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Search for new gamma-ray binaries among runaway stars

M. Carretero-Castrillo,[*] M. Ribó[1] and J. M. Paredes

Universitat de Barcelona, ICCUB, IEEC-UB,
Barcelona, Spain

E-mail: mcarretero@fqa.ub.edu, mribo@fqa.ub.edu, jmparedes@ub.edu

Gamma-ray binaries are systems composed of a massive O or Be-type star and a compact object that show a non-thermal energy distribution that peaks in the MeV-GeV band. Currently, only 9 of such systems are known, and those containing O-type stars are runaways. Because some properties of these systems are not fully understood, the discovery of new gamma-ray binaries may help to answer many open questions, and eventually may open new ones. To discover new gamma-ray binaries we search for runaway stars within catalogs of massive stars using Gaia astrometric data. We present here the current status of our project with tens of new runaway O and Be stars identified, together with preliminary multi-wavelength information.

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[1]Serra Húnter Fellow
[*]Speaker

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1. Introduction

Gamma-ray binaries are systems composed of a massive O or Be-type star and a compact object that have a non-thermal energy distribution that peaks in the MeV-GeV band. These systems are perfect laboratories where particle acceleration and emission/absorption mechanisms can be tested against periodically changing conditions thanks to their binary nature. In addition, some gamma-ray binaries are runaways ([1], [2], [3]), which are systems that move with a high peculiar velocity with respect to its environment [4]. However, only 9 gamma-ray binaries are known. Therefore, there are still many open questions about them ([5]). On the other hand, massive stars have masses greater than 8 $M_{\odot}$ and usually form in binary systems. During the evolution of the binary system, the most massive star evolves faster and may explode as a supernova, forming a compact object. As a consequence of the supernova explosion the system suffers a kick. In case of a symmetric kick, the binary system will remain bound if less than half of the total mass is lost. In such case the system could became runaway. Our aim is to search for new gamma-ray binaries through O and Be massive runaway stars. To detect stars as runaways, we need good-quality measures of proper motions, parallaxes and eventually radial velocities. Thus, we cross-match massive star catalogs with the *Gaia* EDR3 catalog, given its accurate and unprecedented precision [6]. Once we have a list of massive runaway stars, we have to search for the non-thermal emission characteristic of gamma-ray binaries. To do this, we have to perform a multi-wavelength study of our candidates.

2. Catalogs

Gaia is a mission of the European Space Agency (ESA) launched in December 2013. The main objective of the mission is to obtain the three-dimensional spatial and velocity distribution of more than a thousand million stars and to determine their astrophysical properties [7]. Over the years, several *Gaia* catalogs have been released with better astrometry and increasing amounts of information. Here we work with the EDR3 release [6]. As regards to massive stars, we work with two catalogs: the Galactic O-star catalog (GOSC) [8], which is a catalog of galactic O-type stars, and the Be Star Spectra (BeSS) catalog [9], which contains classical Be stars, Herbig Ae/Be stars, and B[e] supergiants. We chose these catalogs because we are interested in working with the stellar companions of gamma-ray binaries, that are of O and Be type. On the one hand, the current version of the GOSC catalog lists 655 early-type stars. After cross-matching this catalog with *Gaia* EDR3 and applying some quality cuts, we obtain the GOSC-*Gaia* EDR3 catalog with 430 stars. On the other hand, the BeSS catalog contains 2330 Be stars, which after the cross-match with *Gaia* EDR3 and the quality cuts, is reduced to the BeSS-*Gaia* EDR3 catalog with 1402 stars.

3. Methodology

In order to classify our stars as runaways, we first have to analyze their velocities. To do this, we have worked with the different reference systems shown in Fig. 1. From the A5 model of [10] we obtain the peculiar velocity of the Sun with respect to the Local Standard of Rest (LSR), the distance to the Galactic center ($R_{\odot}$), and information about the Galactic rotation curve. Since *Gaia* EDR3 does not provide enough radial velocities for our stars, we impose as radial velocity the one the

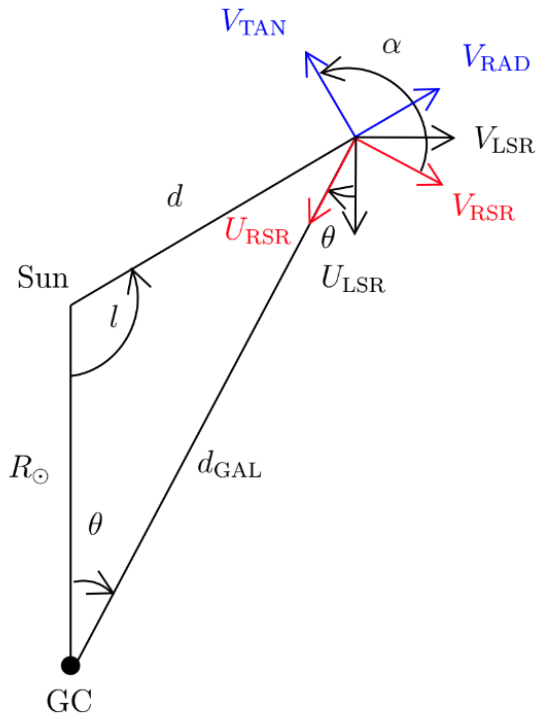

Figure 1: Sketch of the different reference frames used in the Galactic plane. Velocities in the LSR and RSR are shown in black and red respectively. The tangential, $V_{\rm TAN}$, and the radial velocity, $V_{\rm RAD}$, are represented in blue. The third velocity components of the LSR and RSR, $W_{\rm LSR}$ and $W_{\rm RSR}$, are perpendicular to this plane.

star would have if it were moving in its Regional Standard of Rest (RSR) according to the Galactic rotation curve considered. Furthermore, we use the parallaxes derived from the photogeometric *Gaia* EDR3 distances from [11]. With all these ingredients and following the transformations given in [12], we can compute the peculiar velocity of the stars with respect to their RSR. However, since our radial velocity is not an observational quantity, we define a new reference system where we can get rid of the radial velocity contribution. The first component of this system is contained in the plane of the sky and is parallel to the galactic plane, $V_{\rm TAN}$. The second component is on the line of sight direction, $V_{\rm RAD}$, and the third component is perpendicular to the Galactic plane, $W_{\rm RSR}$. We can now leave the radial velocity component and work with the two dimensional (2-D) system ($V_{\rm TAN}$, $W_{\rm RSR}$).

Our catalog contains both field stars that follow the Galactic rotation curve and runaway stars that deviate significantly from it. We show in Fig. 2 the histograms of the velocities $V_{\rm TAN}$ and $W_{\rm RSR}$ binned at 2 km s^{-1}. Most of the velocities follow approximately a Gaussian distribution centered around 0 km s^{-1} $(\mu_{V_{\rm TAN}}, \mu_{W_{\rm RSR}})$ and with standard deviation of 6−8 km s^{-1} $(\sigma_{V_{\rm TAN}}, \sigma_{W_{\rm RSR}})$, which correspond to the field stars. Stars that deviate significantly from the Gaussian behavior are runaways. In order to identify them we have defined a 2-D ellipse from the velocity distributions at a 3σ confidence level:

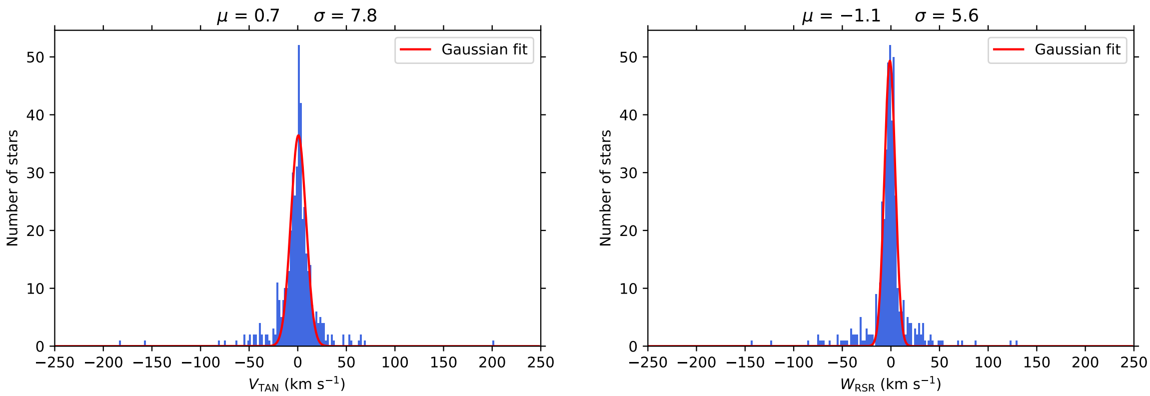

Figure 2: Histograms of the velocity distribution of V_{TAN} (left) and W_{RSR} (right) for the stars of the GOSC-*Gaia* EDR3 catalog. The red line shows a Gaussian fit to the data with a binning of 2 km s^{-1}.

$$E = \frac{\left(V_{\mathrm{TAN}} - \mu_{V_{\mathrm{TAN}}}\right)^2}{\left(3 \cdot \sqrt{\sigma^2_{V_{\mathrm{TAN}}} + \sigma^2_{V_{\mathrm{TAN}*}}}\right)^2} + \frac{\left(W_{\mathrm{RSR}} - \mu_{W_{\mathrm{RSR}}}\right)^2}{\left(3 \cdot \sqrt{\sigma^2_{W_{\mathrm{RSR}}} + \sigma^2_{W_{\mathrm{RSR}*}}}\right)^2} \quad (1)$$

where $\left(\sigma_{V_{\mathrm{TAN}*}}, \sigma_{W_{\mathrm{RSR}*}}\right)$ are the individual uncertainties of the velocities of each star. Therefore, we classify as field stars the ones having $E < 1$ and as runaway stars those with $E > 1$. In the (V_{TAN}, W_{RSR}) plane, field stars are contained approximately in a 2-D ellipse, which would be a real 2-D ellipse if the velocity uncertainties were the same for all stars.

4. Results

Following Sect. 3 and Eq. 1, we computed the velocities of our stars and identified which of them are runaways. For the GOSC-*Gaia* EDR3 catalog, we obtained 110 runaway stars, corresponding to 25.6% of the catalog. Their peculiar velocities ranges from 16 to 290 km s^{-1}. As regards to the velocity distributions, the Gaussian fits with a binning of 2 km s^{-1} provide standard deviations of $\sigma_{V_{\mathrm{TAN}}}$ = 6.8 km s^{-1}, $\sigma_{W_{\mathrm{RSR}}}$ = 5.2 km s^{-1}. The 2-D velocity distribution of the GOSC-*Gaia* EDR3 catalog can be seen in Fig. 3. Field stars, which are shown in blue, are around the (0,0) velocities with some dispersion, while runaway stars, which are shown in red, have clearly high velocities. We compare our work with that of [13] and we found some runaways already obtained in that work. Furthermore, we identified as runaway a previously known gamma-ray binary, LS 5039, which stellar companion is of O type. The other known runaway gamma-ray binaries containing O-type stars were not contained in the GOSC catalog. As for the BeSS-*Gaia* EDR3 catalog, we obtained 83 runaway stars, corresponding to 6% of the catalog. In this case the peculiar velocities range from 16 to 140 km s^{-1} and the standard deviations are $\sigma_{V_{\mathrm{TAN}}}$ = 9.2 km s^{-1}, $\sigma_{W_{\mathrm{RSR}}}$ = 4.9 km s^{-1}.

Once we have our list of runaways we have to study which of these objects have properties similar to the ones of gamma-ray binaries. Given that these kind of binaries display non-thermal emission from radio to GeV/TeV energies, we have to perform a multi-wavelength study of our runaways. As a first step, we have inspected different radio catalogs and found counterparts for 2% of the runaways in the GOSC- and the BeSS-*Gaia* EDR3 catalogs. However, a careful inspection of these counterparts is still needed to test for plausible hints of gamma-ray binaries.

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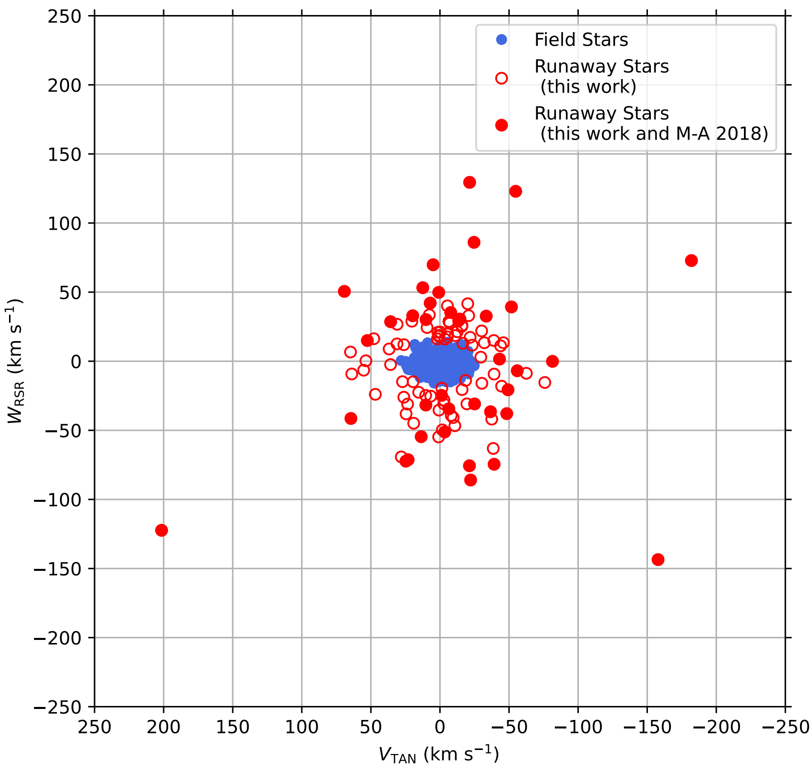

Figure 3: W_{RSR} as a function of V_{TAN} for the GOSC-*Gaia* EDR3 catalog. Field stars are represented in blue while runaway stars are shown in red. Two kinds of red points are shown: runaway stars from this work (empty red circles) and runaway stars from this work that were already found by [13] (filled red circles).

5. Conclusions and outlook

We have searched for runaways among O and Be stars using *Gaia* EDR3 catalog and a new method based on significant deviations of the star velocities with respect to the Galactic rotation curve. The unprecedented accuracy of the *Gaia* EDR3 data has allowed us to find around 200 massive runaway stars. We found runaway velocities up to 300 km s^{-1}, encompassing the ones of known gamma-ray binaries. As for the search for non-thermal emission, we found that only 2% of the runaways have a radio counterpart. However, we should extend this search for non-thermal emission to other wavelengths to conduct deeper studies of runaway stars and to build a list of good candidates for gamma-ray binaries. As an outlook, we plan to conduct VHE observations of selected sources to unveil their possible TeV emission.

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