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Not peer-reviewed version

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Posted Date: 8 August 2023

doi: 10.20944/preprints202308.0598.v1

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Article

Gaia BH1: A Key for Understanding the Demography of Low- q Binaries in the Milky Way Galaxy

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Abstract: The recently discovered Gaia BH1 binary system, a Sun-like star and a dark object (presumably a black hole), may significantly change our understanding of the population of low- q binaries. The paper presents the components mass ratio distributions of binary systems of different observational classes. They all demonstrate a significant shortage of low- q systems. It is shown that this shortage can be filled with the help of search and study of objects like Gaia BH1. In addition, an approximate mass-temperature relation and mass ratio – magnitude difference relation for main-sequence stars are presented here.

Keywords: binary stars; orbital; eclipsing; spectroscopic; mass ratio distribution; Gaia

1. Introduction

In [1] it is reported about the discovery of binary system Gaia DR3 4373465352415301632 with unusual components. It is a bright, nearby Sun-like star ($T_{\text{eff}} = 5850$ K, $\log g = 4.5$) with mass $m_2 = 0.93$ (hereafter masses are given in solar mass), orbiting a dark object with mass $m_1 = 9.62 \pm 0.18$. The authors [1] believe that the dark object is a black hole, have given it the designation Gaia BH1 and admit that the origin of the system is uncertain. In [2] a boson star was proposed as an explanation of the nature of the dark object. We assume that this object really consists of a black hole and a Sun-like star, and there is nothing unusual about the origin of this binary system, Gaia BH1 just exhibits a rather small value of the q (the mass ratio of the components), which was even smaller in the epoch when the black hole was a massive star. Below we show the importance of such objects in our understanding low- q systems demography.

2. Mass ratio distribution of binaries

The statistics of binary systems with small component mass ratio $q (=m_2/m_1)$, so called low- q binaries, is poorly understood. Obviously, the components of such systems have, as a rule, very different luminosities. This high brightness contrast prevents the detections of such systems by astrometric, interferometric, photometric, spectroscopic, and other methods. This strong selection effect leads to the fact that modern catalogues and databases of binary stars of different observational types contain predominantly high- q binaries, while high-contrast systems remain undetected.

Indeed, the content of the catalogues of the main observational classes of binary stars show a relative abundance of high- q and an obvious lack of low- q systems.

2.1. Spectroscopic binaries

To construct q -distribution of spectroscopic binaries we have taken 1642 SB2 systems from the SB9 catalogue [3]. Their K_1/K_2 distribution (which is in fact q -distribution) is represented by the blue histogram in Figure 3. Here K_1 , K_2 are velocity amplitude of primary and secondary component, respectively.

2.2. Orbital binaries

Kepler's Third Law allows one to calculate the total mass (so called dynamical mass) of a binary system, for which period, semi-major axis and trigonometric parallax is known (this information is

usually available for orbital binaries: visual binaries with orbital solution). Alternatively, individual masses of (at least main-sequence) components (so called photometric mass) can be calculated from their visual brightness, trigonometric parallax, interstellar extinction and the mass-luminosity relation. This was performed by [4] for 3350 objects from the Sixth catalog of orbits of visual binary stars, ORB6 [5]. 326 of them demonstrate a decent agreement of dynamical and photometric masses. Their q -distribution is represented by the red histogram in Figure 3.

2.3. Double lined eclipsing binaries

Components of detached double lined eclipsing binaries (DLEB) satisfy the criterion that the mass and radius of them be known to $\pm 3\%$ or better. [6] make a critical compilation of 95 DLEB systems. Their q -distribution is represented by the green histogram in Figure 3.

2.4. Detached main-sequence eclipsing binaries

It is impossible to estimate the mass ratio of the components of an eclipsing binary without additional spectroscopic or astrometric observations. However, it is possible to roughly estimate the effective temperature ratio of the components. [7] proposed the following relation:

$$\left(\frac{T_{\text{eff},1}}{T_{\text{eff},2}}\right)^4 \approx \frac{1 + 0.4A_1}{1 + 0.4A_2} \quad (1)$$

where $T_{\text{eff},i}$ are effective temperature of the components, and A_1 , A_2 are depth of primary and secondary minimum, respectively.

To transfer the temperature ratio to the mass ratio, one can use well-studied DLEB objects, mentioned above, with highly accurate parameter values. Mass and effective temperature of DLEB components from [6] are shown in Figure 1. Three giants and components of the least massive system in the list, CM Dra, were removed from the set. Linear approximation was performed in logarithmic scale:

$$\log T_{\text{eff}} = 0.645 \log(m/m_{\odot}) + 3.730, \quad (2)$$

with correlation coefficient is 0.989 (a more detailed mass-temperature relation can be found, e.g., in [8]). This allows us to derive q from T_{eff} ratio:

$$\log q = \frac{1}{0.645} \log \left(\frac{T_{\text{eff},2}}{T_{\text{eff},1}} \right). \quad (3)$$

To construct a q -distribution for eclipsing binaries we used objects from the Catalogue of eclipsing variables, CEV [9]. The relation (2) is valid only for main-sequence stars, so we have selected only DM (detached main-sequence) systems from CEV. We selected systems that have DM evolutionary class published in the literature or assigned as a result of our own classification [10]. For 973 of them the depths of both minima are known, and for them the procedure of q estimation was performed.

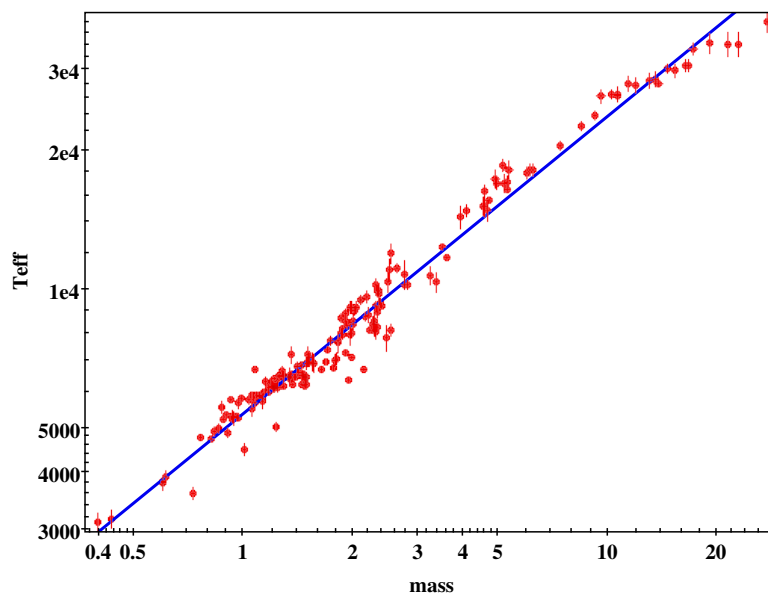


Figure 1. Mass ($m/m_{\odot}$) vs. T_{eff} of DLEB [6]. Blue line is a linear approximation.

2.5. Gaia DR3 non single stars

Gaia DR3 archive [11] provides access to a table containing Non single star (NSS) orbital models for sources compatible with an orbital two-body solution (NSS two body orbit, see description at https://gea.esac.esa.int/archive/documentation/GDR3/Gaia_archive/chap_datamodel/sec_dm_non--single_stars_tables/ssec_dm_nss_two_body_orbit.html). This covers astrometric binaries, spectroscopic binaries, eclipsing binaries and certain combinations thereof. This table was cross-matched with table of masses derived from the non-single stars solutions with orbital parameters in the DR3 NSS two body orbit table (Binary masses, see description at https://gea.esac.esa.int/archive/documentation/GDR3/Gaia_archive/chap_datamodel/sec_dm_performance_verification/ssec_dm_binary_masses.html). The resulting table contains 198880 binaries.

Masses of both components are derived here for three observational types of binaries: Orbital+SB2 (visual binaries with known orbital elements observed also spectroscopically, with lines of both components in spectrum), EclipsingSpectroSB2 (combined eclipsing binary + spectroscopic orbital model), Eclipsing+SB2 (double-lined eclipsing binaries, see Section 2.3). In all these cases mass of the primary component derived directly from the Non Single Stars solutions. These three observational types are represented by 46, 3, and 109 binary systems, respectively. Their q -distribution is shown by the magenta histogram in Figure 3.

In all other cases (Orbital+M1, 113246 binaries, SB1+M1, 60474 binaries, AstroSpectroSB1+M1, 17646 binaries, SB2+M1, 3945 binaries, Orbital+SB1+M1, 3026 binaries, Eclipsing+SB1+M1, 311 binaries, EclipsingSpectro+M1, 74 binaries), mass of the primary component is the input mass from isochrone fitting, see Appendix D of [12].

2.6. Interferometric binaries

The masses of binary stars can not be determined from interferometric observations, but it is often possible to estimate the magnitude difference, dm , or brightness ratio b_1/b_2 of the components. In particular, the dm or b_1/b_2 values are contained in the catalogues/lists presented in Table 1: Balega+ [14], CHARM2 [15], Strakhov+ [16].

Table 1. Catalogues/lists of interferometric binaries.

Catalogue	N_{dm}	$N_{0.1}$	Star	b_1/b_2	dm	SpT	q
Balega+	111	0	θ Ori A		3.23	B0V	0.45
CHARM2	313	0	ρ Ari	23.8	3.44	A3V	0.23
Strakhov+	372	1	HD 340178	315.5	6.25	A3	0.09

N_{dm} is the number of dm -measurements, $N_{0.1}$ is an estimated number of binaries with mass ratio $q \leq 0.1$, Star is the catalogued MS-object (earlier than mid-A) with the largest brightness ratio; its b_1/b_2 , dm , spectral type, and q (estimated from Figure 2) are also provided.

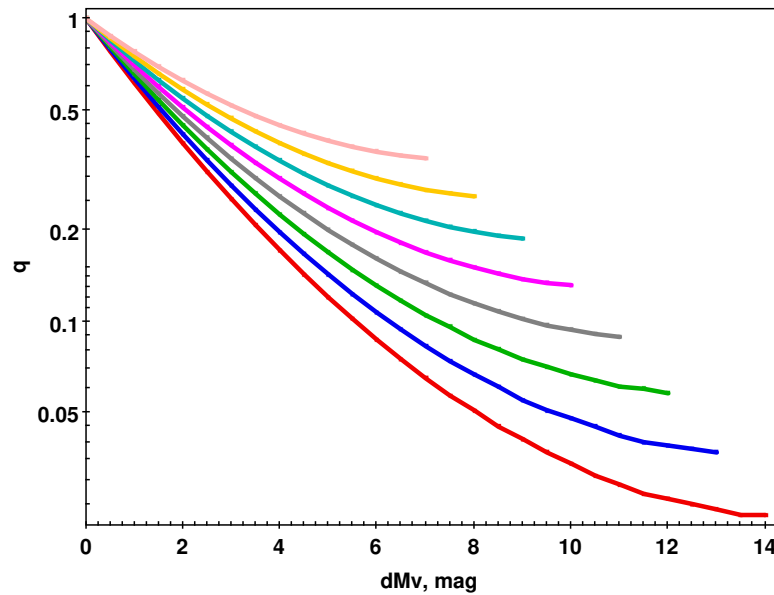


Figure 2. Mass ratio - magnitude difference relation for main-sequence binaries. Different curves represent relations for the following primary magnitudes M_{V1} (from top to bottom): 2, 1, 0, -1, -2, -3, -4, -5 mag. It corresponds, approximately, main-sequence spectral types A5, A1, B8, B4, B2.5, B1.5, B0, O8 [13], respectively. Secondary magnitude M_{V2} varies from M_{V1} to 9.0 mag (M0V). Note a logarithmic scale for Y-axis.

Unfortunately, due to the non-linearity of the mass-luminosity relation (MLR), it is not possible to unambiguously match the values of dm and q . But such relations can be obtained by fixing the mass (or luminosity) of one of the components. Figure 2 shows the relations for the fixed luminosity of the main component. The primary magnitude M_{V1} takes values 2, 1, 0, -1, -2, -3, -4, -5 mag, which correspond approximately to main-sequence spectral type A5, A1, B8, B4, B2.5, B1.5, B0, O8, respectively (the spectral types were estimated according to [13]). The luminosity of the secondary varies from M_{V1} to 9.0 mag (which corresponds roughly to M0V). The MLR from [8] was used in the calculations:

$$\log m(M_V) = 0.525 - 0.147M_V + 0.00737M_V^2, \quad (4)$$

which is valid for $-5.0 < M_V < 9.0$ mag.

Let us estimate from Figure 2 the dm values for systems whose component mass ratios can reach $q=0.1$ and less. It can be seen that the difference in the magnitudes of the components dm should be at least 9.0^m (for mid-A primaries) or 5.5^m (for late-O primaries), which, according to

$$dm \equiv m_2 - m_1 = 2.5 \log(b_1/b_2) \quad (5)$$

or

$$b_1/b_2 = 10^{0.4dm}, \quad (6)$$

correspond to the brightness ratio $b_1/b_2 \approx 4000$ and 160, respectively. The analysis of the interferometric catalogues mentioned above shows that the fraction of objects with such significant dm is vanishingly small (see the $N_{0.1}$ value in Table 1). Table 1 also contains information on the MS-object in the given catalogue, which has largest observed brightness ratio and which is earlier than mid-A. Thus, the results of modern interferometric observations also contain very poor data on low- q binaries.

The resulting q -distributions are shown in Figure 3. The figure does not reflect the real q -distributions of binary systems, it only demonstrates the degrees of our ignorance of the real situation in the low- q systems for binaries of various observational classes. It can be seen from Figure 3 that when studying systems with $0.1 \leq q \leq 0.5$ we can only count on the spectroscopic binaries, i.e., we are limited to relatively bright stars. The most dramatic situation is for Gaia non single stars and detached main-sequence eclipsing binaries, where we can analyze only systems with $q > 0.9$. It seems promising to combine data from the (very representative catalogue) NSS (see Section 2.5) with a source of accurate data on spectroscopic binaries SB9 (see Section 2.1). Preliminary results of such a study can be found, for example, in [17].

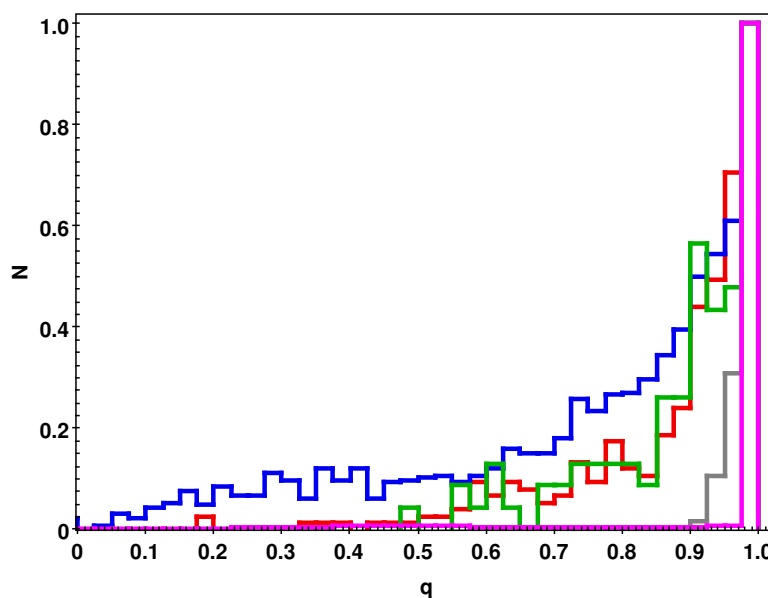


Figure 3. q -distribution of spectroscopic SB2 (blue), orbital (red), DLEB (green), detached main-sequence eclipsing (grey), and Gaia DR3 (magenta) binaries. The histograms are normalized to the maximum.

It should be added that the distribution of binary systems by the (relatively easily obtained from observations) mass ratio of the components for MS [18] and preMS [19] stars is a perfect tool for determining the shape of the stellar initial mass function (IMF), which can not be observed directly and should be estimated from the indirect techniques [20] (see also the recent study on the relationship of IMF, pairing function and q -distribution [21]).

3. Gaia BH1 – a rare low- q binary

In Section 2 it was shown that we have a notable lack of information about low- q systems. From this point of view, the Gaia BH1 is a very valuable finding, the importance of which cannot be overestimated. Indeed, the mass of the black hole indicates that the initial mass of the massive component, according to the remnant mass versus initial stellar mass relation, was (depending on the details of the presupernova evolution of massive stars, especially relating to convection and mass loss) $m_{1,\text{ini}} = 23$ to $27 m_{\odot}$ [22,23]. This means that mass ratio of the pre – Gaia BH1 object was $q = 0.03$ - 0.04 , a value completely unattainable with current observations of binary stars.

Note that the orbital period $P_{\text{orb}} = 185.6$ days and modest eccentricity $e = 0.45$ of Gaia BH1 exclude the matter transfer in the system, now or in the past.

Therefore, it seems useful to continue the search for similar objects in the Gaia data archive. In particular, three low- q candidates can be recommended from the NSS two body orbit list mentioned in Section 2.5. These candidates, together with Gaia BH1, are presented in Table 2. In addition to the identifiers and component masses, Table 2 contains information on the Non-single-star (NSS) solution type (here “Orbital” means “Orbital model for an astrometric binary” and “AstroSpectroSB1” means “Combined astrometric + single lined spectroscopic orbital model”). This search will make it possible to accumulate the necessary statistics for analyzing low- q systems. In addition, it will be possible to learn to take into account the selection effects, that distort the statistics of binary systems of different observational classes.

Table 2. Gaia BH1 and other candidates to low- q binaries.

Source ID	NSS solution type	$m_1/m_\odot$	$m_2/m_\odot$
4373465352415301632 (BH1)	Orbital	0.95	12.81
1864406790238257536	AstroSpectroSB1	2.40	20.08
3640889032890567040	Orbital	1.01	123.47
6281177228434199296	Orbital	0.95	11.91

Funding: This research was funded by the Ministry of Science and Higher Education of the Russian Federation, according to the research project 13.2251.21.0177 (075-15-2022-1228).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: The author thanks Dana Kovaleva for the valuable remarks and suggestions.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SB9	9th Catalogue of Spectroscopic Binary Orbits
ORB6	Sixth Catalog of Orbits of Visual Binary Stars
DLEB	Double lined eclipsing binaries
CEV	Catalogue of eclipsing variables
DM	Detached main-sequence
NSS	Non single star
INT4	Fourth Catalog of Interferometric Measurements of Binary Stars
CHARM2	An updated Catalog of High Angular Resolution Measurements
MLR	Mass-luminosity relation
IMF	Initial mass function

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