Searching for gamma-ray binaries using GOSC and *Gaia* DR2

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Gamma-ray binaries, which contain a massive star and a compact object, are very interesting astrophysical laboratories because particle acceleration and radiation/absorption mechanisms are modulated by the orbital phase. However, only 8 of such sources are currently known: 4 composed of an O-type star and 4 of a Be-type star, being the systems with an O-type star runaways with respect to their environment. *Gaia* DR2 provides us with useful information of positions, proper motions and distances for 1332 million sources. To search for new gamma-ray binaries we have studied a sample of 370 O-type stars from the GOSC catalog. In *Gaia* DR2 all sources are treated as single stars. Therefore, we could expect bad astrometric solutions for some gamma-ray binaries because *Gaia* DR2 does not fit the 7 orbital parameters for binaries. We have used the *RUWE* quality indicator provided by *Gaia* DR2 to distinguish between bad astrometric solutions ($RUWE > 1.15$) and good astrometric solutions ($RUWE \leq 1.15$). Among the 370 O-type stars we have found 36 with bad astrometric solutions, some of which could be gamma-ray binaries. We have also computed the peculiar velocities of the remaining 334 O-type stars and found 74 runaways, some of which could also be part of new gamma-ray binaries. We conclude with a short discussion and an outlook of future work.

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1. Introduction

Gamma-ray binary systems are a particular type of X-ray emitting binaries composed of a compact object orbiting around a massive star and distinguished by their emission peak beyond 1 MeV in the non-thermal spectral energy distribution. We only know 8 of such systems: 4 composed of an O-type star and 4 of a Be-type star. Since they perform as astrophysical laboratories because their particle acceleration and absorption/radiation mechanism are modulated by their orbital phase, it is important to discover new similar systems. This work has the aim to search for new gamma-ray binary systems. To do that we have used a sample of 370 O-type stars from the GOSC catalog [1][2] and their astrometric and photometric parameters from *Gaia* DR2 [3][4]. We have developed two different studies. In the first one we have analyzed the *Gaia* DR2 goodness of fit. This catalog uses a 5-parameter solution (position, parallax and proper motion) and does not take into account the eventual 7 orbital parameters of a binary system when it fits the astrometric model. For this reason we expect a bad-behaved solution for stars belonging to binary systems. The other study has focused on the runaway nature of gamma-ray binaries. The evolution of these systems begins with two Main Sequence massive stars in a circular orbit. The most massive star evolves faster until it collapses and forms a neutron star (NS) compact object after its explosion as a supernova (SN). This explosion gives a kick to the binary system that can be symmetric or asymmetric, and can disrupt it depending on the explosion [5]. Due to this kick, the massive optical star can reach a high peculiar velocity with respect to its environment and became a runaway star. We have analyzed the peculiar velocity of the stars of our sample in order to determine if they can be considered as runaway stars.

2. The Catalog

To do our study we have started by using the 618 early type stars from the GOSC catalog [1][2]. We have cross-matched them with the data from *Gaia* DR2 in order to obtain their astrometric parameters. In this process we have lost some stars which do not appear in *Gaia* or have duplicated `source_id`. We also have removed stars with multiple component, according to the GOSC catalog information, and also the stars with spectral type later than B2. Our first study consists on searching for bad-behaved solutions that could be due to stars belonging to binary systems. However, we do not want to find those bad-behaved solutions because of large errors in the parallaxes, saturation or other bad parameters. Therefore, we cleaned our sample to obtain stars with relatively reliable astrometric data, which is also good for our second study. To do that we have applied the following quality cuts: 5 parameter solution, $G \geq 6$, `visibility_periods_used` ≥ 10 [6], `mean_varpi_factor_al` $\in [-0.23, 0.32]$, $|$`parallax_over_error`$| \geq 5$ [7] and positive parallaxes. Finally, we have obtained a sample of 370 O-type stars, located at distances between 0.1 and 6.2 kpc and in a Galactic latitude range between $-17°$ and $+13°$. Their G magnitude distribution is between 6 and 14 and it is centered around the value 9 (see Figure 1). Most of the stars are located in clusters or in associations, which are crowded star forming regions.

3. Analysis of the Goodness of fit

As we have explained in the Introduction, *Gaia* DR2 [3][4] does not take into account the 7
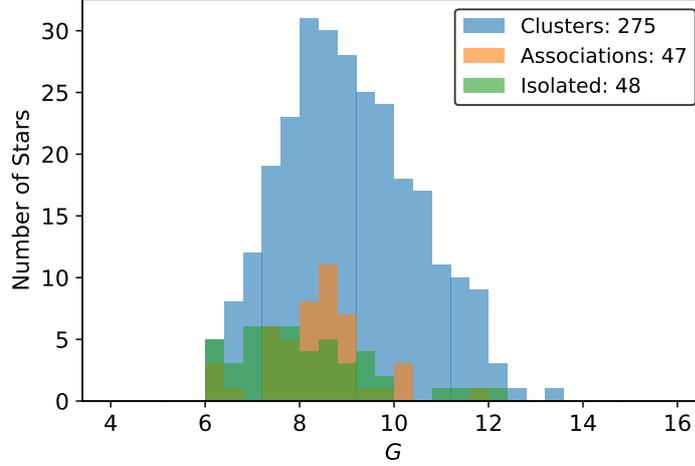
Figure 1: *G* distribution for the sample of 370 O-type stars. We show the number of stars that are located in clusters, associations or that are isolated stars according to the information provided by the GOSC catalog.

orbital parameters to fit binary systems. For this reason, we expect bad-behaved solutions for some binaries. *Gaia* DR2 provides us with several goodness of fit indicators that allow us to determine the quality and reliability of the astrometric data and to distinguish between well- and bad-behaved solutions. The most useful indicators are the Unit Weight Error (*UWE*) and the Renormalized Unit Weight Error (*RUWE*), both Gaussian distributions centered at a value of 1 [8]. They are defined as:

$$UWE = \sqrt{\frac{\chi^2}{\nu}} \, , \qquad RUWE = \frac{UWE}{U_0(G,C)} \, , \qquad (3.1)$$

where χ^2 is the along scan direction chi-square statistic, ν is the number of degrees of freedom and U_0 is a tabulated value that depends on G magnitude and the color index of the star. As the *UWE* indicator depends on the *G* magnitude and the color index, we have focused on the results obtained with the *RUWE* indicator. In Figure 2 we show both distributions for the 370 O-type stars. The values around 1 correspond to well-behaved solutions, while the values located at the tail of the distribution correspond to bad-behaved solutions. In order to separate both results, we have followed the method described in [8] but using a different sample more similar to the one of our O-type stars. We have obtained a threshold equal to 1.15 for the *RUWE* indicator, which means that values higher than this limit correspond to bad-behaved solutions. In our sample of 370 O-type stars, 36 of them have *RUWE* > 1.15, i.e, they have bad-behaved solutions. Some of them could be gamma-ray binary systems.

4. Searching for Runaway stars

O-type massive stars that belong to gamma-ray binaries present high peculiar velocities with respect to their environment [9][10][11]. We have analyzed the velocities of the stars from our sample in order to search for runaway stars. Taking into account the results of the previous section,
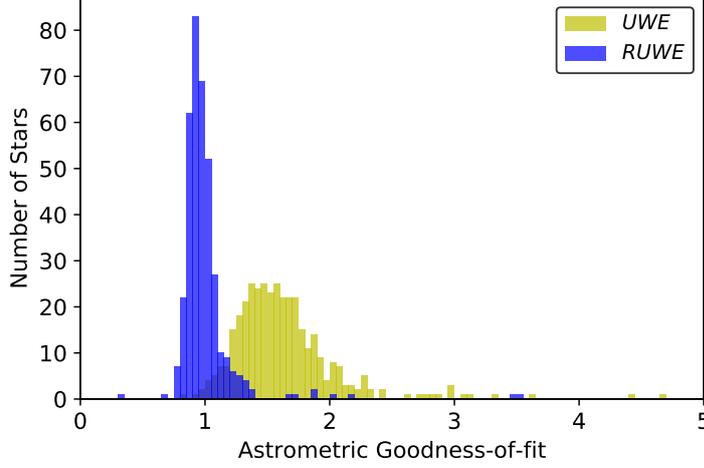
Figure 2: *UWE* and *RUWE* distributions for the 370 O-type stars.

we have only considered the stars with a well-behaved solution ($RUWE \leq 1.15$). Therefore, we have only analyzed a sample of 334 O-type stars. The A5 model from [12] provides us with the values of the peculiar velocity of the Sun relative to the Local Standard of Rest (LSR). The same model gives us the information of the Galactic rotation curve. Using the transformations in [13], we have obtained the peculiar velocity of the stars with respect to their Regional Standard of Rest (RSR):

$$V_{\mathrm{pec}} = \sqrt{U_{\mathrm{RSR}}^2 + V_{\mathrm{RSR}}^2 + W_{\mathrm{RSR}}^2} \tag{4.1}$$

where U_{RSR} is positive toward the Galactic center, V_{RSR} is defined toward the direction of the Galactic rotation and W_{RSR} is positive toward the North Galactic Pole (NGP). To calculate the peculiar velocity we need to know the radial velocity of the stars, but *Gaia* DR2 only provides us with this value for 6% of the stars in our 334 O-type stars sample. To deal with this problem we have imposed a heliocentric radial velocity that minimizes the peculiar velocity with respect to the RSR[1]. This assumption affects mainly the velocity components in the Galactic Plane because our 334 O-type stars are basically at small Galactic latitudes. In order to separate the radial velocity contribution in the plane components, we have defined a new reference system formed by one component perpendicular to the line of sight direction (V_{TAN}) and another component in the line of sight direction (V_{RAD}). These two components are referred to the RSR and they are calculated as a rotation of the (U_{RSR}, V_{RSR}) coordinates. The third component (W_{RSR}), perpendicular to the

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[1]Note that this value is not zero. In fact, for stars in the Galactic Plane (where we assume that the Sun is located), it corresponds to the heliocentric radial velocity of the RSR measured from the LSR, considering the chosen Galactic rotation curve, plus the radial velocity of the LSR as seen from the Sun. For stars above and below the Galactic Plane, the chosen heliocentric radial velocity to minimize the peculiar velocity has a component outside of the Galactic Plane, and thus it is slightly different (but never more than 5 km s^{-1}) than the heliocentric radial velocity of the RSR measured from the LSR, considering the chosen Galactic rotation curve, plus the radial velocity of the LSR as seen from the Sun. This is a conservative assumption.
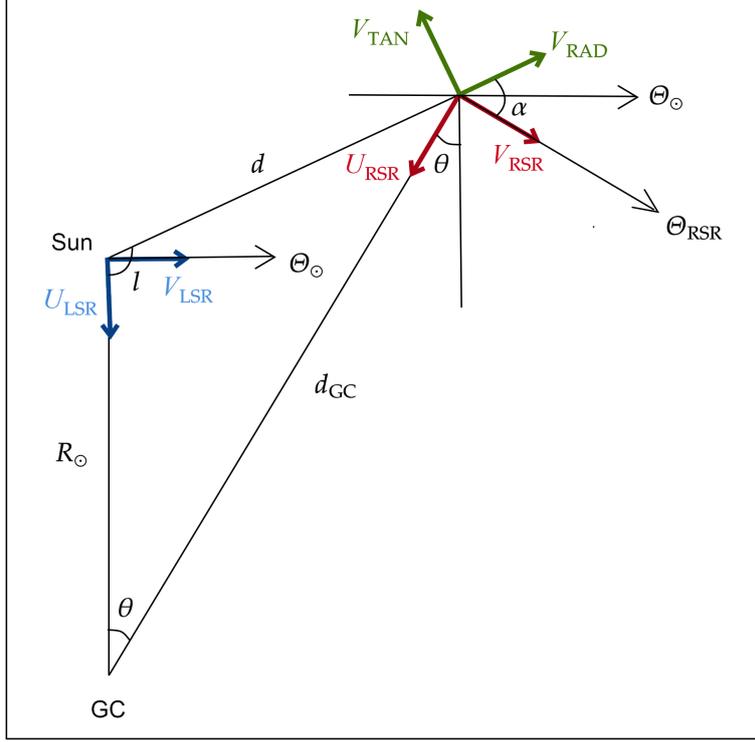
Figure 3: Reference systems in the Galactic Plane (W_{LSR} and W_{RSR} velocities are perpendicular to it).

Galactic Plane, is not affected by this change of reference system. In Figure 3 we show a diagram of the reference systems used in this study.

The advantage of using this new reference system is that the V_{RAD} component is zero for stars located in the Galactic Plane and typically smaller than 5 km s^{-1} for stars at small Galactic latitudes (see footnote 1). Therefore, to do our study we have used a 2-D approach (V_{TAN}, W_{RSR}). Our 334 O-type star distribution is composed of field stars, which define the environment velocity, and runaway stars, which have significant peculiar velocities with respect to their environment. In order to determine a criterion to separate the field stars from the runaway stars, we have defined the following ellipse:

$$E = \frac{(V_{\mathrm{TAN}} - \mu_{V_{\mathrm{TAN}}})^2}{\left(3 \cdot \sqrt{\sigma_{V_{\mathrm{TAN_d}}}^2 + \sigma_{V_{\mathrm{TAN_*}}}^2}\right)^2} + \frac{(W_{\mathrm{RSR}} - \mu_{W_{\mathrm{RSR}}})^2}{\left(3 \cdot \sqrt{\sigma_{W_{\mathrm{RSR_d}}}^2 + \sigma_{W_{\mathrm{RSR_*}}}^2}\right)^2} \tag{4.2}$$

where ($\mu_{V_{\mathrm{TAN}}}$, $\mu_{W_{\mathrm{RSR}}}$) and ($\sigma_{V_{\mathrm{TAN_d}}}$, $\sigma_{W_{\mathrm{RSR_d}}}$) are the mean and the standard deviation of Gaussian fits to the velocity distributions, respectively, and ($\sigma_{V_{\mathrm{TAN_*}}}$, $\sigma_{W_{\mathrm{RSR_*}}}$) are the uncertainties computed for the velocities of each star. All stars that are outside the surface defined by this ellipse ($E > 1$) have been classified as runaway stars while the stars within the surface of this ellipse ($E \leq 1$) have been classified as field stars. In Figure 4 we show the velocities in the 2-D approach of our 334 O-type stars sample. We observe that the field stars are located around the origin while the runaway stars are roughly outside a centered ellipse.

We show in Figure 5 the Aitoff projection in Galactic coordinates of our 334 O-type stars
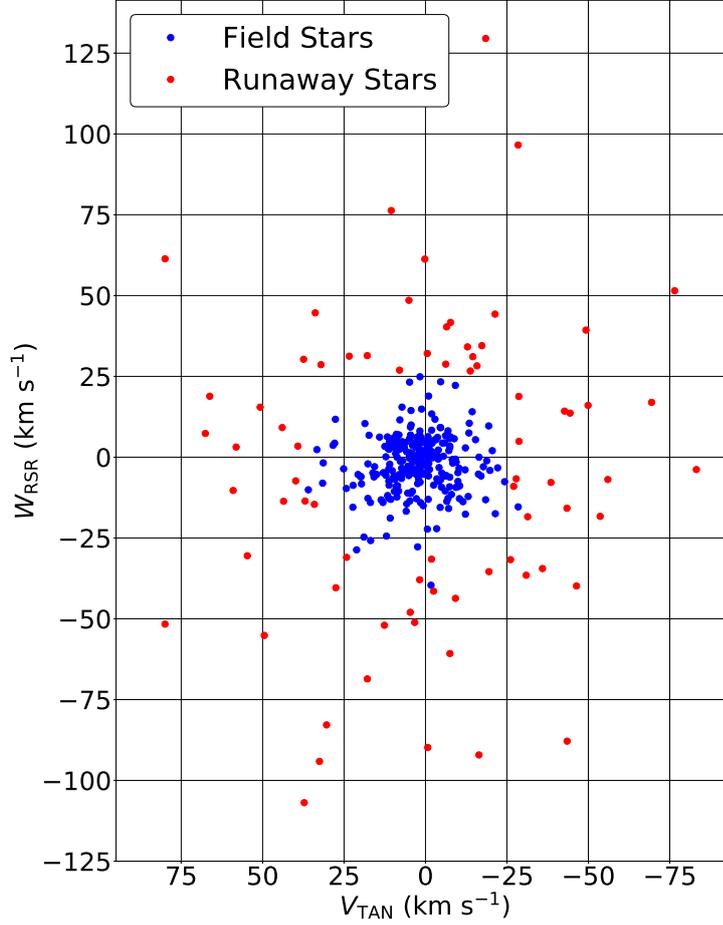
Figure 4: Distribution of V_{TAN} vs W_{RSR} for the sample of 334 O-type stars with $RUWE \leq 1.15$.

sample. Note that the dispersion of the runaway stars with respect to the Galactic Plane is higher than the dispersion of the field stars.

From a total of 334 stars, we have obtained 74 runaway stars, with peculiar velocities between 28 and 133 km s^{-1}. Some of them could be gamma-ray binaries.

5. Discussion and Outlook

The formation of gamma-ray binary systems takes place in the forming region close to the Galactic Plane. This is determined by the O-type field star region (OFSR), where field stars remain during the span of their lives. The characteristic lifetime of the gamma-ray binary phase is at most of the order of 10^5 years [14]. For this reason, the candidates to be gamma-ray binaries had to be
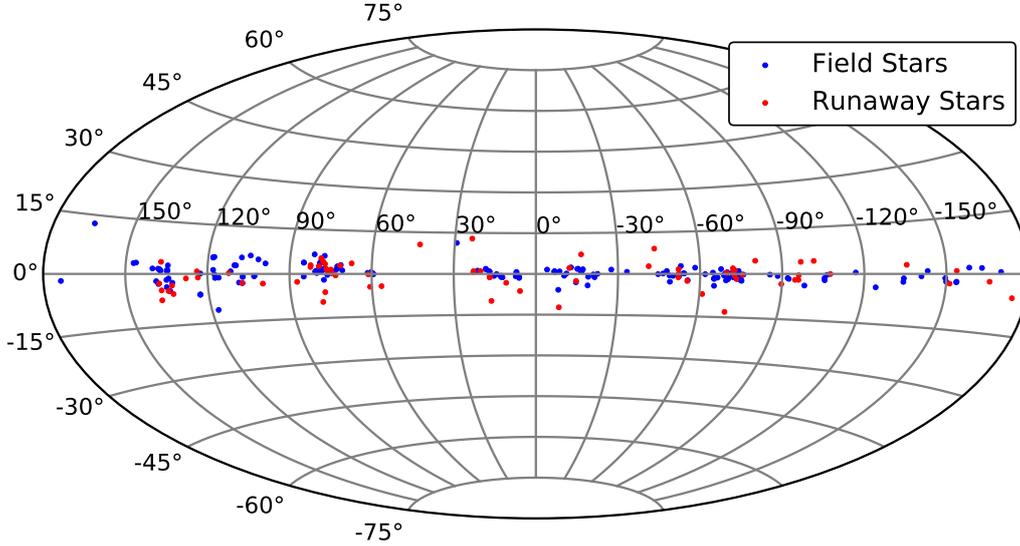
Figure 5: Aitoff projection in Galactic coordinates of the 334 O-type stars with $RUWE \leq 1.15$.

located in the OFSR in the last 10^5 years. Among the 74 runaway stars, 61 were within the OFSR in the last 10^5 years, therefore, they could be gamma-ray binary systems. From the 74 stars, 24 are located in the H.E.S.S. Galactic Plane Survey area [15] and 2 are within the 95% c.l. contours of a source listed in the 4th*Fermi*-LAT source catalog [16]. One of these 2 stars belongs to the known gamma-ray binary system LS 5039.

Among the 36 stars with bad astrometric solutions, all of them were in the OFSR in the last 10^5 years, 11 are located in the H.E.S.S. Galactic Plane Survey area and 2 are within the 95% of c.l. contours listed in the 4th*Fermi*-LAT source catalog.

The outlook for future research is the study of these gamma-ray binary candidates. It will be necessary to search for non-thermal emission in other catalogs, measure the radial velocities and search for radial velocity variability to unveil possible orbital motion. These are future targets for CTA. In addition, similar studies could be conducted with databases of Be stars, for which Gaia DR3 could also provide relevant information regarding emission line features.

Acknowledgments

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