HIDDEN POPULATION OF ALGOLS

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\textbf{Abstract.} We present results of Monte Carlo simulation aiming at the estimate of the frequency of semi-detached Algol-type binaries among the stars observed as single ones. When account is made for various detection biases (mostly due to inclination of orbits), the fraction of Algols among Galactic disk stars appears to be 0.1–0.2\%. However, this number should be regarded as a lower limit only, since there are still unaccounted selection effects and other types of photometrically unresolved binaries. Hidden binarity appears to be an important phenomenon that should be taken into account when considering stellar statistics and construction of fundamental relations between stellar parameters.

\textbf{Key words:} Stars: binaries: eclipsing — binaries: close

1. INTRODUCTION

Binary stars can be detected by various techniques. Components of the closest pairs can be resolved, so that the stars are observed as visual or interferometric binaries. For more distant (and, consequently, photometrically unresolved) binaries, a successful combination of the inclination and size of the orbit, as well as of components’ parameters, can lead to observed eclipses and/or Doppler shift of spectral lines. Close binaries in late stages of their evolution can demonstrate variability in X-ray or radio emission.

However, at least a part of binary systems remain undiscovered by modern techniques. In particular, a close binary, observed as an eclipsing variable, would not be detected were its orbit inclination less than 30–40°, as we show below. Such
“pole-on” binaries look like single stars. As a result, the single star statistics is biased, and we should take this into account when constructing calibrating relations like the mass-luminosity relation (Malkov 2007), compiling the luminosity function (discussed in Piskunov & Malkov 1991 and Malkov et al. 1998 for main-sequence and pre-main-sequence stars, respectively), or estimating the local missing mass (Malkov 1994).

The principal goal of this work is to compare the numbers of stars classified as Algol-type eclipsing binaries (hereafter Algols) based on their light curves and those semi-detached systems with similar components where eclipses are not observed. In the present study, we limit ourselves to Algols, as they are one of the most representative types of eclipsing binaries. Stars of other types will be examined in further studies.

2. CLASSIFICATION OF ALGOLS

A classification scheme for semi-detached systems was proposed by Popper (1980), who divided them into three groups: (i) the more massive systems in which the hotter component is an early B-type star and the cooler one, a star of type B or early A; (ii) the more “typical” Algol systems of lower mass in which the more massive component has a spectral type in the range from mid-B to early F and the companion is of type F or later; (iii) later-type subgiant and giant semi-detached systems. In the present study, we deal with group (ii) stars.

One of the most comprehensive sources of data on Algols is the Catalogue of (411) Algol type binary stars by Budding et al. (2004). It contains, in particular, data on physical parameters of the components (mass, luminosity, temperature, radius, etc.), when known. Analysis of these data together with those from the Surkova & Svechnikov (2004) catalogue of Algols shows that, in the majority (about 70%) of Algols, the accretor is hotter, smaller, more massive and more luminous than the donor. In the remaining 30% of objects, the accretor is hotter, larger, more massive and more luminous than the donor. Hereafter we call such stars “regular” and “inverse” Algols, respectively.

It should be noted that, according to Budding et al. (2004) and Surkova & Svechnikov (2004) data, there are a few (about a dozen) so-called “rare” Algols, where the accretor is hotter, smaller, more massive and less luminous than the donor. Examples are HH Car and KU Cyg. Finally, there is an extremely small class of the (so-called “marginal”) Algols, where the accretor is hotter, smaller, less massive and more luminous than the donor. SS Cam belongs to that class, and about five more systems are considered to be candidates to “marginal” Algols.

Assuming similar conditions for formation of all Algols, it can be supposed that “marginal”, “rare”, “regular” and “inverse” Algols represent four consequent stages of evolution of a semi-detached binary. Note that, in all cases, the accretor is hotter than the donor.

3. MONTE CARLO SIMULATIONS

We generate a set of objects with primary constrained pairing (here we use the classification scheme terms of pairing scenaria proposed by Kouwenhoven et al. 2008) of objects. The mass $m_a$ of the primary (hotter, more massive accretor) is drawn from a pre-assumed mass distribution $f_a(m)$, and the mass ratio $q$ is drawn
from a mass ratio distribution $\eta(q)$. Finally, the donor mass $m_d = q m_a$ is calculated. We use $f_a(m) \propto m^{-2.5}$ for $m_a$ from 1 to 5 $m_\odot$, adopted from Eretnova and Svechnikov (1994, their Fig. 1b) for low-mass short-period semi-detached systems (so-called R CMa systems) and “typical” semi-detached systems, and $\eta(q) \propto q^{-2.8}$ for the mass ratio range from 0.10 to 0.75 (adopted from Svechnikov et al. 1989, their Fig. 20a).

According to evolutionary considerations, we discard pairs where $m_d \leq 0.15 m_\odot$ or $m_d + m_a > 6.25 m_\odot$. Here, the lower limit for $m_d$ is the minimum mass of a He white dwarf, while the upper limit for the total mass is defined by adopted limit of $m_a \leq 5$.

It was shown by Popova et al. (1982) that the distribution of binaries over semi-major axes of orbits $a$ was satisfactorily described by the function $dN \sim d \log a$ for $10 R_\odot \leq a \leq 10^6 R_\odot$. Eretnova and Svechnikov (1994, their Fig. 3b, upper panel) confirm this distribution, and we use it over the $\log a$ range from 0.7 to 1.5. All systems are assumed to be circularized.

The orbits were assumed to be equiprobably oriented, resulting in a distribution of inclinations proportional to $\sin i$. Systems have a homogeneous spatial distribution. To estimate interstellar extinction, we use the standard cosecant law (Parenago 1940) with the coefficients $a_0 = 0.0016$ mag/pc and $\beta = 114$ pc, found by Sharov (1964).

Thus, we varied $m_a$, $q$, all orbital elements, and the distance to the system according to the above-mentioned functions.

The presence and depth of an eclipse in a system depend on components’ radii and temperatures and on the orbital inclination. To estimate effective temperatures of donors and accretors, we used the $T_{\text{eff}}$ – mass relations from Svechnikov et al. (1989). Radii of donors and accretors were estimated using relations from Svechnikov et al. (1989) and Gorda & Svechnikov (1998), respectively. Accretors were assumed to satisfy the main-sequence mass-radius relation, and donors were assumed to fill their Roche lobes. The Roche lobe radius was calculated according to Eggleton (1983).

We collected statistics of eclipsing and non-eclipsing simulated systems separately. If a given system happens to be eclipsing, we calculate its brightness in maximum, depth of primary minimum, and orbital period. Dependence of the primary minimum depth $A_1$ on the orbital inclination $i$ for simulated systems is shown in Fig. 1. It can be seen that $A_1$ can reach 4.5 mag (systems with maximum $T_{\text{eff}}$ difference of components demonstrate values that large) and that “extremely edge-on” systems ($i > 75^\circ$) cannot produce very shallow ($A_1 < 0^m.01$) minima.

4. OBSERVATIONAL DATA

To verify our procedure, we have compared characteristics of the simulated eclipsing binaries to those of observed Algols. The latter ones were drawn from the Catalogue of Eclipsing Variables, CEV, compiled by Malkov et al. (2006) mainly from the General Catalogue of Variable Stars, GCVS (Samus et al. 2013), upgraded by Avvakumova et al. (2013), and uploaded into the Binary stars database, BDB (Kaygorodov et al. 2012, Kovaleva et al. 2015). The results of our simulations were tested against a CEV-based sample of 415 Algols with original classification and 1726 systems classified as Algols using the procedure suggested by Malkov et al. (2007) and substantially modified by Avvakumova &
Malkov (2014), altogether 2141 systems.

Figure 2 illustrates the brightness (magnitude in maximum) distribution of catalogued Algols. One can see that the sample can be considered complete down to $V = 10.5$. This value will be used to correct the simulated sample for incompleteness.

Obviously, the simulated sample should be corrected for some selection effects. The depth of the primary minimum $A_1$ versus maximum system brightness is plotted in Fig. 3. An “avoidance triangle” in the lower right corner reflects the
difficulties in observations of shallow minima for faint stars. Consequently, we have discarded all stars with $A_1 < 0.12 \cdot V - 0.93$ (the solid line in Fig. 3) from the final statistics. Also, one can note a lack of stars in the upper right corner resulting from the absence of faint, high-amplitude systems in observational statistics: in their minimum brightness, they are too faint to be detected, classified, and included in the catalogues.

Besides the stars fainter than $V = 10.5$ and stars that fall in the “avoidance triangle” (see the previous paragraph), we have also removed stars with $A_1 < 0.05$, as there are no such “extremely shallow minimum” Algols in the CEV catalogue.

Distribution of the catalogued Algols over the brightness is compared with that for the Tycho-2 Catalogue (Høg et al. 2000) stars in Fig. 4.

4. COMPARISON OF SIMULATED AND OBSERVATIONAL DATA

Distributions of simulated and catalogued Algols over the depth of primary minima (Fig. 5) and the orbital periods (Fig. 6) demonstrate a satisfactory agreement between calculations and observations. In particular, we have managed to reproduce a quasi-triangle period distribution with a maximum at $\sim 2$ days. However, a few longest-period (periods longer than $\sim 15$ days) systems could not be
Our simulation procedure produces both “regular” and “inverse” Algols (see Section 2). The resulting fraction of simulated “inverse” eclipsing binaries among all, “regular” and “inverse”, systems is 0.22, which is reasonably close to the observational value of 0.3.

5. RESULTS AND DISCUSSION

After verification of the procedure, we compare, for our simulation, the number of Algols with eclipses and number of systems where eclipses are not observed. Distributions of all simulated systems and systems with eclipses over their brightness are shown in Fig. 7.

To assess the extent to which “pole-on” Algols can distort the observational statistics of single stars, one should compare, for a given visual magnitude, the
number of all observed stars and the number of observed Algols, corrected for systems where eclipses are not observed. This can be estimated from Figs. 4 and 7. For \( V = 8^m \), for instance, per 1000 Tycho-2 stars, one Algol is observed (and catalogued in CEV), and one more is hidden due to the “pole-on” orientation. Corresponding estimates for \( V = 10^m \) give a similar result: every 2500 Tycho-2 stars contain one observed and 4.3 hidden Algols.

So, as our analysis shows, some 0.1 to 0.2% of observed stars are, in fact, semi-detached binaries. Can we ignore this effect when making statistics of single stars? Probably not, due to the following reasons.

- The effect is not evenly distributed in the HRD. The majority of Algols, when observed as a single star, are classified as MS stars. On the other hand, Tycho-2 catalogue stars, used for comparison, are of all luminosity classes, and their additional selection should be performed to make our estimates
Fig. 8. Distribution of simulated systems over the accretor’s effective temperature: all systems (solid line) and systems with eclipses (dashed line).

Further, our results are averaged over B to G spectral types, but, as Fig. 8 shows, the effect is stronger for cool stars. Consequently, statistics of F-type stars is distorted stronger than our averaged estimates predict.

We have studied only one (though one of the most numerous) type of eclipsing binaries. Other representative types (detached main-sequence stars, contact W UMa stars, etc.) also contribute to the problem.

In the present study, we do not deal with systems undergoing the second mass exchange. Under certain conditions, a compact object, accreting the matter from its donor, may not produce X-ray or UV radiation and, consequently, will be observed as a single star. They appear to be not very important, but it is probably advisable to estimate a number of such systems and their influence on MS-star statistics.

Here we assume that if a system can demonstrate eclipses with minimum depth $A_1 > 0.05$, it is discovered as a binary with probability $P = 1$. Actually, this is not the case unless we deal with results of automatic surveys for variable stars, microlensing events, or exoplanets. Usually such surveys cover only small area on the sky.

In the comparison of our model to catalogued data, we were restricted by the CEV completeness limit for Algols. However, as can be seen in Fig. 7, the fainter objects we consider, the larger the fraction of hidden Algols is, i.e. the stronger is the effect.

We did not account for other observational biases, namely, some long period systems are missed in the model. However, this effect cannot be very important due to relatively small number of long-period systems (see, e.g., Fig. 6).

All of the listed reasons magnify the effect described above and increase, to varying degrees, relative amount of photometrically unresolved binaries among
observed “single” stars. We suppose that estimates made in this paper should be increased by an order of magnitude and will reach 1 to 2%, but this is a subject of a future study.

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