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New runaway O-type stars in the first Gaia Data Release

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Abstract. We have detected 13 new runaway-star candidates of spectral type O combining the TGAS (Tycho-Gaia Astrometric Solution) proper motions from Gaia Data Release 1 (DR1) and the sample from GOSSS (Galactic O-Star Spectroscopic Survey). We have also combined TGAS and Hipparcos proper motions to check that our technique recovers many of the previously known O-type runaways in the sample.

Keywords. astrometry, stars:early-type, Galaxy:kinematics and dynamics

1. Introduction

On 14 September 2016 the first Gaia Data Release (DR1) was presented (Brown *et al.* 2016). Gaia DR1 includes parallaxes and proper motions from TGAS (Tycho-Gaia Astrometric Solution) for the majority (but not all) of the Tycho-2 stars. The excluded Tycho-2 stars include all of the very bright objects but also some dimmer ones. TGAS proper motions exist for a significantly larger number of stars than for Hipparcos and, for the stars in common between both catalogs, they are more precise.

The Galactic O-Star Spectroscopic Survey (GOSSS, Maíz Apellániz 2011) is obtaining $R \sim$2500, high-S/N, blue-violet spectroscopy of all optically accessible Galactic O stars. To this date, three survey papers (Sota *et al.* 2011, 2014; Maíz Apellániz *et al.* 2016) have been published with a total of 590 O stars. Several additional hundreds have already been observed and will be published in the near future.

2. Data and methods

Our initial plan with Gaia DR1 was to analyze the parallaxes in order to increase the meager number of useful trigonometric distances available for O stars (van Leeuwen 2007; Maíz Apellániz *et al.* 2008). However, the TGAS parallaxes for O stars provide little new information, as the brightest O stars are not included and only one star, AE Aur, has $\pi_o/\sigma_\pi > 6$, where π_o is the observed parallax and σ_π is the parallax uncertainty. It should be remembered that, in general, $<d> \neq 1/\pi_o$, that is, the inverse of the observed parallax is not an unbiased estimator of the trigonometric distance (Lutz & Kelker 1973; Maíz Apellániz 2001, 2005).

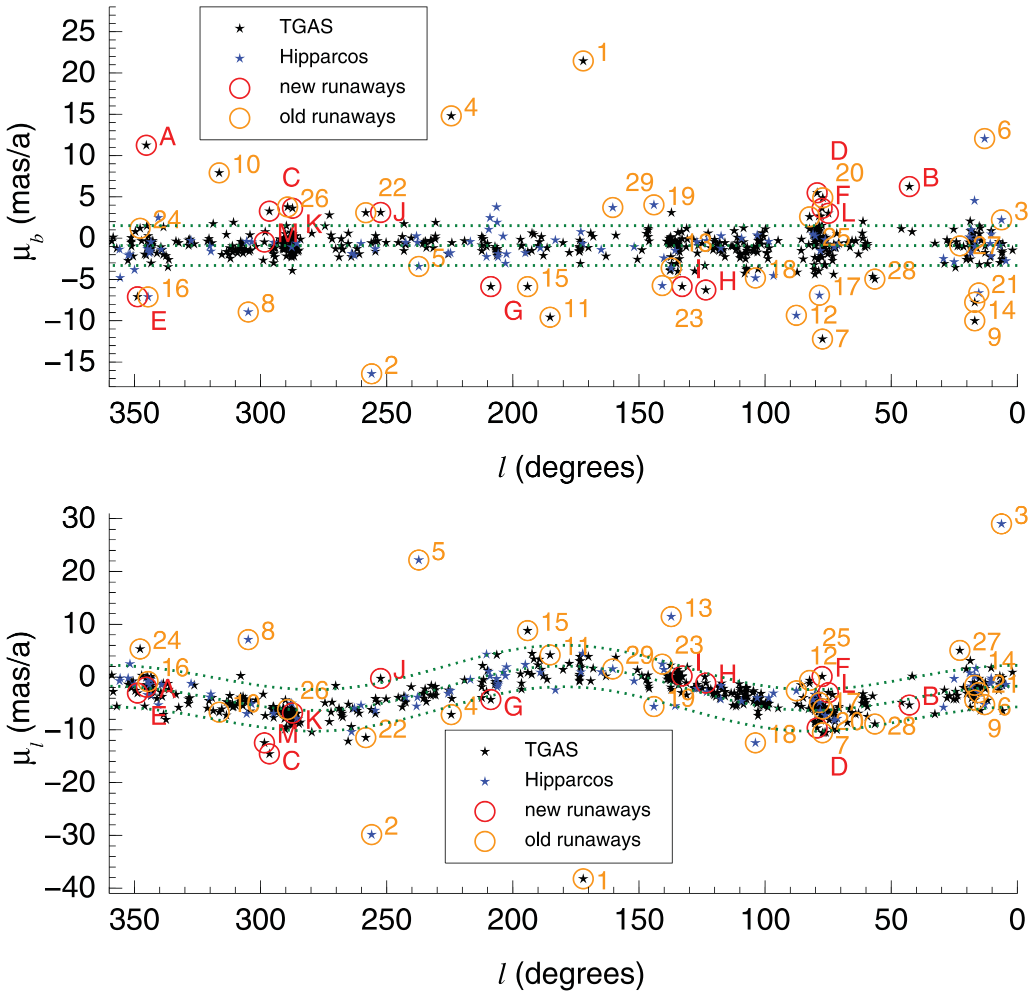

Figure 1. Galactic latitude (top) and longitude (bottom) TGAS (black) and Hipparcos (blue) proper motions for the O-star sample in the sample. Circles and IDs identify runaway candidates, both new (red, letters) and previously known (orange, numbers). See Table 1 for ID correspondences. The dotted green lines represent the functions and 2σ deviations used to detect runaway candidates.

On the other hand, the TGAS proper motions proved to have useful information. By cross-matching TGAS and GOSSS (including unpublished objects) we found 525 Galactic O stars with proper motions, of which we discarded 5 due to their large uncertainties. For the unmatched GOSSS stars we searched for Hipparcos proper motions and discovered another 96 objects, of which 7 were discarded for the same reason. That left us with a total of $520 + 89 = 609$ Galactic O stars with good TGAS or Hipparcos proper motions (of those, 427 are in the published GOSSS papers).

The proper motions in RA (μ_α) and declination (μ_δ) were transformed into their equivalents in Galactic latitude (μ_b) and longitude (μ_l). A robust mean for μ_b (reflecting the solar motion in the vertical direction), $<\mu_b>$, and a robust standard deviation, σ_{μ_b}, were calculated. For μ_l we robustly fitted a functional form $f(l) = a_0 + a_1 \cos l + a_2 \cos 2l$ and we also calculated the robust standard deviation, σ_{μ_l}, from the fit. Results for stars with good TGAS or Hipparcos proper motions are shown in Fig. 1.

To detect runaway stars we computed the normalized difference (in standard deviations) of the difference between the observed proper motions and the fitted ones i.e.:

$$\Delta = \sqrt{\left(\frac{\mu_b'}{\sigma_{\mu_b}}\right)^2 + \left(\frac{\mu_l'}{\sigma_{\mu_l}}\right)^2},$$

where $\mu_b' = \mu_b - <\mu_b>$ and $\mu_l' = \mu_l - f(l)$ are the corrected proper motions, and sorted the results from largest to smallest (Table 1). This 2-D method is simpler than a full computation of the 3-D velocities (e.g. Tezlaff *et al.* 2011) and can yield false positives and negatives (see below), but it has the advantage of being self-contained and, therefore, less prone to errors introduced by the required external measurements in the 3-D method (distances and radial velocities).

3. Results

The runaway star candidates detected by our 2-D method are shown in Table 1, divided in previously known and new objects. The cut in Δ is the same in both cases and was empirically established at 3.5 (the stars at the top of the lists, AE Aur and HD 155 913, have values of 27.6 and 10.1, respectively) by comparing our results with those of Tetzlaff *et al.* (2011).

To check for false negatives in our list, we searched Tetzlaff *et al.* (2011) for runaway candidates with $P_{v_{\rm pec}} > 0.5$ missing in Table 1 but present in our sample. There are 33 objects missing but, of those, 30 were detected by Tetzlaff *et al.* (2011) based mainly on their radial velocities as they have (a) $P_{v_{\rm r,pec}} > P_{v_{\rm t,pec}}$ and (b) $P_{v_{\rm t,pec}} < 0.5$. One of the remaining three objects is HD 93 521, the highest - by far - latitude Galactic O star ($b = 52^{\rm o}$), which is difficult to detect in a 2-D method designed for objects near the Galactic Plane. The other two, HD 108 and HDE 227 018, have TGAS proper motions with significantly smaller uncertainties and closer to the mean values than the Hipparcos values, which were the ones used by Tetzlaff *et al.* (2011). Hence, a 3-D reanalysis would likely reduce their $P_{v_{\rm t,pec}}$. Therefore, we conclude that our method correctly picks up those runaway stars with large tangential velocities but, as expected, misses some which are moving mostly in a radial direction.

What about false positives? The final answer will lie, of course, in future work, but there is a good reason why the new 13 objects had not been detected before as runaways. Eight of them do not have Hipparcos proper motions and the remaining five were not included in Tetzlaff *et al.* (2011). Another indirect evidence in favor of the reality of the runaway condition for the new candidates is that in several cases it is possible to trace back the past motion of the star through its corrected proper motion to a cluster or an association as its possible origin (Table 1). Note that three of the new candidates are in the Cygnus region of the Galactic Plane (ALS 11 244, HDE 229 232 AB, and HD 192 639). For HD 46 573 we detect a bow shock in WISE images whose relative position with respect to the star is consistent with the corrected proper motion (Fig. 2).

4. Future work

Our plans for the incoming years are:

• Calculate extinction corrections (both $E(4405-5495)$ and R_{5495}) for all the stars in the sample with CHORIZOS (Maíz Apellániz 2004) using the Maíz Apellániz *et al.* (2014) family of extinction laws in order to obtain accurate spectroscopic parallaxes and compare them with the Gaia trigonometric parallaxes.

Table 1. Previously known O-type runaway stars (left) and new candidates (right). Each list is sorted by Δ, the normalized deviation from the mean latitude and longitude proper motions for their Galactic longitude. An ID (a number for previously known objects, a letter for new ones) is provided for each star in order to identify it in Fig. 1. The T/H flag indicates the origin of the proper motions (TGAS or Hipparcos, respectively). All new candidates have TGAS proper motions. Reference codes are listed in the bibliography. GP stands for Galactic Plane. The corrected proper motions are in mas/a.

Previously known				New candidates				
ID	Name	T/H	Ref.	ID	Name	μ'_b	μ'_l	Possible origin
1	AE Aur	T	H01	A	HD 155 913	12.14	0.17	NGC 6322
2	ζ Pup	H	H01	B	ALS 18 929	7.14	−1.15	GP, 10.6° away
3	ζ Oph	H	H01	C	HD 104 565	4.16	−8.80	GP, 4.0° away
4	HD 57 682	T	M04	D	ALS 11 244	6.38	−3.34	Cyg OB2
5	μ Col	H	H01	E	HD 155 775	−6.20	−1.10	—
6	HD 157 857	H	M04	F	HDE 229 232 AB	4.50	6.38	NGC 6913
7	Y Cyg	T	M05a	G	HD 46 573	−4.97	−4.66	GP, 2.6° away
8	HD 116 852	H	M04	H	BD +60 134	−5.38	2.04	Cas OB7
9	V479 Sct	T	R02	I	HD 12 323	−4.96	2.13	Per OB1
10	HD 124 979	T	T11	J	CPD -34 2135	4.00	4.74	—
11	HD 36 879	T	M04	K	HD 94 024	4.52	−0.64	Carina Nebula
12	68 Cyg	H	T11	L	HD 192 639	3.90	3.28	Dolidze 4
13	HD 17 520 A	H	M04	M	AB Cru	0.42	−6.83	—
14	BD -14 5040	T	G08					
15	HD 41 997	T	M04					
16	HD 152 623 AaAbB	H	M05b					
17	HD 201 345	H	T11					
18	λ Cep	H	H01					
19	α Cam	H	M05b					
20	HD 192 281	T	M04					
21	HD 175 876	H	T11					
22	HD 75 222	T	T11					
23	HD 14 633 AaAb	H	T11					
24	HD 153 919	T	M04					
25	HD 195 592	T	T11					
26	HD 96 917	T	T11					
27	BD -08 4617	T	M04					
28	9 Sge	T	M04					
29	ξ Per	H	H01					

- Extend the analysis to the rest of the OB stars. This will allow us to search for additional runaway stars and redo the study of the spatial distribution of OB stars in the solar neighborhood of Maíz Apellániz (2001) with the much better Gaia data.
- Use the multiepoch OWN (Barbá *et al.* 2010 and contribution by the same author in these proceedings), IACOB (Simón-Díaz *et al.* 2015 and contribution by the same author in these proceedings), and CAFÉ-BEANS (Negueruela *et al.* 2015) data to obtain radial velocities for OB stars corrected for binarity as a necessary step to accurately calculate their 3-D velocity.
- Expand the GOSSS sample by observing new stars.
- Incorporate the results from the new Gaia Data Releases.

Figure 2. WISE W3+W2+W1 RGB mosaic of HD 46 573. The green arrow indicates the TGAS original proper motion and the yellow arrow the corrected proper motion (see text). Note how the bow shock correctly aligns with the proper motion. The field size is 6.′87 × 6.′87 with N to the top and E to the left.

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