STATISTICAL INVESTIGATION OF SPECTROSCOPIC BINARY STARS

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ABSTRACT

A catalog of physical parameters of about 1000 spectroscopic binary stars (SB), based on the Batten catalog, its extensions, and newly published data has been compiled. Masses of stars' components (M_1 and M_2), mass ratios of components ($q = M_1/M_2$) and orbital angular momenta are computed, wherever possible. It is probable that the initial mass function of the primaries is non-monotonic and is described only approximately by a power-law. The distribution of q of double-line SB has a sharp maximum near q = 1, that of single-line SB, near q = 0.3. SB with $1.5 \lesssim M_1/M_\odot \lesssim 10$ and semiaxes of orbits $a \lesssim 10\ R_\odot$ probably do not form. A number of assumed "initial" distributions of M_1, q and a were transformed with the aim of obtaining "observed" distributions taking into account the observational selection due to the luminosities of the components, their radial velocities, inclinations of the orbits, and the effects of matter exchange between the components. The best agreement with the observations is obtained for the combination of a power-law initial mass function $\xi(M) \sim M^{-2.35}$, a distribution of q with a maximum near 1 and a distribution of semiaxes with $dN/da \sim 1/a$.

In order to investigate the origin and evolution of close binary stars (CBS) it is necessary to know the distribution of and correlation between the masses of their components M_1 and M_2, semiaxes of their orbits a, mass ratios of the components $q = M_2/M_1$, etc. The only source of this information is the catalogs of spectroscopic binary stars (SB) for which under certain assumptions it is possible to compute M_1, M_2, a and q. We have compiled a catalog of SB, based on the 6th Batten catalog (Batten, 1967), its extensions (Pedoussant and Ginestet, 1971; Pedoussant and Carquillat, 1973), and data published up to the end of 1978. Now it contains data on about 1000 stars. It appeared possible to compute M_1, M_2, a and q for 292 stars with two visible spectra (SB2) and 534 stars with one visible spectrum (SB1). The obtained distributions are by no means the real "innate" distributions of stellar

M. J. Plavec, D. M. Popper and R. K. Ulrich (eds.), Close Binary Stars: Observations and Interpretation, 15–22.

parameters. Because of this we tried to to find the latter by correcting some trial initial distributions for effects of observational selection and stellar evolution.

Referring for computational details and more extensive accounts to our papers (Kraitcheva et al., 1978, 1979; Piskunov et al., 1979) we shall report here some of the most interesting results.

Our results indicate that SB2s are mostly systems prior to mass exchange. Because of this they are well suited for a determination of the initial mass function (IMF) of the primaries of CBS. To get the IMF the observed number of stars with a given M_1 must be divided by the product of the volume of space in which systems with given M_1 are seen and their lifetime. The IMF of 121 SB2s with known inclinations of orbits is shown in Fig. 1. On the average $dN \sim M^{-1.3}\, dM$. The difference from the slope of Salpeter's IMF for single stars is partly due to the selection effects and partly, as it seems to us, to the increased interest of observers in the massive CBS.

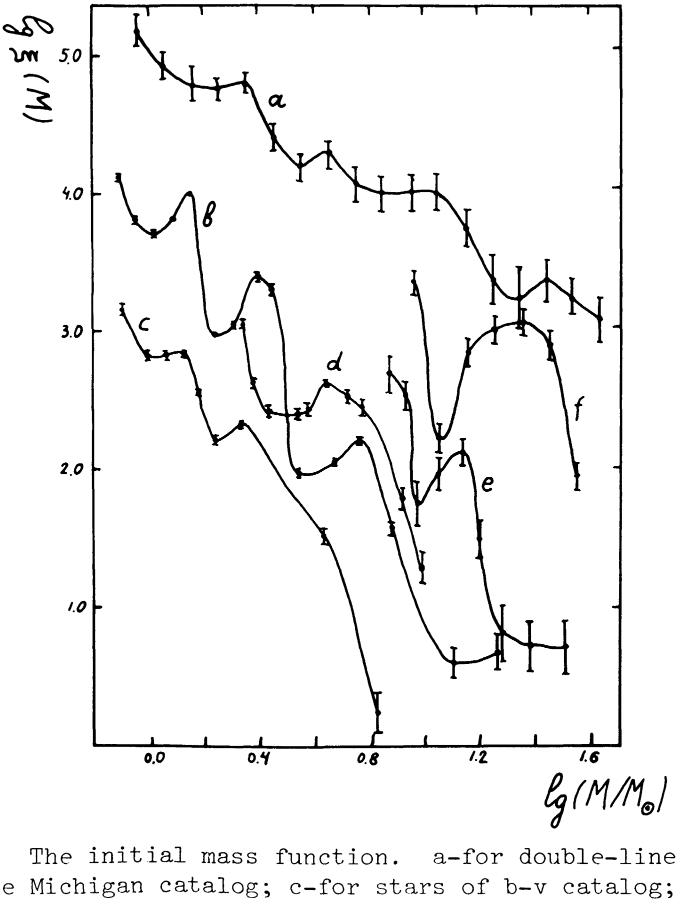

Fig. 1. The initial mass function. a-for double-line SB; b-for stars of the Michigan catalog; c-for stars of b-v catalog; d-for stars of u-b catalog; e-for the brightest stars of LMC clusters; f-for the brightest field supergiants. Dispersion ($\sqrt{n}$) is shown.

Popov (1968) and Svechnikov (1969) on the basis of much more limited data claimed that the IMF may be non-monotonic. With the aim of studying this problem in more detail, we computed the IMF using the spectra of single main-sequence stars ($\sim$ 15000 stars from the Michigan catalog by Houk and Cowley, 1975), colors b-v and u-b of main sequence stars ($\sim$ 2700 and $\sim$ 1600 stars, respectively, from the catalog of Mermilliod and Nicolet, 1977), luminosities of the brightest stars of the LMC ($\sim$500 stars, Hodge et al., 1970), spectra of Ia-Ib field supergiants ($\sim$700 stars, Piskunov, 1977). Almost all IMF are non-monotonic with some details recurring in the same mass intervals. Our results are not convincing enough for assertion that the IMF is really non-monotonic. The problem deserves further examination (see also Piskunov et al., 1979)

As SB2s are mostly systems prior to mass exchange, their distribution in the a-M plane (Fig. 2) reflects their distribution at the time of formation. The bottom line in Fig. 2 corresponds to the ZAMS contact systems with components of equal mass. The $a < 10\ R_{\odot}$, $M_1 > 1.5\ M_{\odot}$ region is almost empty. There are no selection effects that prevent discovery of stars with such parameters. Three stars that lie in this region, BV 382 Cep, UZ Pup, and V Sge display mass exchange and are probably evolved To explain the existence of the empty region we may assume that $a \sim 10\ R_{\odot}$ corresponds to the maximum angular momentum of a protostar in hydrostatic equilibrium on the Hayashi border. If the masses of the components are lower than about $1.5\ M_{\odot}$, the magnetic braking continuously supported by convection in the envelopes may be effective enough for gradual shrinking of the orbit up to contact. This is similar to the process proposed by Eggleton (1976) as an explanation of the origin of the cataclysmic variables. Detached RS CVn stars, as follows from the time scales (10^7 years) of the decrease of their periods (Hall, 1978), may be in a similar evolutionary stage. Thus the region with $a < 10\ R_{\odot}$, $M_1 < 1.5\ M_{\odot}$ is continuously filled by stars, but the region with larger masses remains empty.

A simple estimate shows that the orbital angular momentum of a contact massive ($M_1 > 10\ M_{\odot}$) binary system with $q \sim 1$ is at least six times higher than the limiting axial angular momentum of a single star with the same mass. We see five possibilities for solving the problem. Angular momentum of a rotating pre-main sequence star may be lost by magnetic braking. A system with $q \ll 1$ or a planetary system or a star with a double core in a common envelope may be formed. Finally, it is possible that massive single stars do not form at all. As concerns double--core stars, they may be stable, at least on a thermal time scale (Tutukov and Yungelson, 1979). Energy of rotation and angular momentum of the cores may be transferred by some mechanism to the common envelope and lost from the surface with the matter. It is possible that some of the Of, Be, or P Cygni type stars are such objects.

We have tried to find "innate" distributions of SBs over their main parameters M_1, a, and q, taking some trivial initial distributions and correcting them for different effects of observational selection and stellar evolution in order to obtain agreement with observed distributions. These effects are: random orientation of orbital planes;

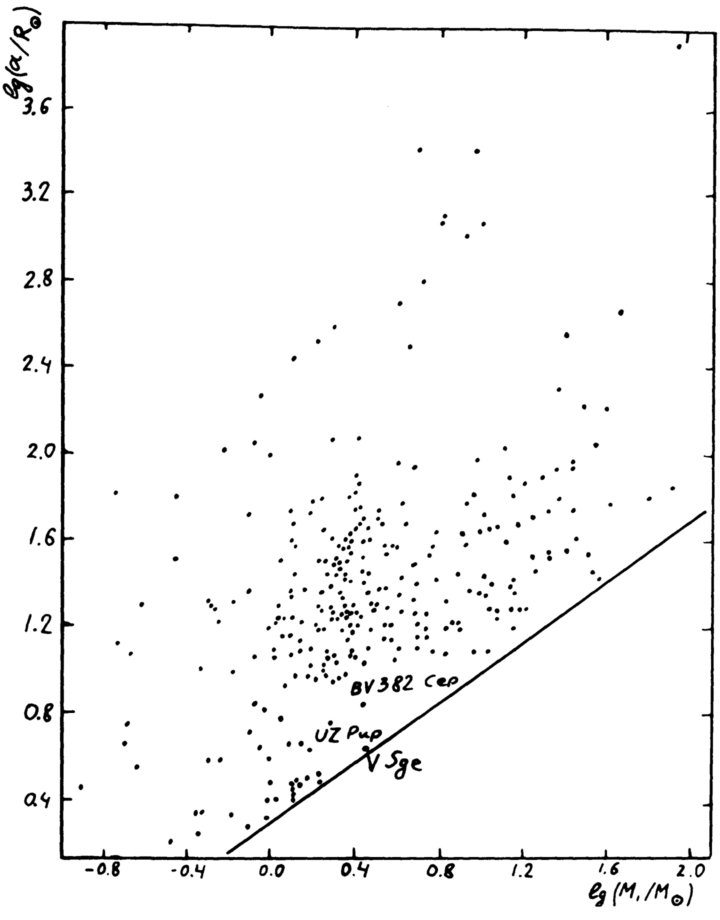

Fig. 2. Double-line SB in lg a-la M_1 plane.

dependence of discovery probability on the semiamplitude of radial velocity K_1 sin i; existence of a lower limit on K_1 sin i which still allows discovery of duplicity by means of spectroscopy and the dependence of this limit on the spectrum of the primary; differences in lifetimes of stars; existence of a limiting visual stellar magnitude for spectroscopic binaries ($\sim 10^m$) and the consequent differences in the limiting distances to observable stars combined with the appropriate spatial distribution (spherical or disc-like); mass exchange between the components leading to changes in their masses, lifetimes, luminosities, semiaxes of orbits; mass loss from the system. In the course of the computation it is possible to separate single- and double-line systems, because for discovery of double spectral lines the semiamplitude of the radial velocity must exceed some limit which depends on the spectrum, and because the difference of visual magnitudes of the components must be less than 1^m.

The theoretical distribution of the mass ratios may be computed as an integral

$$\frac{dN}{dq} = \phi_1(\phi)\int_{M_{1_{\min}}}^{M_{1_{\max}}} \int_{a_{\min}}^{a_{\max}} \int_0^{\pi/2} \phi_2(M_1)\ \phi_3(M_1)\ \phi_4(q,M\ ,a,i)\ \phi_5(a)\ dM_1 da\ di$$

where ϕ_1 is the distribution of q, ϕ_2 the IMF, ϕ_3 is the product of the lifetime of the system with given M_1 - T and of volume of space in which is system is seen -V, ϕ_4 describes the dependence of detection probability on the semiamplitude of the radial velocity, ϕ_5 is the distribution of semiaxes ($\int_{a_{\min}}^{a_{\max}} \phi_5(a)\ da = 1$, and $\int_0^1 \phi_1(q)\ d(q) = 1$). Here functions ϕ_1, ϕ_2, ϕ_5 are our trial functions. Similar expressions could be written for dN/dM_1 and dN/da. Distributions of parameters of systems prior and post mass exchange (we shall name the latter "evolved" systems) can be computed similarly using different integration limits and taking into account changes in the properties of binaries caused by mass exchange/loss from the system. All numerical data necessary for the computations could be found either from the analysis of the catalog of SBs or in the results of evolutionary computations for single and double stars (for more details see the paper by Kraitcheva et al., 1979).

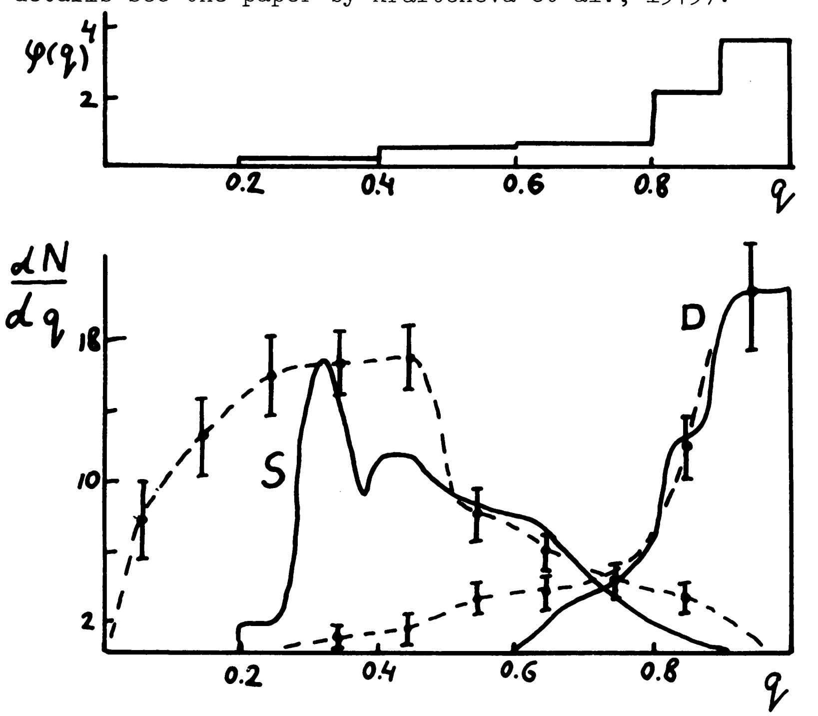

Fig. 3. The initial distribution of binaries over the mass ratio (ϕ) and observed distributions for single-line binaries (S) and double line binaries (D).

We have tried three distributions over q: 1) one with a maximum near q = 1 (Fig. 3a) (Popov, 1970; Lucy and Ricco, 1979); 2) a bimodal one in which the number of systems with $q > 0.4$ is roughly equal to the number of them with $q < 0.4$ (see e.g. Trimble, 1976); 3) one with the number of systems increasing with decreasing q (see e.g. Jashek, 1976). As an initial distribution of masses of unevolved primaries we have used the power law $\phi_2(M_1) = 0.03\ M_2^{-2.35}$ with $M_{1\ min} = 0.8\ M_\odot$, $M_{1\ max} = 30\ M_\odot$; the initial distribution of semiaxes was $\phi_5(a) = 1/a$, with a_{min} corresponding to contact on the ZAMS, $a_{max} = 2000\ R_\odot$. We used a smooth IMF because its nonmonotony is still questionable and because we were interested in the most general properties of distributions.

The best agreement with the observations both in the shape of the curves and in the ratio of numbers of SB1 and SB2 Ns/Nd has been obtained for the case of the initial $\phi_1(q)$ with a maximum near q = 1: see Fig. 3 in which we show both the "theoretical" distribution and the distribution of stars in our catalog smoothed over q; the latter is close to that obtained by Trimble (1976).

Our computations showed that the most severe selection factor is the dependence of the probability of discovery on the semiamplitude of radial velocity. It allows discovery of only about 1/3 of all SBs. This suggests once more that probably almost all stars are members of binaries and that single stars are rather exceptions to the rule. The factor V · T that reaches its maximum value near $\lg M_1 = 0.3 - 0.4$ cuts out low-mass systems because of their weakness and high-mass systems because of their short lifetimes.

It appears that the "theoretical" double-line systems and single-line systems with $q > 0.4$ are mostly unevolved systems; single-line systems with $q < 0.4$ are mainly evolved main-sequence systems. Among the "theoretical" double-line stars about 1/3 are the "A"-systems, 2/3 are "B" and "C"-systems; this proportion is close to that for the observed stars. For unevolved single-line systems this proportion is 1/4 and 3/4. (Here A,B,C are the conventional types of close binaries (see e.g. Paczynski, 1971).) Probably, the initial $\phi_1(q)$ after Popov (1970) with maximum near q = 1 underestimates the number of systems with low q. However, the bimodal initial $\phi_1(q)$ (Trimble, 1976) produces a theoretical value of Ns/Nd twice as large as the observed one. The initial function $\phi_1(q)$ which increases towards small q's produces distributions that do not agree with observations either in their shapes or in Ns/Nd. The "theoretical" number of evolved systems with low q's increases if we take into account possible mass and momentum loss from the system.

The theoretical distributions dN/dM_1 for SB2 and SB1 and dN/da for SB2 agree satisfactorily with the observed ones. The deficit of systems with $\lg a = 0.5 - 0.9$ and $\lg M_1 = 0.0 - 0.3$ may be explained by the existence of an empty "region" in the $a - M_1$ plane (see above). Our trial distribution $\phi_5(a) \sim 1/a$ probably overestimates the number of very close systems. This causes the shift between the observed and computed distributions of single-line systems.

Summarizing, the analysis of the catalog of SB itself and the computation of "theoretical" distributions of CB parameters which take into account the effects of observational selection and stellar evolution, has provided much information on vital properties of CBs. The above described method of computation has shown its great efficiency and will be extended to take into account still unconsidered effects.

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DISCUSSION FOLLOWING TUTUKOV AND YUNGELSON

Lucy: How do you eliminate evolved--i.e., post-mass-exchange-systems from your sample of SBI's?

Tutukov: We did not make that but our program simulates a simple approximation of evolution of a component. All systems with $\Delta M_b \lesssim 1^m$ are counted by the program as single line binaries if the luminosity and the semi-amplitude of the radial velocity were enough to distinguish the star as a binary. The nature of the hidden component isn't important in this case.