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Letter to the Editor

New runaway OB stars with HIPPARCOS

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Abstract. A Monte Carlo method for detection of runaway OB stars from observational data is proposed. 61 runaway OB star candidates have been detected by an analysis of Hipparcos proper motions. The peculiar tangential and total transverse velocities have been determined for these stars. A list of the detected runaway star candidates is presented. The evidence of a discrepancy between photometric and parallactic distances of runaway OB star candidates is presented.

Key words. astrometry – stars: early-type – stars: kinematics – pulsars: general

1. Introduction

Runaway OB stars are a subset of OB stars which have high spatial velocities (i.e. velocities corrected for solar motion and differential rotation of the Galaxy), exceeding a certain limit and reaching up to 200 km s^{-1}. These stars are characterized by an almost complete absence of duplicity and multiplicity (Blaauw 1993).

Over forty years ago, Blaauw (1961) discovered 19 OB runaway stars. He took as definition of a runaway a peculiar velocity exceeding 40 km s^{-1}. Some of the velocity vectors of the detected runaways point back to their presumed birthplace in young open clusters and OB associations. The research of runaway stars was considerably extended by Gies & Bolton (1986) and Gies (1987). On the basis of the Hipparcos proper motions a subset of O and Wolf-Rayet stars has been investigated and 9 O-type and 5 WR runaway stars have been detected, some of which were not previously recognized as runaways (Moffat et al. 1997, 1998).

Today there are two plausible theories on the origin of OB runaways. The first theory is the binary-supernova scenario (Blaauw 1961), postulating the high-velocity release of the initially less massive component of an OB binary as a consequence of the supernova explosion of the primary component. The binary scenario can also lead to acceleration of the SN remnant NS/BH if the system separates (see Vanbeveren et al. 1998, and references therein). The second theory is the cluster ejection scenario (Poveda et al. 1967; Leonard & Dunkan 1988, 1990), where a star is ejected via dynamic interaction between stars in a young, compact cluster. It is accepted that both theories may be valid (Moffat et al. 1997, 1998). If a massive star becomes runaway due to cluster ejection and its age a is maximum a few million years, the remains of the dense cluster somewhere along the kinematic path of the runaway should still be observable (Vanbeveren et al. 1998; Hoogerwerf et al. 2001).

Previous statistical searches of the runaway OB stars have been mainly based on spatial or radial velocity data. The examination of the Hipparcos proper motions of OB stars has given us the possibility to detect new runaways. It is interesting to compare the kinematical properties obtained from proper motions of OB stars – progenitors of pulsars – with the kinematical properties of pulsars, since kinematical properties of pulsars are obtained mainly from proper motion data. While examining the proper motion data we have considered stars located within a 2 kpc (from the Sun) cylinder, with the axis along the z-direction, assuming that within this area the rotational curve of the Galaxy is well established and our sample of the OB stars is representative.

2. Estimation of the peculiar tangential velocities and errors in peculiar tangential velocities

The Hipparcos mission has enabled us to measure proper motions with high accuracy for about 120 000 stars. The statistical analysis based on the proper motion data of the Hipparcos for 66 known runaway O-type stars from the list of Cruz-Gonzales et al. (1974) and for the 67 WR stars was accomplished in the papers (Moffat et al. 1997, 1998). Within the limits of uncertainty, the results based on the radial velocity data appeared to be compatible with the results based on the proper motions at distances of several kpc. For statistical analysis on the basis of the Hipparcos data (http://cadcwww.dao.nrc.ca/astrocat/hipparcos/) we have compiled a catalogue of proper motions (μ_α, μ_δ), their uncertainties ($\sigma_{\mu_\alpha}, \sigma_{\mu_\delta}$) and other basic parameters for 2228 OB stars (O-B2V stars and all O and B giants/supergiants) with the target of detecting runaway stars.

The selection of OB stars in the Hipparcos catalogue is nearly complete up to $V = 10$ mag and we can suppose that the sample of OB stars from the 2 kpc cylinder is representative.

To detect runaway stars from the proper motion data we have used a method based on the approach worked out in the papers (see Moffat et al. 1997, 1998, and references therein). It is known that the tangential velocity of a star is related to the proper motion by the equation

$$v_{\rm t}({\rm km\,s^{-1}}) = Kr({\rm kpc})\mu({\rm mas/yr}), \tag{1}$$

where $K = 4.740$. Runaways must satisfy the selection criterion:

$$(v_{\rm t})_{\rm pec} > 42 + \sigma_{(v_{\rm t})_{\rm pec}}\ {\rm km\,s^{-1}}, \tag{2}$$

where $(v_{\rm t})_{\rm pec}$ is a computed tangential component of peculiar velocity, and $\sigma_{(v_{\rm t})_{\rm pec}}$ is its standard deviation. The base value of 42 km s^{-1} is consistent with a criterion based only on the radial velocity data above 30 km s^{-1} (e.g. Cruz-Gonzales et al. 1974), i.e. allowing for a factor $\sqrt{2}$ for two components of velocity $(v_{\rm t})_{\rm pec}$. To obtain the peculiar tangential velocities we have calculated proper motion components $\mu_{\rm l}$ and $\mu_{\rm b}$ in the Galactic coordinate system:

$$\mu_{\rm l} = \mu_\alpha \cos\psi + \mu_\delta \sin\psi, \tag{3}$$

$$\mu_{\rm b} = -\mu_\alpha \sin\psi + \mu_\delta \cos\psi, \tag{4}$$

where ψ – the parallactic angle is obtained from:

$$\cos\psi = \frac{\sin\delta_{\rm G}\cos\delta - \cos\delta_{\rm G}\sin\delta\cos(\alpha-\alpha_{\rm G})}{\cos b}, \tag{5}$$

$$\sin\psi = \frac{\sin(\alpha-\alpha_{\rm G})\cos\delta_{\rm G}}{\cos b}, \tag{6}$$

where α, δ are the equatorial coordinates of a star, $\mu_\alpha = \frac{{\rm d}\alpha}{{\rm d}t}\cos\delta$ and $\mu_\delta = \frac{{\rm d}\delta}{{\rm d}t}$ – components of proper motion in the equatorial coordinate system, $\mu_l = \frac{{\rm d}l}{{\rm d}t}\cos b$ and $\mu_b = \frac{{\rm d}b}{{\rm d}t}$ – components of proper motion in the Galactic coordinate system (l, b). $\alpha_{\rm G} = 192\overset{\circ}{.}85948$, and $\delta_{\rm G} = 27\overset{\circ}{.}12825$ – coordinates of the Galactic pole for epoch 1991.25 recommended by the Hipparcos consortium. The observed tangential velocities $v_{l{\rm t}} = Kr\mu_l$ and $v_{b{\rm t}} = Kr\mu_b$ can be expressed as:

$$v_{l{\rm t}} = (v_{l{\rm t}})_\odot + (v_{l{\rm t}})_{\rm rot} + (v_{l{\rm t}})_{\rm pec}, \tag{7}$$

$$v_{b{\rm t}} = (v_{b{\rm t}})_\odot + (v_{b{\rm t}})_{\rm rot} + (v_{b{\rm t}})_{\rm pec}, \tag{8}$$

where basic solar motion

$$(v_{l{\rm t}})_\odot = U_\odot \sin l - V_\odot \cos l, \tag{9}$$

$$(v_{b{\rm t}})_\odot = U_\odot \cos l \sin b + V_\odot \sin l \sin b - W_\odot \cos b, \tag{10}$$

where $U_\odot, V_\odot, W_\odot = 9, 11, 6$ km s^{-1}.

Galactic rotation is expressed as:

$$(v_{l{\rm t}})_{\rm rot} = R_0(\omega - \omega_0)\cos l - \omega r \cos b, \tag{11}$$

$$(v_{b{\rm t}})_{\rm rot} = -R_0(\omega - \omega_0)\sin b \sin l, \tag{12}$$

for distance from the Sun r in kpc with

$$R^2 = R_0^2 + r^2\cos^2 b - 2rR_0\cos b\cos l. \tag{13}$$

A flat rotation for galactocentric distances (in kpc) $3 \le R \le 18$, with $\omega = \omega(R, z) = \frac{V_0}{R}$ is adopted and $\omega_0 = \frac{V_0}{R_0}$, where $z = r|\sin b|$ is the distance perpendicular to the Galactic plane, the solar galactocentric distance $R_0 = 8.5$ kpc and circular Galactic rotational velocity $V_0 = 220$ km s^{-1}.

For the O-type stars we have used the photometric distances from the catalogue (Cruz-Gonzales et al. 1974). For the B-type stars we have calculated photometric distances from the equation:

$$5\lg r - 5 = V - M_v - A_v, \tag{14}$$

where V is the Hipparcos magnitude transformed into the V band, M_v is the absolute magnitude, and A_v is the interstellar extinction calculated from the equation:

$$A_v = 3.0[(B-V) - (B-V)_0], \tag{15}$$

where $(B-V)$ and $(B-V)_0$ are the observed and intrinsic colors respectively. For B-type stars the values of M_v and $(B-V)_0$ were taken from (Deutschman et al. 1976). Finally, for the peculiar tangential velocity we have

$$(v_{\rm t})_{\rm pec} = \sqrt{(v_{l{\rm t}})^2{}_{\rm pec} + (v_{b{\rm t}})^2{}_{\rm pec}}, \tag{16}$$

where $(v_{l{\rm t}})_{\rm pec}$ and $(v_{b{\rm t}})_{\rm pec}$ are derived from Eqs. (7) and (8), and for the total transverse velocity

$$v_{\rm tr} = Kr\mu, \tag{17}$$

where $\mu = \sqrt{\mu_\alpha^2 + \mu_\delta^2}$.

Errors in peculiar tangential velocities can be calculated using error propagation in all the observed quantities, which is assumed independent. 30% uncertainty in the photometric distances, corresponding to 0.7 mag rms error in distance modulus is due to cosmic scatter in M_v for single OB star (Moffat et al. 1997, 1998; Mdzinarishvili 2004). According to Moffat et al. (1997, 1998) while estimating the errors in peculiar tangential velocities some difficulties arise: "...this technique of error calculation works well for relatively small errors: for large errors – as prevail in some cases – this will tend to overestimate the lower error and underestimate the upper error bound. However, for such non-linear functions, there is no standard way to correct for this...". In our opinion this difficulty can be simply overcome as follows.

A Monte Carlo procedure for simulating errors of observed quantities (assuming the error distribution law is Gaussian for μ_α and μ_δ and log-normal for r) can be applied. For each simulation of μ_l, μ_b and r we can calculate $(v_{\rm t})_{\rm pec}$ according to Eq. (16). After many repetitions of the Monte Carlo procedure we can estimate an expected mean $(v)^0_{\rm pec}$, a standard deviation $\sigma_{(v_{\rm t})_{\rm pec}}$, percentiles of the distribution – $(v_{\rm t})^{\rm p}_{\rm pec}$, etc. (Devore 1995). For detection of runaway stars, it is more convenient to use percentiles of the distribution instead of the standard deviation since the distribution of $(v_{\rm t})_{\rm pec}$ is not Gaussian. Instead of the criterion (2) we propose to use the following criterion

$$(v_{\rm t})^{\rm p}_{\rm pec} > 42\ {\rm km\,s^{-1}}, \tag{18}$$

Table 1. A list of the detected runaway OB star candidates.

HIP	*HD/BD*	Sp. type	$(v_t)_{pec}$ km s^{-1}	v_{tr} km s^{-1}	$(v_t)^*_{pec}$ km s^{-1}	*HIP*	*HD/BD*	Sp. type	$(v_t)_{pec}$ km s^{-1}	v_{tr} km s^{-1}	$(v_t)^*_{pec}$ km s^{-1}
2702	3175	B5III	95.05	62.57		73 720	133 294	B8II	87.21	107.05	
4384	5342	B8II	56.60	43.04	10.68	73 778	132 791	B9II/III	83.88	126.20	
5778	7374	B8III	62.38	59.47	34.80	74 660	134 959	B2Ia	82.22	98.33	
13 489	18 100	B5II/III	131.68	111.01		75 711	137 595	B2II/III	228.81	245.44	
14 514	19 374	B1.5V	78.47	67.40	39.79	80 338	147 648	B8II	158.57	171.62	7.16
24 575	34 078	O9.5Vvar	120.19	107.00	103.76	81 153	149 363	B0.5III	145.30	156.09	
26 272	36 879	O7.5III	81.47	89.12		81 362	149 881	B0.5III	64.25	48.85	
27 204	38 666	B1IV/V	78.81	67.06	51.20	81 696	150 135	O7V	87.34	84.67	
29 147	41 997	O7	75.90	84.35		81 904	150 608	B9II/III	66.67	81.17	30.99
29 201	42 259	B0V	85.91	90.20	25.97	82 171	150 898	B0Iab	133.23	162.39	
29 317	41 689	B1Vn...	95.29	91.02		82 217	151 346	B8II	104.01	116.06	15.33
29 678	43 112	B1V	98.73	93.49	58.17	82 625	152 160	B8/B9II	95.83	113.49	
30 071	44 182	B8II	57.51	42.39		83 509	153 772	B2V	73.35	59.32	
31 365	259 954	B2IV	76.21	70.19		87 164	161 653	B2II	59.53	54.83	19.46
34 117	53 269	B9III	145.43	143.53		87 287	162 365	B2IV	61.57	54.52	
35 707	57 682	O9V	98.81	96.97		89 902	167 806	B2V	80.85	80.42	40.14
36 243	58 683	B8III	69.61	82.63	59.80	90 074	168 733	B7Ib/II	120.12	133.71	10.28
36 799	60 930	B9II	150.70	198.75	24.29	100 170	192 273	B2V	61.37	74.16	
38 184	63 655	B8/B9II	56.20	49.85	33.58	101 350	195 965	B0V	69.63	61.62	31.34
41 603	71 833	B8II	109.38	92.307	39.30	101 729	+45 3230	B0III	68.22	31.64	
46 592	82 011	B9III	86.16	93.91		102 999	198 846	B0IVv SB	129.64	159.53	
47 370	83 866	B8II	91.20	149.51	11.47	104 361	201 522	B0V	63.74	33.20	7.44
48 128	84 971	B2V	73.15	43.17		105 811	204 172	B0Ib	74.04	79.53	
48 715	86 606	B1Ib	194.03	147.28	69.82	106 917	205 805	B7III	935.12	952.91	84.11
54 524	—	B6III	123.87	170.64	17.65	110 266	212 043	B6II	133.41	117.92	17.79
55 051	97 991	B1V	269.90	243.86		111 086	213 236	B8II	213.87	225.26	30.84
57 870	103 101	B4III	142.78	161.30	42.03	111 544	214 168	B2V	60.28	52.33	
65 890	116 852	O9Ib	120.80	91.46		111 563	214 080	B1/B2Ib	238.49	255.13	
66 524	118 450	B5II	383.90	422.62	108.52	112 022	214 930	B2IV	68.23	71.43	
69 640	124 300	B2V	49.80	12.32	18.43	113 735	217 505	B2III/IV	85.50	125.80	
						114 998	219 639	B5II/III	98.93	106.94	

Notes: Entries are ordered by the increasing HIPPARCOS number of a star. The values for $(v_t)^*_{pec}$ which have unreliable HIPPARCOS distance estimates (with relative uncertainties more than 50%) are missed.

where $(v_t)^p_{pec}$ is, say, the 10th percentile of the distribution of $(v_t)_{pec}$. In this case, if the criterion is satisfied, we are sure at about the 90% confidence level that a runaway star has a velocity over 42 km s^{-1}.

It should be noted that the Monte Carlo method can be used for detection of runaway OB stars from radial velocities as well.

3. Discussion and conclusions

The results of our calculations are given in Table 1. The designations in Table 1 are as follows: *HIP* is the Hipparcos number of a star, *HD/BD* is the HD or BD number, Sp. type is the spectral type of a star, $(v_t)_{pec}$ is the calculated peculiar tangential velocity, v_{tr} is the calculated value of the total transverse velocity of a star, $(v_t)^*_{pec}$ is the calculated peculiar tangential velocity according to the distance estimates of the Hipparcos precise parallax data. As seen from Table 1, 61 runaway OB star candidates have been detected. The eight stars: HD 34078, HD 41997, HD 116852, HD 214930, HD 149363, HD 19374, HD 38666, and HD 86606 were recognized as runaways earlier by Blaauw (1961), Moffat et al. (1997, 1998) and Hoogerwerf et al. (2001). The rest of stars from our list are recognized as runaway candidates for the first time.

Mdzinarishvili (2004) detected 19 runaway O stars from HIPPARCOS data.The search was made without a distance

Table 2. Photometric (r) and parallactic (r^*) distances of OB runaway candidates.

HIP	r	r^*	*HIP*	r	r^*	*HIP*	r	r^*	*HIP*	r	r^*	*HIP*	r	r^*
	kpc	kpc		kpc	kpc		kpc	kpc		kpc	kpc		kpc	kpc
4384	1.78	0.55	29 678	0.75	0.42	48 715	1.96	0.63	81 904	0.39	0.22	104 361	1.83	0.42
5778	0.98	0.15	36 243	0.15	0.13	54 524	1.42	0.30	82 217	1.08	0.25	106 917	2.61	0.27
14 514	0.56	0.23	36 799	2.02	0.42	57 870	0.30	0.10	87 164	1.79	0.36	110 266	1.26	0.26
24 575	0.52	0.44	38 184	0.94	0.57	66 524	1.43	0.44	89 902	0.65	0.31	111 086	0.98	0.19
27 204	0.62	0.40	41 603	1.17	0.41	69 640	1.94	0.22	90 074	1.08	0.19			
29 201	1.59	0.41	47 370	1.84	0.41	80 338	1.33	0.15	101 350	1.24	0.52			

limit from the Sun. It was confirmed that 7 stars were recognized earlier as runaways by Moffat et al. (1997, 1998). Two stars: CD-4911137 and HD 168941 were classified by them as O-type stars in their list of runaways while in the HIPPARCOS catalogue they were classified as B-type stars. In that case calculations show that they should not be runaways.

Using photometric distances for OB stars we assume that there is no systematic error in the distance scale and we have only random errors with known relative uncertainties (about 30%). In our sample of the detected probable runaways in the Hipparcos catalogue only 28 stars have distance estimates with relative uncertainties less than 50%. Table 2 shows that in all cases parallactic distances are less than photometric ones and this discrepancy should be systematic. For that reason peculiar velocities were recalculated using the Hipparcos distance estimates. The calculated values of $(\upsilon_t)^*_{\rm pec}$ are given in Table 1.

The designations in Table 2 are as follows: *HIP* is the Hipparcos number of a star, r is the photometric distance calculated according to Eq. (14), r^* is the distance calculated from the Hipparcos parallactic data with relative uncertainties less than 50%.

As seen from Table 1 eight stars: HD 34078, HD 38666, HD 43112, HD 86606, HD 103101, HD 118450, HD 205805 and HD 58683 have peculiar velocities $(\upsilon_t)^*_{\rm pec}$ over 42 km s^{-1}. In our opinion, these stars are more likely candidates as runaway OB stars than others from Table 1 since they have reliable parallactic data.

The comparison of values $(\upsilon_t)_{\rm pec}$ with $(\upsilon_t)^*_{\rm pec}$ in Table 1 shows that the very high peculiar velocities which are calculated for some stars (i.g. for HD 205805 $(\upsilon_t)_{\rm pec}$ = 935.12 km s^{-1}) should be caused by the errors in the photometric distance scale. It should be noted that very high peculiar velocities of some pulsars (see Lyne & Graham-Smith 1998, and references therein) can analogously be the result of errors in distance scale which depends on the accepted model for the Galactic distribution of free electrons.

The detected discrepancy between photometric and parallactic distances makes it questionable to use photometric distances in the study of OB stars space distribution and kinematics. That point needs further investigation.

In study of pulsar kinematics, the total transverse velocities are often used instead of the peculiar transverse velocities. In that case it is accepted that the influence of the basic solar motion and the Galactic differential rotation is negligible against the high peculiar velocities of pulsars (see Lyne & Graham-Smith 1998, and references therein). As seen from Table 1 the values of $(\upsilon_t)_{\rm pec}$ and $\upsilon_{\rm tr}$ are considerably different in some cases. In our opinion, it is preferable to use $(\upsilon_t)_{\rm pec}$ instead of $\upsilon_{\rm tr}$ in statistical studies.

We believe that detected runaway OB candidates with Hipparcos can be used in further investigations on the origin and evolution of OB runaways in the Galaxy.

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