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I. Kinematics*

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Abstract. Reliable systemic radial velocities are almost impossible to secure for Wolf-Rayet stars, difficult for O stars. Therefore, to study the motions - both systematic in the Galaxy and peculiar - of these two related types of hot, luminous star, we have examined the Hipparcos proper motions of some 70 stars of each type. We find that (a) both groups follow Galactic rotation in the same way, (b) both have a similar fraction of "runaways", (c) mean kinetic ages based on displacement and motion away from the Galactic plane tend to slightly favour the cluster ejection over the the binary supernova hypothesis for their formation, and (d) those with significant peculiar supersonic motion relative to the ambient ISM, tend to form bow shocks in the direction of the motion.

Key words: astrometry – stars: kinematics – stars: early-type – stars: Wolf-Rayet – Galaxy: kinematics and dynamics

1. Introduction

The most massive stars are the H-burning O stars and their descendants, the He-burning Wolf-Rayet stars. It has been known for a long time that a significant fraction of these stars lies well outside the boundaries defined by their likely birth places in open clusters and OB associations. In view of the potential confusion in the Galactic plane caused by inaccuracies in distances especially of single stars, some of these stars manifest themselves most clearly by their large separations from the Galactic plane, or their rapid motion. Over 35 years ago, Blaauw (1961) recognized 19 O-type "runaways", i.e. O stars having space motions greater than 40 km s^{-1}, some of whose velocity vectors point back to their origin in recognized clusters or associations. This study was significantly extended later by Gies & Bolton (1986) and Gies (1987). The observed runaway nature of some WR stars was first discussed by Moffat & Isserstedt (1980).

Two plausible theories for the origin of runaways remain, after elimination of the possibility of confusion with hot, low-mass subdwarfs (Gies & Bolton 1986). The first theory is the binary-supernova (SN) scenario (Blaauw 1961), favoured by Stone (1991). The second theory is the cluster ejection scenario (Poveda et al. 1967), in which a star is ejected via dynamical interaction between stars in a young, compact cluster. The second one is favoured by Gies & Bolton (1986) and Leonard & Duncan (1990). In fact, both may be operating.

The complete scenario of massive binary evolution was first worked out by van den Heuvel (1973) and Tutukov & Yungelson (1973):

$$(1) O + O \rightarrow (2) WR + O \rightarrow (3) c + O \rightarrow (4) c + WR \rightarrow (5) c (+) c,$$

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* Based on data from the ESA Hipparcos astrometry satellite. Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

in which c stands for "compact" companion, a neutron star or black hole, left after the supernova explosion of its progenitor. In this scenario, it is the more massive star that evolves faster at first. Wind mass-loss (possibly assisted by Roche-lobe overflow in the closest massive binaries) makes O stars evolve into lower-mass WR stars, which also evolve along a sequence from cool to hot subtypes within the WN and then WC sequences. This occurs for each component in turn, i.e. at (1) $\rightarrow$ (2) and (3) $\rightarrow$ (4). At the end of the WR phase, it is assumed that the star explodes as a SN, at both (2) $\rightarrow$ (3) and (4) $\rightarrow$ (5). If the first SN explosion is symmetric, the binary system will remain bound, since the less massive star explodes, leading in principal to the class of massive X-ray binaries (MXRB). If the first SN is asymmetric, the binary system may disrupt, depending on the magnitude and direction of the extra kick velocity (De Cuyper 1982). The latter disruptive case may be much more common, explaining the origin of some of the high-velocity pulsars and the low frequency of MXRBs among O-type stars in general and high-velocity O stars in particular (van Oijen 1989; see also van den Heuvel & van Paradijs 1997 for the importance of kick velocities; however see also De Cuyper 1982). In either case, the SN explosion is very short compared to the orbital period, so that the stars receive a recoil velocity, i.e. become runaway, with velocities reaching up to 200 km s^{-1} for the closest, most massive pre-SN binaries. In the case of the second SN, it is the more massive star that explodes, so that the system, if it has not already separated after the first SN, will normally become unbound, producing *two* high-velocity, single pulsars. In rare cases, the binary can survive this second SN, producing a binary pulsar (De Cuyper 1985).

Our confidence in the binary-SN scenario was considerably enhanced very recently by the discovery of a WR star in the well-known, but highly reddened 4.8-hour period MXRB Cyg X-3 (van Kerkwijk et al. 1992; van Kerkwijk 1993). Previously to this, none of the suspected WR + c systems (Moffat 1982) showed any significant accretion-type X-rays, making their existence questionable. The presence of one clear WR + c system (and possibly one other, HD 197406: Marchenko et al. 1996) is, within the small number statistics, compatible with the relative lifetimes ($\sim$ 10%) of mainly He-burning WR stars versus the 24 known MXRB main-sequence stars. Possibly, the majority of the runaway WR stars are also single, as for O runaways, having been disrupted in most cases by an asymmetric SN.

On the other hand, the existence of systems (1), (2), (3) and (5) is well established: O + O and WR + O binaries have been known for over half a century, with binary frequencies close to 40% (Garmany, Conti & Massey 1980; Moffat et al. 1986); O + c systems were discovered in the late 1960's from X-ray satellites; runaway neutron stars were discovered not long after the first pulsar was discovered in 1968. Even the association of MXRBs with massive runaways seems now assured (van Oijen 1989), thanks to better statistics, despite some previous doubts (e.g. Gies & Bolton 1986).

The cluster-ejection scenario makes predictions that are somewhat different compared to the binary-SN hypothesis, although both can lead to massive runaways *per se*. In particular, while the cluster-ejection scenario slightly favors the observed low, but non-zero O + O binary frequency among runaways and accounts better for runaway pairs like AE Aur/μ Col, both scenarios can lead to the large range of runaway space velocities observed, reaching up to some 200 km s^{-1}. However, the binary SN scenario appears to do better in accounting for observed space frequencies, low-mass cut-off, velocity-mass correlation, kinematical ages and presence of MXRBs among the OB runaways (Stone 1991). However, some of Stone's results may be invalidated by his restrictive subsample of main sequence massive close binaries, all having the same initial orbital period and mass ratio. Nevertheless, Blaauw (1993) also notes that the SN scenario allows better for the high frequency of fast rotators and abundance anomalies among O runaways, compared to low-velocity O stars. Indeed, the mere existence of MXRBs proves that SN do take place in massive binaries, which must lead to runaway speeds even if the explosion is symmetric, although most SN are highly asymmetric and lead to disruption and hence single runaways. Nevertheless, a certain fraction of O and WR runaways may have been ejected from compact clusters.

The bulk of these previous studies is based primarily on radial velocities (RV). Proper motions were known, but only for the brighter stars, and with a precision inadequate for viable studies. For WR stars, RVs are virtually useless to determine systemic radial motion; even the more extreme O stars (those with emission lines in their visible spectra) tend to have negatively biased RVs. For these reasons, three independent groups were granted Hipparcos time in 1982 to obtain systematically more precise proper motions of the bulk of the Galactic WR stars down to a feasible magnitude limit, as well as a pre-selected (to keep the numbers reasonable) group of Galactic O stars. This paper presents the merged results of these programs.

The aims are to use these proper motions to:

1. explore Galactic rotation,
2. compare peculiar motions and runaway properties of O and WR stars,
3. determine kinematic ages from the component of peculiar motion perpendicular to the Galactic plane, and
4. look for a correlation of bow shocks with projected direction of motion on the sky of stars moving at supersonic speed with respect to the ISM (RVs are less useful for this).

The tracing back of the origin of motion to parental clusters/associations will be left for a future study, when the proper motions of the clusters/associations themselves have been properly re-assessed using Hipparcos (cf. de Bruijne et al. 1997; Hoogerwerf et al. 1997; de Zeeuw et al. 1997). This must be combined with evolutionary models (e.g. cf. van Rensbergen, Vanbeveren & de Loore 1996).

2. Selection of targets

The proper motion of a star is related directly to the (total) tangential velocity by the well-known transformation

$$\mu(\mathrm{mas/yr}) = v_t(\mathrm{km/s})/[Kr(\mathrm{kpc})],$$

where K = 4.740. Thus, the detection of runaways with $v_t \approx$ 100 km/s can be made out to r = 7(4) kpc for a nominal precision of $\sigma_\mu \approx 1$ mas/yr at the 3(5)σ level. Such is the case with Hipparcos, although more distant stars will often be fainter and have larger errors.

Guided by this, we first selected all Galactic WR stars from the catalogue of van der Hucht et al. (1981) with $v \lesssim 12$ mag (slightly revised magnitudes are found in van der Hucht et al. 1988). This is a nice coincidence with the observability limit of the catalogue: $v \approx 13$. In actual fact, due to feasibility constraints of Hipparcos, only 67 WR stars were observed, which includes all Galactic WR stars down to v = 12, except: WR25 (at v = 8.2, one of 22 stars to v = 9; this is unfortunate, since WR25 exhibits the largest X-ray flux known for any Galactic WR star); WR85, 92 (2 of 18 stars with v = 10...11; this excludes WR43, the dense core of the cluster NGC 3603); WR12,30,75,93,143,152 (6 of 24 stars with v = 11...12); and the *addition* of WR61, 121 (2 of 26 stars with v = 12...13). These 67 stars are thus nearly complete to $v \lesssim 12$, and represent about one third of all presently known WR stars in the Galaxy (van der Hucht 1996).

A total of 66 O stars were selected from the catalogue of Cruz-Gonzalez et al. (1974), among the 72 stars with peculiar radial velocity components $|(v_r)_{pec}| > 30$ km/s, after subtracting off the Solar motion and Galactic rotation according to their recipe. Six of these 72 stars were not observable with Hipparcos. This selection is nearly complete to $V \approx 10$ mag, i.e. about two mags brighter than the WR sample.

Also observed were the 8 MXRBs known at the time of application (Forman et al. 1978). All O and WR stars observed here with Hipparcos (ESA 1997) will be listed and discussed in the next section.

3. Reduction

Hipparcos provides astrometric data, with errors, for positions α, δ; proper motions μ_α (the factor $\cos\delta$ is already included), μ_δ; and parallaxes π, for the epoch 1991.25, in addition to photometric data, which will be the subject of a second paper (Marchenko et al. 1997). Only 4 O stars and 1 WR star have reliable parallaxes; two of them (γ Vel and ζ Pup) have been studied elsewhere (van der Hucht et al. 1997; Schaerer et al. 1997).

In addition to the random peculiar motions of stars in the Galaxy, the bulk of the systematic angular motion arises due to differential Galactic rotation. It thus makes most sense to transform from the equatorial to the Galactic coordinate system. We do this using the values recommended by the Hipparcos consortium:

$$\sin b = \cos\delta\cos\delta_G\cos(\alpha-\alpha_G) + \sin\delta\sin\delta_G,$$
$$\tan(l-l_\Omega) = [\sin\delta - \sin b\sin\delta_G]/[\cos\delta\sin(\alpha-\alpha_G)\cos\delta_G],$$

where $\alpha_G = 192\overset{\circ}{.}85948$, $\delta_G = 27\overset{\circ}{.}12825$ and $l_\Omega = 32\overset{\circ}{.}93192$.

Then we transform the proper motions (Trumpler & Weaver 1953; Scheffler & Elsässer 1987):

$$\mu_l = \mu_\alpha\cos\psi - \mu_\delta\sin\psi,$$
$$\mu_b = \mu_\alpha\sin\psi + \mu_\delta\cos\psi,$$

where ψ is the parallactic angle satisfying:

$$-\cos b\cos\psi = \cos\delta_G\sin\delta\cos(\alpha_G-\alpha) - \sin\delta_G\sin\delta,$$
$$\cos b\sin\psi = \cos\delta_G\sin(\alpha_G-\alpha).$$

The observed proper motions can then be expressed as sums of basic Solar motion, Galactic rotation, and peculiar motion:

$$\mu_l = (\mu_l)_\odot + (\mu_l)_{rot} + (\mu_l)_{pec},$$
$$\mu_b = (\mu_b)_\odot + (\mu_b)_{rot} + (\mu_b)_{pec},$$

where

$$Kr(\mu_l)_\odot = U_\odot\sin l - V_\odot\cos l,$$
$$Kr(\mu_b)_\odot = U_\odot\cos l\sin b + V_\odot\sin l\sin b - W_\odot\cos b$$

for distance from the Sun, r, in kpc and μ in mas/yr, and $U_\odot, V_\odot, W_\odot = 9, 11, 6$ km/s (Delhaye 1965). Galactic rotation is written as:

$$K(\mu_l)_{rot} = [R_o/(r\cos b)](\omega-\omega_o)\cos l - \omega,$$
$$K(\mu_b)_{rot} = -(R_o/r)(\omega-\omega_o)\sin b\sin l,$$

with

$$R^2 = R_o^2 + r^2\cos^2 b - 2rR_o\cos b\cos l.$$

We also take $z = r\sin b$ for the distance perdendicular to the Galactic plane. Here we adopt a flat rotation curve with

$$\omega \equiv \omega(R,z) = V_o/R, \qquad \omega_o = V_o/R_o,$$

in which Solar galactocentric distance R_o = 8.5 kpc and circular Galactic rotation velocity V_o = 220 km/s, adequate for galactocentric distances $3 \lesssim R$(kpc) $\lesssim 18$ (Kerr & Lynden-Bell 1986).

For the O stars, distances were adopted based on photometric techniques by Cruz-Gonzalez et al. (1974), with updates/corrections using reliable Hipparcos parallaxes for 4 stars (γ Cas, μ Col, ζ Pup, λ Cep) and Hipparcos stellar magnitudes (transformed to the V-band). Furthermore, the distances were updated from the catalogues of Humphreys (1978), Savage et al. (1985) and Diplas & Savage (1994). For the MXRBs, we used the mean values from van Oijen (1989). In the case of the WR stars, distances are adopted from the catalogue of van der Hucht et al. (1988), with an update for γ Vel based on the new, reliable parallax from Hipparcos. The radial velocities and spectral types of the O stars are in accordance with Cruz-Gonzalez et al. (1974), with further corrections from Humphreys (1978), Gies & Bolton (1986), Gies (1987), Levato et al. (1988). The spectral types of the WR stars are adopted from van der Hucht et al. (1988) with some minor modifications.

A summary of the pertinent data for all 141 stars is presented in Table 1[1].

[1] Recall that Table 1 can only be retrieved electronically - see footnote to the title.

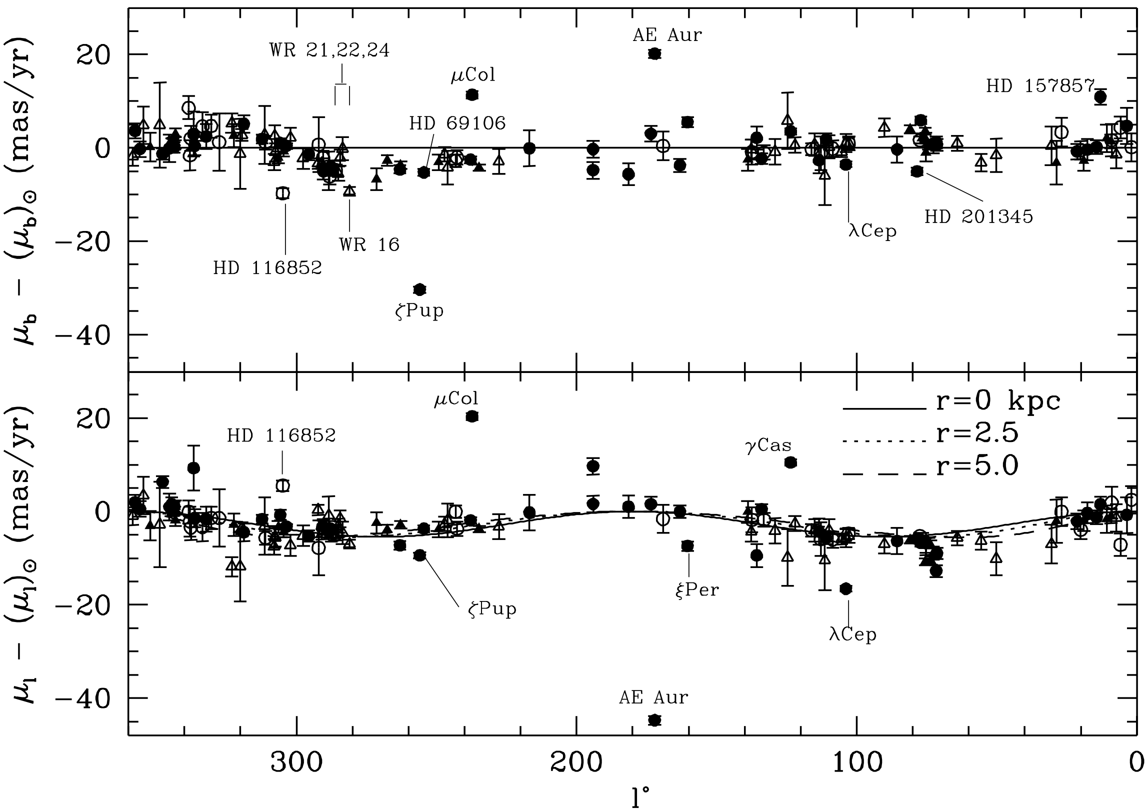


Fig. 1. Net proper motion $\mu - \mu_{\odot}$ versus Galactic longitude for each of the l and b components. Circles refer to O stars, triangles to WR. Filled symbols are for $r \leq 2.5$ kpc, open symbols $r > 2.5$ kpc. The zero line is drawn in for the b component. Flat rotation curves (V_o = 220 km/s, R_o = 8.5 kpc) are shown for the l component: solid, dotted, and dashed curves are for r = 0, 2.5, 5.0 kpc, respectively. Stars that deviate by at least 10 σ_μ in either l or b are identified.

4. Analysis and results

4.1. Galactic rotation

First, we check for differential Galactic *angular* rotation by plotting separately the Galactic longitudinal and latitudinal components of proper motion after removal of the basic Solar motion, versus longitude (see Fig. 1). Except for the Solar correction (especially for nearby stars), the positions of the data-points are only weakly dependent on distance. This is useful, since the bulk of the distance estimates are photometric, with relatively large errors (typically ± 30%). In Fig. 1, we have superposed the expected Galactic angular rotation (see previous section) in l for b = 0 (the dependence on b for typical small values of b is very weak) and for three distances, which span the distance range for the bulk of the data. Note again the weak dependence on the distance. The rotation effects in b also depend on b, but these are negligeably small and thus not shown.

Fig. 1 shows that the O stars and the WR stars are fairly well mixed, with two effects emerging: (1) A global double-wave trend in μ_l versus l, with minima (zero actually) in absolute value at l = 0° and 180°, as expected from the rotation model. The perfect double sine-wave for zero distance becomes increasingly distorted with larger distance, with maxima in absolute value spreading out gradually below l = 90° and above l = 270°. (2) The weak dependence of the model curves on distance allows one to easily locate stars that deviate significantly from the trend of Galactic rotation (but conversely makes proper motions essentially useless for rotation parallaxes, given the observational uncertainties). In Fig. 1 and Table 2 we identify those stars for which at least one of the componenets of proper motion deviates from the curve, appropriate for the distance, by more than 10σ. These stars have very significant peculiar motion relative to the general Galactic rotation curve. More modestly deviating stars can be easily identified in Table 1.

Fig. 1 also reveals ranges in Galactic longitude, where coherent deviations appear to occur, in particular in μ_b for l = 260° − 300° and in μ_l for l = 160° − 200°. These may be due to large-scale deviations from the assumed circular rotation, towards the Carina region and the anticenter, respectively.

4.2. Peculiar tangential motions

Significant peculiar proper motion does not necessarily imply fast *absolute* tangential motion in $km\,s^{-1}$. To obtain tangential velocities, we have no choice but to take published photometric distances, since geometric distances are still not precise enough for most OB and WR stars. The peculiar (total) tangential mo-

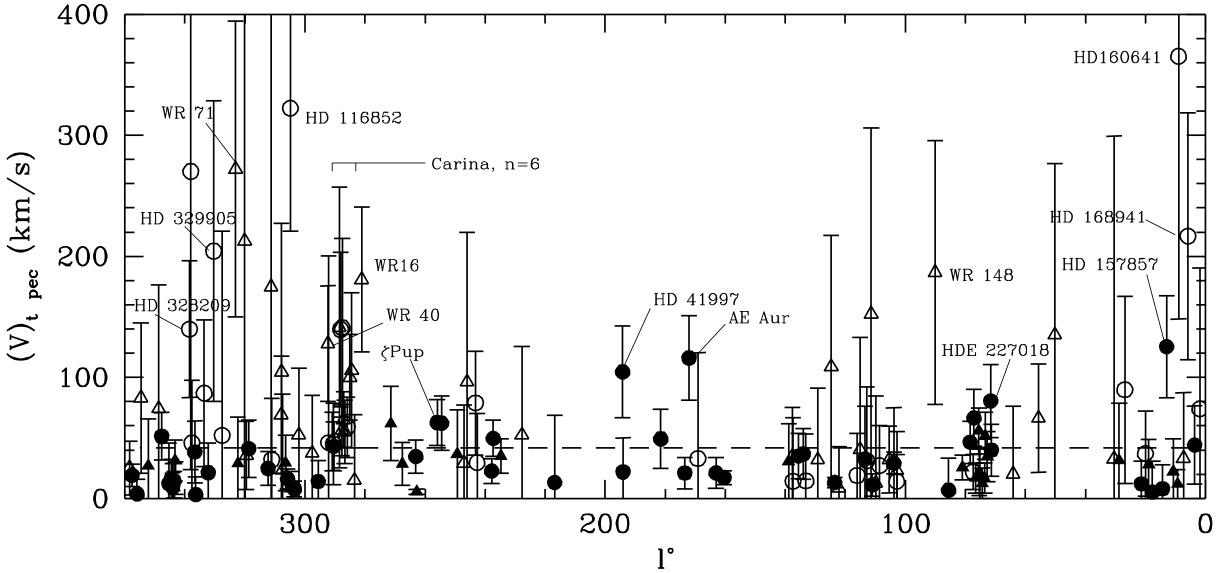


Fig. 2. Peculiar tangential motion of all O and WR stars from Table 1, versus Galactic longitude. Symbols are as in Fig. 1. The dashed horizontal line refers to the base limit of 42 km/s for selecting runaways based on peculiar tangential velocities. Stars with $(v_t)_{pec} > 42 + \sigma_{(v_t)_{pec}}$ km/s are identified.

tions (see Table 1 and Fig. 2) were calculated using

$$(v_t)_{pec} = Kr\sqrt{(\mu_l)^2_{pec} + (\mu_b)^2_{pec}}.$$

Errors in $(v_t)_{pec}$, $\sigma_{(v_t)_{pec}}$, are calculated using error propagation in all the observed quantities, assumed to be independent, and assumimg a 30% uncertainty in the distances, corresponding to a 0.7 mag rms error in distance modulus, quite reasonable given the cosmic scatter in M_v for single OB and WR stars. 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 bound and underestimate the upper error bound. However, for such non-linear functions, there is no standard way to correct for this. In any case, this effect will be partly compensated for by the increase in $(v_t)_{pec}$ introduced by the same error bias. By not correcting for either of these, we tend to err on the conservative side.

In order to make a meaningful selection of runaways based on *tangential* motion alone, we adopt the criterion

$$(v_t)_{pec} > 42 + \sigma_{(v_t)_{pec}}\ \mathrm{km/s}.$$

The base value of 42 km s^{-1} is consistent with a selection in $|(v_r)_{pec}|$ alone above 30 km s^{-1} (e.g. Cruz-Gonzalez et al. 1974), i.e. allowing for a factor $\sqrt{2}$ for the *two* components of velocity that go into μ_{pec}.

This criterion leads to a selection of 19 stars, 6 WR and 13 O-type (see Table 3 for a detailed list). Note that only eight of these have very significant peculiar proper motion according to Table 2; because of large distances, 11 new stars have appeared in Table 3. Within the small numbers, there is no reason to assume that WR and O stars differ at all in their frequency of runaways. In any case, the pre-selection of O stars with high $|(v_r)_{pec}|$ may account for the slightly higher number of O runaways. Four stars in the Carina region have large $(v_t)_{pec}$; some of these may be spurious, being part of a global velocity perturbation in this localized region of the Galaxy. The average runaway frequency in our overall sample is 14%. This seems low, but is compatible with the observed runaway frequency of O stars from RVs, allowing for our somewhat more severe selection here to allow for a one-σ error. Following Stone (1991), extrapolating this distribution tail to a Gaussian would lead to significantly higher frequency for the so-called high-velocity massive stars.

Some stars in Table 3 deserve special mention. While several O type RV runaways appear in our peculiar tangential motion study, some others are missing (e.g. μ Col); this is not surprising, however, since high peculiar motion need not always appear in both the radial and tangential components simultaneously (see below). Among the WR stars, neglecting the Carina region, there is a preference for WN8 stars to be runaway, based on peculiar motion. This is reinforced by the known very high $(v_r)_{pec}$ of the runaway WN8 star WR 124 (Moffat et al. 1982), whose $(v_t)_{pec}$ is not well determined here, and the avoidance of clusters by the WN8 subclass (Moffat 1989). Other WN8 stars could have high $(v_r)_{pec}$, without having been observed as such. Even the strange SB1 binary WR 148 with WN7 subclass (WN8h according to the revised classification of Smith et al. 1996) may be related to these objects. The only other non-Carina WR runaway in Table 3 is WR71 (WN6, a previously suspected runaway: Isserstedt et al. 1983).

We now compare the peculiar tangential and radial motions of the O stars in Fig. 3, in which we have reduced the total tangential component from two to one dimension through division by $\sqrt{2}$. In preparation for this figure, we have updated many of the Cruz-Gonzalez et al.(1974) RVs and recalculated the So-

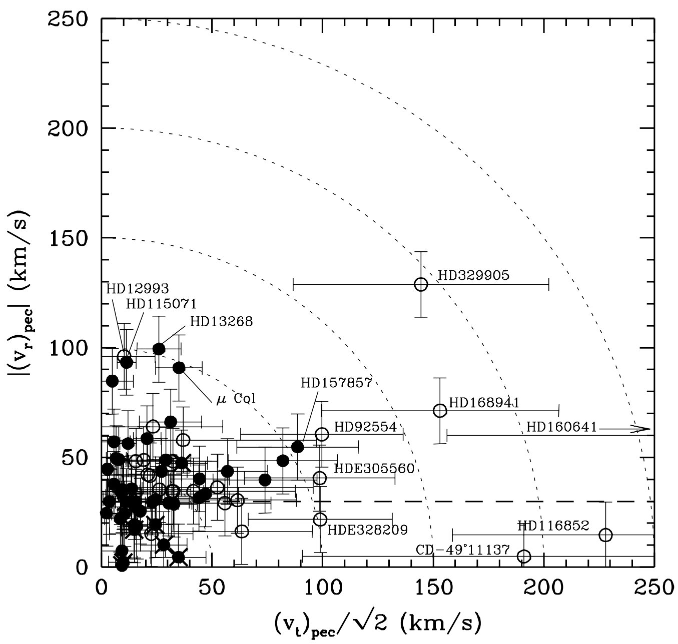


Fig. 3. Absolute value of peculiar radial velocity versus peculiar tangential velocity normalized to one component, for the program OB stars. Symbols are as in Fig. 1, with additional crosses indicating MXRBs. The horizontal dashed line indicates the Cruz-Gonzalez et al. (1974) cutoff in $|(v_r)_{pec}|$. The dashed arcs refer to lines of constant $[(v_r)^2_{pec} + (v_t)^2_{pec}/2]$. Some of the most extreme stars are identified.

lar correction and Galactic rotation in a way that is consistent with our above treatment of the tangential data. In particular, we write the observed component of heliocentric radial velocity:

$$v_r = (v_r)_\odot + (v_r)_{rot} + (v_r)_{pec},$$

in which

$$\begin{aligned}(v_r)_\odot &= -U_\odot \cos l \cos b - V_\odot \sin l \cos b - W_\odot \sin b,\\ (v_r)_{rot} &= R_o(\omega - \omega_o) \cos b \sin l.\end{aligned}$$

We have adopted $\sigma_{v_r} = 15\,\mathrm{kms}^{-1}$ uncertainty level in the observed RVs for calculating the error bars in Fig. 3. All the O-star RV data are summarized in Table 1.

Fig. 3 shows that some dozen O-stars now have peculiar RVs that are *below* the Cruz-Gonzalez et al. (1974) limit to be classified as RV runaways (30 km s^{-1}). Also, the majority (but not all) of the MXRBs lie below the limit, since they were not selected for high $|(v_r)_{pec}|$. However, as expected, many stars with low $|(v_r)_{pec}|$ have high $(v_t)_{pec}$, and *vice versa*, within the prescribed RV cutoff of the Cruz-Gonzalez et al. (1974) RV data. The overall impression here is that, within the errors, both radial and tangential data give consistent results, leading to a more-or-less circular distribution centred on (0,0) in the $|(v_r)_{pec}| - (v_t)_{pec}/\sqrt{2}$ plane. Note that some runaways have both components large. This situation reassures us that obligatorally taking only *tangential* peculiar motions for the WR stars is a statistically sound procedure for recognizing some WR runaways.

4.3. Kinematic ages

Kinematic ages (τ_{kin}) are important to constrain the origin of the runaways. They can be obtained in principle for individual stars from the distance to their origin divided by the runaway (i.e. peculiar space) velocity. For the SN binary scenario, one should have $\tau_{kin} \approx 0.3\tau_{nuc}$, where τ_{nuc} is the current nuclear age of the *observed* star (Stone 1991). For the cluster ejection scenario, $\tau_{kin} \approx \tau_{nuc}$. Two methods can be used to trace the place of origin: from the natal cluster/association or from the Galactic plane. If one cannot locate unambiguously a natal cluster or association in the Galactic plane, this technique must be abandoned. As noted in the Introduction, we will not deal with this method here; we will concentrate on the latter method.

Assuming all massive stars are born in or near the Galactic plane (and in clusters/associations), one can obtain τ_{kin} simply from the current separation from the plane ($z = r \sin b$) and the current velocity perpendicular to and away from the plane (massive runaways are too young to have peaked and be returning to the plane: Gies & Bolton 1986). The latter can be written

$$Z = Kr(\mu_b)_{pec} \cos b + (v_r)_{pec} \sin b.$$

For the majority of our objects, b is small, so Z depends mainly on $(\mu_b)_{pec}$. In any case, systemic RVs are generally not known for WR stars; hence we will simply take as adequate approximation for all stars in this context

$$Z \cong Kr(\mu_b)_{pec}.$$

Following Scheffler & Elsässer (1987), one has the equation of motion perpendicular to the Galactic plane for any given star, valid out to $z \approx 0.5$ kpc:

$$\ddot{z} = -\alpha^2 z,$$

with $\alpha^2 \equiv (\partial K_z/\partial z)_{z=0}$, in which K_z is the restoring force per unit mass towards the plane. Scheffler & Elsässer give $\alpha \simeq 3 \times 10^{-15}\,\mathrm{s}^{-1} \simeq 0.1\,\mathrm{kms}^{-1}\mathrm{pc}^{-1}$. More recent studies (Kuijken & Gilmore 1989a,b; cf. also Bhattacharya et al. 1992) show that such a linear acceleration-distance law is limited to $|z| \lesssim 0.1$ kpc only (where the disk potential dominates), beyond which the slope gradually flattens to a value dominated by the halo for $|z| \gtrsim 0.7$ kpc. However, as we shall see below, our analysis will be limited to stars below $|z| \approx 0.35$ kpc, for which a value of $\alpha \sim 0.06$ km s^{-1} pc^{-1} $\sim 2 \times 10^{-15}\mathrm{s}^{-1}$ is most representative. The scatter in the data does not justify going beyond a linear force law; thus we adopt this value from here on. Integration leads to

$$\begin{aligned}z &= a \sin \alpha t,\\ Z &= a\alpha \cos \alpha t.\end{aligned}$$

The sinusoidal oscillation about the plane occurs with period $P = 2\pi/\alpha \simeq 100$ Myr and maximum separation $a = Z_o/\alpha$, where Z_o is the initial perpendicular velocity in the plane at $t = 0$. Since we do not know Z_o for each star, we eliminate a by taking the ratio

$$Z/z = \alpha/(\tan \alpha t).$$

Table 2. Program stars with the most significant deviation ($\geqq 10\sigma$)in μ_l or μ_b from Galactic rotation

HD	$(\mu_l)_{pec}/\sigma_{(\mu_l)_{pec}}$	$(\mu_b)_{pec}/\sigma_{(\mu_b)_{pec}}$	Comments
66811 = ζ Pup	-10.0	-74.3	known runaway
34078 = AE Aur	-72.7	40.1	known runaway
38666 = μ Col	46.6	20.5	known runaway
5394 = γ Cas	32.3	8.6	MXRB, nearby
210839 = λ Cep	-28.6	-8.5	known runaway
116852	15.1	-13.9	
86161 = WR16	-2.6	-14.4	
157857	1.7	13.2	known runaway
90657 = WR21	2.4	-12.5	SB2
92740 = WR22	-0.9	-11.1	SB2
192163 = WR136	-10.8	6.9	
192281	-2.3	10.7	
24912 = ξ Per	-10.0	8.6	known runaway
69106	1.4	-10.0	

Note: the stars are ordered in decreasing absolute deviation in σ_{pec} in either of the galactic coordinates. “Nearby” if $r < 0.4kpc$. Known runaways after Gies (1987) and Blaauw (1993).

Table 3. Stars with $(v_t)_{pec}kms^{-1} > 42 + \sigma_{(v_t)_{pec}}$, in order of HIP number.

HD/DM	Sp	Other	$\|f/\sigma_f\| > 10$?	Known runaway?	SB?	Comments
34078	AE Aur	O9.5V	yes	yes		
41997		O7.5V(n)				
66811	ζ Pup	O4I(n)f	yes	yes		rapid rotator
86161	WR16	WN8	yes			strongly variable
$*$ 90657	WR21	WN4 + O4-6	yes		SB2	
$*$ 92554		O9.5II				
$*$ 92740	WR22	WN7 + O6.5-8.5	yes		SB2	
$*$ E305560		O9.5III				
96548	WR40	WN8		(yes)		highly variable
116852		O9III	yes			
E329905		O9I				
143414	WR71	WN6		(yes)		highly variable
E328209		O9.5Ia				
157857		O6.5III(f)	yes	yes		
160641	V 2076 Oph	O9.5Ia			SB?	
168941		O9.5II				
227018		O6.5III				
192281		O5Vn((f))p	yes			
197406	WR148	WN7 + B(c?)		(yes)	SB1	variable

Note: $*$ indicates Carina region. f refers to σ_{pec} in l or b. WR runaway status suspected (Moffat & Isserstedt 1980). AE Aur, WR16 and HD 116852 have $(v_t)_{pec} > 42 + 2\sigma_{(v_t)_{pec}}$ km/s.

In order to apply the above scenario to our sample, it is not useful to look at *individual* runaway stars, in view of the large errors both in tangential velocity and in distance. However, grouping also poses a problem, since different stars will have different nuclear ages. O stars have lifetimes $\tau_{tot} \sim$ 2-10 Myr, compared to $\sim$ 2-7 Myr for WR stars at $Z_\odot$ (Maeder & Conti 1994). The upper limit for the latter decreases for lower metallicity. In the Solar environment of the Galaxy, allowing for the strong bias of the IMF towards lower-mass stars (as reflected by the preponderance of late-type O stars in Table 1, which are also the progenitors of WR stars) a typical mean value lies in the range $\tau_{tot} \approx$ 8-9 Myr for the average O star and $\tau_{tot} \approx$ 5-6 Myr for the average WR star. In a random sample, $\tau_{nuc} \sim \tau_{tot}/2$ for O stars and $\tau_{nuc} \sim \tau_{tot}$ for WR stars (since the WR He-burning phase is short compared to the progenitor main sequence phase). Thus, a global value $\tau_{nuc} \approx 5$ Myr probably reflects a good overall average for the (statistically more viable) combined O and WR stars in our sample.

We therefore adopt $t = \tau_{kin} = const$ in the above equation, and make a linear fit $Z = c_1 + c_2 z$. [We also assume equal weights; otherwise the result will be fortuitously dominated by a small number of data points of very high weight.] Avoiding the

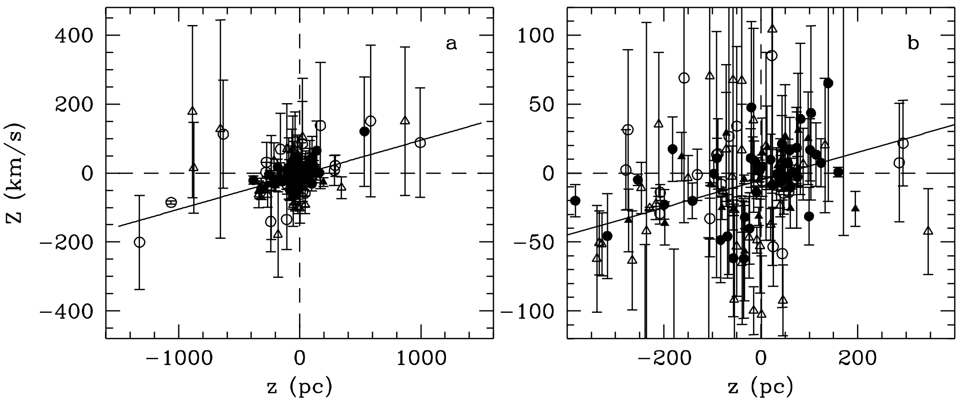


Fig. 4a and b. Velocity perpendicular to the Galactic plane $Z = Kr(\mu_b)_{pec}$ versus separation from the Galactic plane $z = r \sin b$, in normal and zoomed scales. Symbols are as in Fig. 1. A linear unweighted fit is shown by the straight line $Z(\mathrm{km/s}) = -5.0 + 0.10z(\mathrm{pc})$.

11 stars beyond $|z| = 360$ pc ($\sim$5 scale heights from the Galactic plane), where errors in distance are large, we find $c_1 = -5 \pm 8\,\mathrm{kms}^{-1}$, $c_2 = +0.10 \pm 0.06\,\mathrm{kms}^{-1}\mathrm{pc}^{-1}$ at the 95% level (this fit is shown in Fig. 4). The positive value of c_2 is compatible with stars leaving the Galactic plane, as expected. Taken at face value, this leads to $\tau_{kin} = 9^{+7}_{-3}$ Myr. This appears to be compatible with the cluster ejection scenario, i.e. $\tau_{kin} \approx \tau_{nuc}$ at the 1σ level.

4.4. Correlation with bow shocks

If v_{pec} is supersonic with respect to the ISM (e.g. $c_{HI} \sim 0.7 - 6\,\mathrm{km\,s}^{-1}$, $c_{HII} \sim 10\,\mathrm{km\,s}^{-1}$: Scheffler & Elsässer 1987), a bow shock (region of enhanced emission) will occur in the direction of motion of the (windy O or WR) star (e.g. Van Buren 1993), assuming a relatively uniform surrounding ISM and neglecting complexities of multi-wind interactions around WR stars. In order to best explore whether the motion of the star is compatible with the formation of such bow shocks, we use only the tangential velocity vector, which is a projection of the space velocity on the sky. The radial component of peculiar velocity will not lead to a clear, unambiguous bow shock arc.

We have thus scanned the literature for arc-shaped bow shocks (enhanced emission in the direction of peculiar tangential motion) around all of our program O and WR stars. About 85% of the OB stars from our list (Table 1) were previously searched for the presence of bow shock-like emissivity on $60\mu m$ IRAS maps by Van Buren et al. (1995). The fraction of OB stars from our list that manifest bow shock-related phenomena is ~ 0.3 (WR stars have not yet been searched systematically for bow-shocks), in complete agreement with the estimation of Van Buren et al. Only 5 of them (HD 34078,41997,66811,210839 and HDE329905) can be recognized as well-established runaways (cf. Tables 2 and 3). Interesting cases (see Table 4) among the OB and WR stars are:

1. HD 189957 is moving toward a bright knot (unresolved bow shock structure?) seen on $60\mu m$ IRAS image (Van Buren et al. 1995).
2. The vector of the peculiar motion of HD 210839 is directed $\sim$along the axis of symmetry of the clearly seen (Van Buren et al. 1995) bow shock structure.

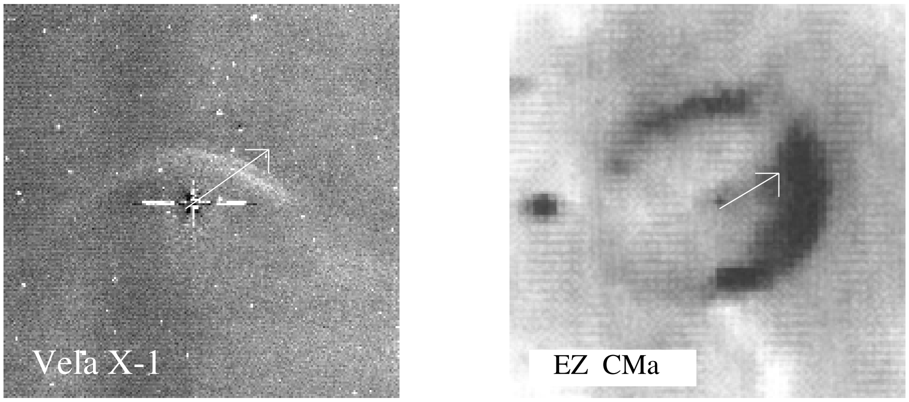
Table 4. OB and WR stars moving towards recognized/potential bow shock structures.

Star	$(\mu_\alpha)_{pec}$	$\sigma_{(\mu_\alpha)pec}$	$(\mu_\delta)_{pec}$	$\sigma_{(\mu_\delta)pec}$
HD 50896=WR6	-4.48	0.43	1.56	0.66
HD 77581=Vela X-1	-4.61	0.58	2.02	0.66
HD 86161=WR16	-9.44	0.60	-0.73	0.65
HD 92809=WR23	-3.18	0.99	-3.06	0.75
HD 96548=WR40	1.08	0.76	-6.64	0.72
HD 117688=WR55	-0.81	1.42	2.42	1.58
HD 187282=WR128	2.99	1.27	-1.79	1.01
HD 189957	-1.37	0.48	1.01	0.50
HD 190918=WR133	-1.73	0.89	-3.06	0.93
HD 191765=WR134	-3.21	0.58	-4.11	0.63
HD 192163=WR136	-5.78	0.49	-2.93	0.53
HD 210839=λCep	-8.12	0.44	-8.95	0.39

3. HD 77581 (Vela X-1). This is an especially interesting case (Kaper et al. 1997). With the new Hipparcos data (see Fig. 5a), we now find that the star is heading right towards the emissivity maximum of the bow shock.
4. WR 6, moving toward the brightest part of the surrounding ring nebula (cf. the maps from Arnal & Cappa 1996; Van Buren et al. 1995; also Fig. 5b here). One is inclined to suggest that this relative brightening is directly related to the bow-shock phenomenon.
5. The same brightening of the surrounding IS media in the direction of the stellar tangential motion is seen for WR 16 and WR 40 (Marston 1995), WR 23 and WR 55 (Chu et al. 1983; Marston et al. 1994), WR 133 (Marston 1996), WR 134 and WR 136 (Miller & Chu 1993; note that for WR 136 the IR maximum is somewhat displaced from the optical maximum - cf. the map from Marston 1996)
6. A spectacular system of shells (Heckathorn et al. 1982; Miller & Chu 1993) is stretched to one side of the tangential motion vector of WR 128.

5. Conclusion

Hipparcos has provided a large, systematic data base of high precision proper motions that yield internal precisions of tan-



a **b**

Fig. 5a and b. Proper motion vectors superposed on ISM emission maps of the surroundings of two sample stars **a** HD 77581 (Vela X-1) and **b** HD 50896 (EZ CMa = WR6). The maps are from Kaper et al. (1997) and Van Buren et al. (1995), respectively.

gential velocities that are comparable to the current uncertainties of radial velocities of Galactic OB and WR stars at distances of several kpc. However, unlike Doppler RVs, the pm's are not biased by line blending and contamination by winds, and are thus probably more robust. This has allowed us for the first time to make a reliable systematic study of the motions of Galactic WR stars and compare them with O stars. The next era of astrometric satellites (e.g. ESA's GAIA: pm's to ± 0.01 mas/yr down to V = 15 mag) promises to be revolutionary.

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