search for distant common proper motion companions of bright stars could fairly easily be made.
van de Kamp: I noticed with pleasure and surprise the van Rhijn curve. Is there no later information? Van Rhijn's work is about 50 years old.
Abt: The faint end of the curve may need revision, the bright portion is all right.