Kinematics and Photometry of O and WR Stars with HIPPARCOS

A. F. J. Moffat and S. V. Marchenko

Département de physique, Université de Montréal, Canada

W. Seggewiss, K. A. van der Hucht, H. Schrijver, B. Stenholm, I. Lundström, D. Y. A. Setia Gunawan, W. Sutantyo, E. P. J. van den Heuvel, J.-P. De Cuyper, and A. E. Gómez

Abstract. We give a brief report of our HIPPARCOS results for a nearly complete, magnitude-limited sample of WR stars, and for a selection of both runaway O stars and massive X-ray binaries.

1. Background

This study is a merger of 3 independent HIPPARCOS projects, submitted in 1982 to investigate the parallaxes and, especially, proper motions of Galactic O and WR stars in the contexts of:
Galactic rotation (radial velocities are essentially useless for WR stars, and are imprecise for O-types); and
Peculiar motions and runaway properties, including those of high-mass X-ray binaries (HMXBs).

2. Target Selection

Our study is based on a selection of:

- 66 runaway O stars with absolute values of radial peculiar motions $\geq$30 km s^{-1} (Cruz-Gonzalez et al. 1974), nearly complete to $V \simeq 10$;
- 8 HMXBs with $V \leq 9$ (Forman et al. 1978); and
- 67 WR stars (van der Hucht et al. 1981), nearly complete to $v \simeq 12$.

3. Results: Astrometry

3.1. Parallaxes

With parallax accuracies of $\pi \pm 1$ mas, typically, only one Wolf-Rayet (γ Vel) and four O stars (ζ Pup, γ Cas, λ Cep, μ Col) are precise enough ($\pi/\sigma_\pi \geq 3$) to be considered reliable. This is not sufficient for a viable statistical study.

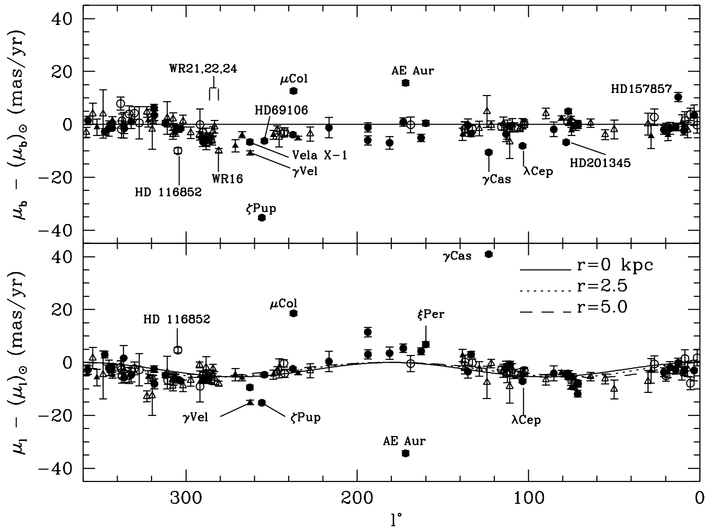

Figure 1. Net proper motion, $\mu - \mu_\odot$, versus Galactic longitude for each of the ℓ and b components. Circles refer to O-type stars, triangles to Wolf-Rayets. Filled symbols are for $r \leq 2.5$ kpc, open symbols $r > 2.5$ kpc. The zero line is drawn in for the b component. Flat rotation curves ($V_0 = 220\,\mathrm{km\,s^{-1}}, R_0 = 8.5$ kpc) are shown for the ℓ component: solid, dotted, and dashed curves are for $r = 0, 2.5$, and 5.0 kpc, respectively. Stars that deviate by at least $10\sigma_\mu$ in either ℓ or b are identified.

3.2. Proper Motions

With $\mu_\alpha, \mu_\delta \pm 1\,\mathrm{mas\,yr^{-1}}$ typically, we are able to examine two important aspects:

- Galactic rotation. As shown in Fig. 1, both O and WR stars follow the same trend. Note, however, that (i) one cannot use proper motions to *determine* reliable Galactic-rotation distances, and (ii) large deviators in Fig. 1 are objects which are very close to us, or runaway, or both.

- Peculiar motions.

  1. Tangential peculiar motions $(v_\mathrm{t})_\mathrm{pec}$ are statistically consistent with radial peculiar motions $(v_\mathrm{r})_\mathrm{pec}$ for O stars (see Fig. 2).
  2. The runaway fraction from $(v_\mathrm{t})_\mathrm{pec}$ is similar for WR and O stars (Table 1), and consistent with radial-velocity selection of O-type runaways (15%; Stone 1991): 13 O stars (18 ± 5%), 8 WR stars (12 ± 4%). Among WR stars, there is some preference for WN8 stars to be runaways.
  3. Kinematic ages (τ_kin), based on distance and motion away from the Galactic plane assuming O and WR stars are born close to the plane, appear to be high (origins in clusters/associations being studied elsewhere):

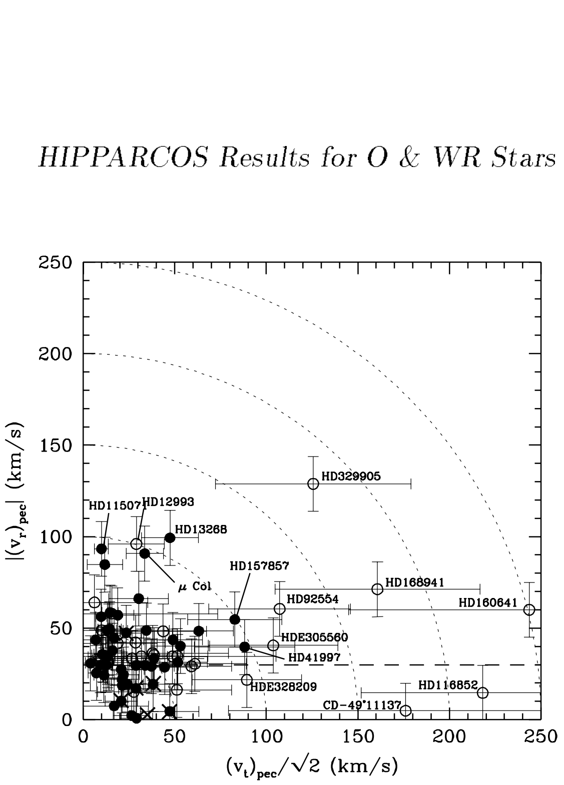

Figure 2. Absolute value of peculiar radial velocity versus peculiar tangential velocity normalized to one component, for the programme OB stars. Symbols are as in Fig. 1, with additional crosses indicating HMXBs. The horizontal dashed line indicates the Cruz-Gonzalez et al. (1974) cutoff in $|(v_{\rm r})_{\rm pec}|$. The dashed arcs refer to lines of constant peculiar space velocity. Some of the most extreme stars are identified.

With the displacement perpendicular to the Galactic plane

$$z = r \sin b = Z_0/\alpha \sin \alpha t \tag{1}$$

and velocity in the z direction

$$Z(\mathrm{km\,s^{-1}}) \simeq 4.74 r(\mathrm{kpc})(\mu_b)_{\rm pec}(\mathrm{mas\,yr^{-1}}) = Z_0 \cos \alpha t, \tag{2}$$

where

$$(\alpha \simeq 3 \times 10^{-15}\mathrm{s}^{-1} \simeq 0.1\mathrm{km\,s^{-1}\,pc^{-1}}), \tag{3}$$

we can eliminate the (*a priori* unknown) initial perpendicular component of velocity Z_0, by taking the ratio $Z/z = \alpha/\tan \alpha t$.
A linear fit $Z(z)$, taking $t \simeq$ constant (mean of all O, WR stars), yields (Fig. 3) $Z(\mathrm{km\,s^{-1}}) = 12 \pm 12 + (0.07 \pm 0.04) z(\mathrm{pc})$. This leads to $t = \tau_{\rm kin} = 10^{+3}_{-2}\,\mathrm{Myr}$, which is slightly greater than the expected mean *full* nuclear age, $\langle \tau_{\rm nucl} \rangle \simeq 6\,\mathrm{Myr}$. One would expect $\tau_{\rm kin} \simeq \langle \tau_{\rm nucl} \rangle /2 \simeq 3\,\mathrm{Myr}$. The difference may be due to a significant component of stars not born in the plane and moving on the 'wrong' direction.

4. Peculiar components of tangential-velocity vectors tend to point towards enhanced emission around stars with strong winds and velocities exceeding the sound speed in the surrounding ISM. Such bow shocks are seen around ~30% of O stars surveyed by IRAS (Van Buren et al. 1995). Examples are shown in Fig. 4.

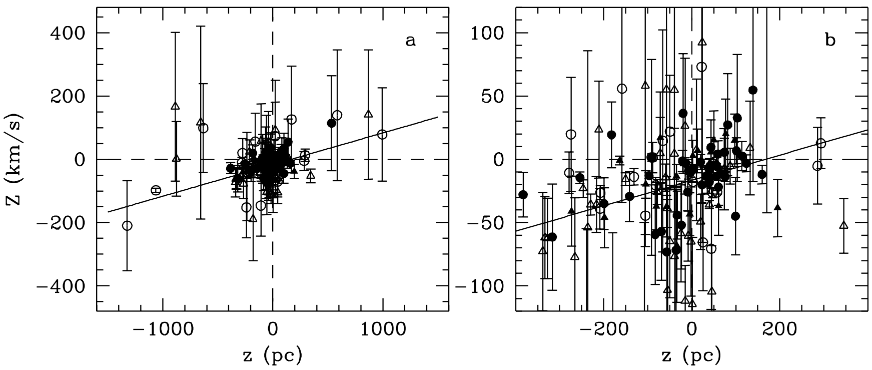

Figure 3. Velocity perpendicular to the Galactic plane, $Z = Kr(\mu_b)_{\rm pec}$, versus separation from the Galactic plane, $z = r \sin b$, in normal and zoomed scales. Symbols are as in Fig. 1. A linear unweighted fit is shown by the straight line $Z(\mathrm{km\,s^{-1}}) = -12 + 0.07z(\mathrm{pc})$

4. Results: Photometry

HIPPARCOS provides a unique, homogeneous set of typically $\sim$110 visual photometric data points ($\sigma_V \simeq 0.01^{\rm m}$ at $V = 6$, increasing exponentially to $0.03^{\rm m}$ at $V = 10$) for each star, spread over 3 years. In the case of the 141 programme O and WR stars here we note:

- The amplitude diagram, $3.28 \times \sigma_V$ vs. V (Fig. 5), allows selection of significantly variable stars.
- Among the $\sim$70 variables (half O, half WR), we confirm the short-term variability of many known spectroscopic binaries, rapid rotators, etc., for amplitudes greater than $\sim 0.03^{\rm m}$, and find the new results: (*i*) Long-term variability for HMXBs (e.g., Fig. 6: HD 102567, HDE 245770, with flaring in perfect and fair coincidence, respectively, with the X-ray light-curve) (*ii*) Previously unknown long-term variations and flaring in several O stars not known to be HMXBs (e.g., Fig. 6: HD 39680, CPD -61° 2163) (*iii*) Long-term variability in two WR stars, previously known to exhibit the shortest known periodicities (7 hr in WR46, 3.5 hr in WR66), and a strong ($\sim 1^{\rm m}$) 'dip' lasting several days in the light-curve of a WC9 star (WR121; see also Veen et al. 1996).

5. Summary of Highlights

We note the following primary results of this study:

- Both O and WR stars follow Galactic rotation in the same way.
- Both O and WR stars show similar runaway frequencies, and tend to be moving away from the Galactic plane on the whole.

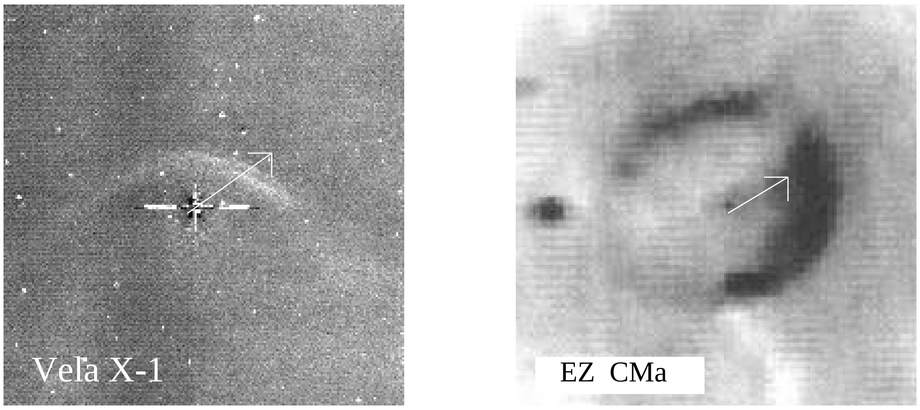

Figure 4. Proper-motion vectors superposed on ISM emission maps of the surroundings of two sample stars (a) HD 77581 (Vela X-1) and (b) HD 50896 (EZ CMa, WR6). The maps are from Kaper et al. (1997) and Van Buren et al. (1995), respectively.

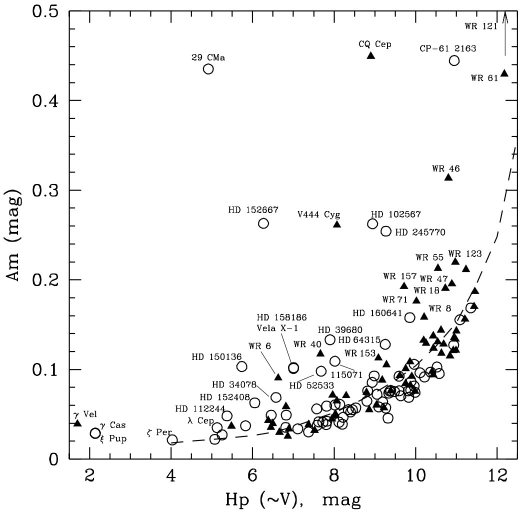

Figure 5. Dependence of the peak-to-valley amplitude of the variability $Am = 3.29 \times \sigma_{\rm Hp}$ on Hp. The ~99.9% detectability threshold is marked by a dashed line. Circles are O stars, triangles WR. The brightest stars and the most variable stars are identified.

Table 1. Runaway candidates based on large peculiar tangential motion, $(v_{\rm t})_{\rm pec} > 42 + \sigma_{(v_{\rm t})_{\rm pec}}$, km s^{-1}.

HD/DM	Other	Sp	$F > 10$?	R?	SB?	Comments
34078	AE Aur	O9.5 V	yes	yes		
41997		O7.5 V(n)				
66811	ζ Pup	O4 I(n)f	yes	yes		rapid rotator
69106		O5e	yes			
86161	WR16	WN8	yes			strongly variable
90657	WR21	WN4 + O4-6	yes		SB2	*
92504		O8.5 II				*
92554		O9.5 II				*
92740	WR22	WN7 + O6.5-8.5	yes		SB2	*
93131	WR24	WN7+a	yes			*
E305560		O9.5 III				*
96548	WR40	WN8		(yes)		highly variable
116852		O9 III	yes			
119078	WR57	WC7				
E329905		O9 I				
143414	WR71	WN6		(yes)		highly variable
E328209		O9.5 Ia				
157857		O6.5 III(f)	yes	yes		
160641		O9.5 Ia			SB?	
168941		O9.5 II				
197406	WR148	WN7 + B(c?)		(yes)	SB1	variable

Notes: $*$ indicates the Carina region (systematic streaming motion?); $F \equiv |f/\sigma_f|$, in which f refers to $\mu_{\rm pec}$ in ℓ or b; R refers to runaway status. Known O runaways are noted mainly by Gies (1987) and Blaauw (1993). WR runaway status was suspected by Moffat & Isserstedt (1980). WR16 and HD 116852 have $(v_{\rm t})_{\rm pec} > 42 + 2\sigma_{(v_{\rm t})_{\rm pec}}$ km s^{-1}.

- Both O and WR stars with significant supersonic peculiar motion tend to form bow-shock enhancements in the surrounding ISM, in the direction of their motion.

- Some O and WR stars show peculiar long-term variability.

6. Conclusion

The precise, large data base provided by HIPPARCOS is unique, although the astrometric precision is still somewhat marginal for viable studies of O and WR stars. ESA's future GAIA project ($\sigma_\mu \simeq 0.01$ mas yr^{-1}, $V \leq 15^{\rm m}$) promises to be revolutionary in this respect!

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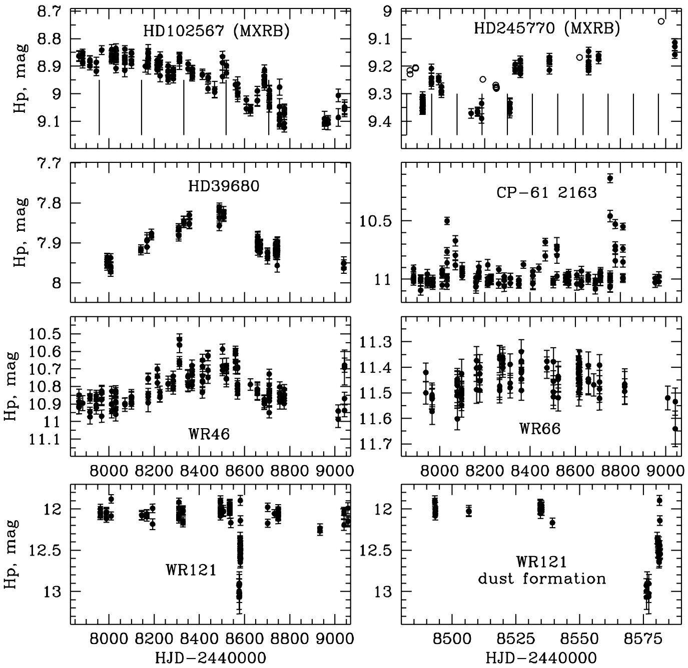

Figure 6. Upper panels: long-term variations and flaring in 2 HMXB (HD 102567 and HDE 245770) with times of periastron passage from X-ray observations indicated by vertical lines. Second panels: long-term variations and flaring in 2 presumably single OB stars, HD 39680 and CPD $-61°2163$. Third and bottom panels: long-term variability in WR46 (WN3p) and WR66 (WN8), and dust-formation episode in WR121 (WC9; normal scale and zoomed).

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