Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
Proceedings IAU Symposium No. 193, ©*1999 IAU*
K.A. van der Hucht, G. Koenigsberger & P.R.J. Eenens, eds.

On the formation of wind bow-shocks around OB runaway stars

Lex Kaper

Astronomical Institute, University of Amsterdam,
Kruislaan 403, NL-1098 SJ Amsterdam, The Netherlands

Fernando Comerón and Orly Barziv

European Southern Observatory,
Karl Schwarzschild Str. 2, D-85748, Garching bei München, Germany

Abstract. The interaction of the stellar wind of a supersonically moving massive star with its surrounding interstellar medium can result in the formation of an observable bow-shock. Recent studies at optical and infrared wavelengths indicate the presence of wind bow-shocks around several OB runaways, including the high-mass X-ray binary system Vela X-1. A large fraction of runaway stars do not seem to form wind bow-shocks. Obviously, when the local sound speed is high ($\sim 100\,\mathrm{km\,s^{-1}}$), as is the case *e.g.*, inside a hot superbubble, the (subsonic) space velocity would not be sufficient to form a bow-shock. Two-dimensional time-dependent hydrodynamical simulations indicate that the bow-shock is generally unstable; for certain combinations of ISM and wind parameters a bow-shock is not formed at all. The runaway nature of Wolf-Rayet stars in relation to the formation of wind bow-shocks is also discussed.

1. Massive stars that run through space

OB runaways are massive stars that travel through interstellar space with anomalously high velocities. The space velocity of these stars can be as high as $100\,\mathrm{km\,s^{-1}}$, which is about ten times the average velocity of 'normal' OB stars in the Milky Way. Several of them can be traced back to a nearby OB association where they seem to have originated from. Based on the pioneering work of Blaauw (1961), a *bona-fide* runaway star fulfills two criteria: *(i)* it has an observed high (*i.e.*, $> 30\,\mathrm{km\,s^{-1}}$) space velocity; and *(ii)* a 'parent' OB association has been identified. It turns out that a significant fraction of the OB stars are runaways; their frequency steeply decreases as a function of spectral type: from about 20% among the O-types (or even twice as high according to Stone 1991) to 2.5% among B0–B0.5, and still lower among B1–B5 (Blaauw 1993). Almost all runaways appear to be single; only in a very few cases is a runaway confirmed to be part of a binary or multiple system (Gies & Bolton 1986). The average distance with respect to the galactic plane is much larger for confirmed runaways than for cluster and association members (Gies 1987). Also many Wolf-Rayet stars lie well outside the galactic plane (Moffat *et al.* 1998). Although based on small-number statistics, OB runaways tend to have high (projected) rotational velocities and relatively high surface helium abundances (Blaauw 1993).

https://doi.org/10.1017/S0074180900205585 Published online by Cambridge University Press

The majority of massive stars are members of an OB association or a cluster; *e.g.*, for the O-type stars about 70% belong to a cluster or association (Gies 1987); given the large fraction of O-runaways, it might well be that all O-type stars are born in associations and that the whole field population consists of runaway stars. The study of runaway stars is, therefore, intimately related to the problem of massive-star formation and evolution.

The two most popular scenarios for the formation of runaway stars are the binary supernova model (Blaauw 1961) and the cluster ejection mechanism (Poveda *et al.* 1967). Blaauw suggested that the supernova explosion of one of the stars in a massive binary (*i.e.*, the initially most massive one) causes the disruption of the binary system since more than half of the total mass of the system would be lost after the supernova explosion of the primary. As a consequence, the remaining (massive) star escapes with a velocity comparable to its (relatively high) orbital velocity before the explosion. The modern version of this scenario includes a phase of mass transfer inverting the original mass ratio, so that the resulting runaway star has a larger probability to remain bound to the compact remnant (a neutron star or a black hole). Also the mass lost through the stellar wind should be taken into account. Mass transfer from the evolved star to the future runaway star may increase its atmospheric helium abundance. Furthermore, the angular momentum associated with the accreted material will result in a higher rotation rate of the future runaway. However, the impact of colliding winds on the mass transfer process remains to be demonstrated. The binary supernova model predicts that many OB runaways should have a compact companion. Searches for compact stars around OB runaways have, however, up to now not been successful (*e.g.*, Gies & Bolton 1986; Philp *et al.* 1996). When the supernova explosion is asymmetric, the system experiences an additional 'kick' which has to be taken into account when calculating the probability whether the system will remain bound. These 'kicks' have been proposed to explain the high space velocities of (single) radio pulsars (*e.g.*, Hansen & Phinney 1997).

The alternative of cluster ejection involves the dynamical interaction in a compact cluster of stars resulting in the ejection of one or more of the members. From their extensive radial-velocity survey of bright OB runaways, Gies & Bolton (1986) concluded that the cluster ejection model has to be favoured. Apart from the lack of observational evidence for the presence of compact companions around OB runaways, the existence of two runaway double-lined spectroscopic binaries cannot be explained with the supernova model. Also the kinematical ages of OB runaways (*i.e.*, the time needed to reach their present position with respect to their 'parent' OB association) is often close to the age of the OB association itself, which is in support of the cluster ejection model. Most likely, runaway stars are formed through both suggested channels.

Kinematic studies of OB stars are hampered by the large distances at which these stars are usually found, making it very difficult to measure tangential velocities accurately. Therefore, most studies have focussed on interpreting only the radial velocity of the stars; this excludes Wolf-Rayet stars, since for these stars the radial velocity is very difficult to determine. This situation has significantly improved after the release of the *Hipparcos* data. Moffat *et al.* (1998)

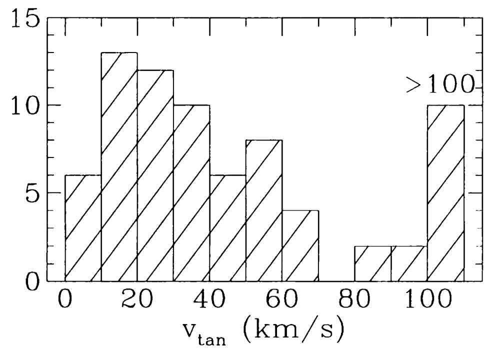

Figure 1. The peculiar tangential velocity measured with *Hipparcos* for the sample of 67 WR stars discussed in Moffat *et al.* (1998). A tail of high-velocity stars is clearly present.

derive[1] the peculiar proper motion (*i.e.*, with respect to the local standard of rest) for a sample of 66 O- and 67 WR-stars and conclude that both groups have a similar fraction of runaways (Fig. 1). Given the large uncertainty in the distances towards the WR stars, it is, however, not straightforward to estimate the accuracy of the derived peculiar motion.

2. Formation of wind bow-shocks

It turns out that many OB and WR stars with high space velocity create an unmistakable signature in the surrounding space. When an OB star moves supersonically through the interstellar medium (ISM), the interaction of its stellar wind with the ISM gives rise to a bow shock. For a better imagination of what is going on, it might be useful to consider the situation in the restframe of the star which 'sees' the ambient medium approaching with a supersonic velocity. The balance between the ram pressures of stellar wind and ambient medium results in the following distance R_0 between the star and the head of the bow-shock (*e.g.*, Wilkin 1996):

$$R_0 = 9.0\,\mathrm{pc}\sqrt{\frac{\dot{\mathrm{M}}_w\,(10^{-6}\,\mathrm{M}_\odot/\mathrm{yr})\,v_w\,(1000\,\mathrm{km/s})}{\rho_a\,(2.6\times10^{-14}\,\mathrm{g/cm^3})\,v_\star^2\,(50\,\mathrm{km/s})}}, \tag{1}$$

where $\dot{\mathrm{M}}_w$ is the wind mass-loss rate, v_w the wind terminal velocity, ρ_a the density of the ambient medium, and $v_\star$ the star's space velocity. Using equation (1) with $\rho_a = 2.6\times10^{-14}\,\mathrm{g\,cm^{-3}}$ ($\equiv 1$ particle $\mathrm{cm^{-3}}$), $v_\star = 50\,\mathrm{km\,s^{-1}}$ and typical values for wind mass-loss rate and terminal velocity, one finds that R_0 is about 50 pc for a WR star, 9 pc for a B1 supergiant, and 5 pc for an O9 main sequence star.

[1]Note that the derived values for μ_l and μ_b in that paper are slightly wrong, due to an error of transformation in the reference source used.

Van Buren & McCray (1988) inspected the *IRAS* all-sky survey at the location of several OB runaways and found extended arc-like structures associated with many of them. The infrared emission results from interstellar dust swept up by the bow-shock and heated by the radiation field of the OB runaways. In a subsequent study (Van Buren *et al.* 1995), wind bow-shocks were detected around one-third of a sample of 188 candidate OB runaways. Moffat *et al.* (1998) stated the statistics for WRs, too, although they are less certain. Thus, the detection of a wind bow-shock can be considered as an observational confirmation of the runaway status of an OB star. Also, the empirical determination of R_0, and other physical properties of the bow shock (*e.g.*, dust/gas temperature and density) provide important constraints on the stellar parameters and the involved physical processes.

3. Numerical simulations

We have performed two-dimensional time-dependent hydrodynamical simulations of the interaction process between the stellar wind of the runaway system and the interstellar medium (Comerón & Kaper 1998). An important difference with most previous simulations is that the effects of a finite cooling time of the shocked stellar wind and thermal conduction have also been taken into account. The observed bow-shock is only the outermost layer of a more complex structure, whose characteristics are determined by the efficiency of the different physical processes operating in the interstellar gas. Proceeding away from the star, one finds in the first place the region of freely flowing wind. This region is bounded by a strong shock, where most of the kinetic energy of the wind is transformed into thermal energy. The hot, low-density shocked gas has a rather slow cooling rate and, while flowing downstream, it provides a cushion supporting the bow-shock against the ram pressure of the ambient gas. The high temperature of the shocked stellar wind, in contact with the warm, dense gas from the ambient medium accumulated in the bow-shock, produces an intense flow of energy from the hot to the warm gas by thermal conduction. The effects of this energy flow are to keep the temperature of the shocked wind at a value of a few million degrees, and to evaporate dense gas from the bow-shock into the hot interior. This produces an interface of intermediate density and temperature between the shocked wind and the bow shock.

By exploring a representative range of the parameter space, the hydrodynamical simulations show that a remarkable diversity of structures can be formed, even with moderate changes in the input parameters. Depending on these, a bow-shock may be stable or unstable, have a simple or a layered structure with different density and temperature domains, or may not form at all. Some examples are shown in Fig. 2. Our simulations suggest that runaway stars with strong stellar winds (or in a dense ambient medium) develop very unstable bow-shocks. On the other hand, for runaways with weak stellar winds or a high space velocity, the shocked ambient gas flows downstream on a timescale much shorter than its cooling time, so that an observable, dense bow-shock does not form at all.

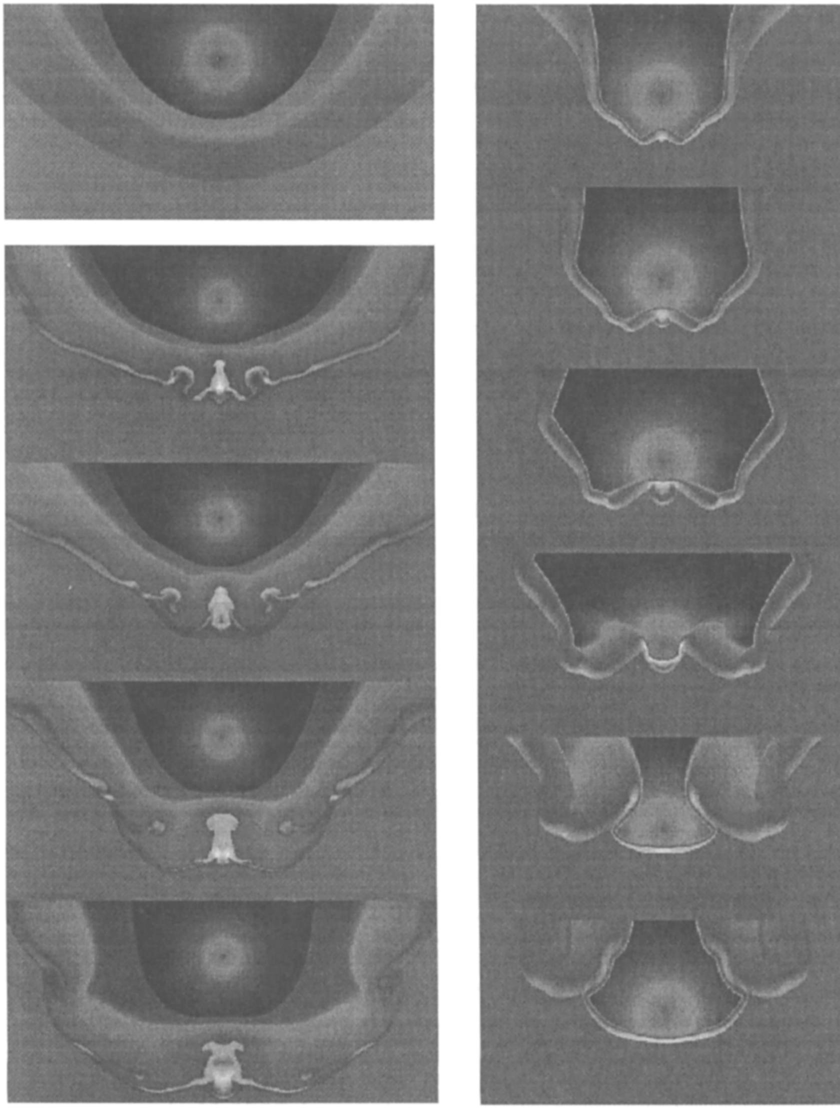

Figure 2. Evolution of the gas density in three different cases (Comerón & Kaper 1998). The *upper left* panel shows the 'weak-wind' case: $\dot{M}_w = 10^{-8}\,M_\odot\,yr^{-1}$, $v_w = 500\,km\,s^{-1}$, $v_{star} = 100\,km\,s^{-1}$, and $n_a = 0.1\,cm^{-3}$ which does not result in the formation of a dense bow-shock. The other four panels in the left column (time-step 5×10^4 yr, time increasing from *top* to *bottom*) show the evolution of the strong-wind case ($\dot{M}_w \times 100$, $v_w = 3000\,km\,s^{-1}$), where a dense, but unstable bow-shock is formed. The *right* column shows from *top* to *bottom* (total time interval 5×10^4 yr) the evolution of a very unstable bow-shock in the isothermal (instantaneous cooling) case. Note that the physical size of the grid depends on the chosen input parameters.

https://doi.org/10.1017/S0074180900205585 Published online by Cambridge University Press

4. Search for bow-shocks around HMXBs

Recently, a wind bow-shock was discovered around the high-mass X-ray binary (HMXB) Vela X-1, indicating a high space velocity of the system (Kaper *et al.* 1997). HD 77581 is the B-supergiant companion of the X-ray pulsar Vela X-1. The supergiant's strong stellar wind is partly intercepted by the orbiting neutron star resulting in the observed X-ray flux. Obviously, this binary system experienced a supernova explosion leading to the formation of the X-ray souce. Because a phase of mass transfer took place in the system, the remnant (in this case a neutron star) could remain bound to its massive OB-star companion when the system received a large kick velocity. The short ($\sim 10^4$ yr) HMXB phase starts when the OB-star becomes a supergiant. The observed wind bow-shock not only shows the runaway nature of Vela X-1, it also indicates the direction of motion of the system. Most likely, Vela X-1 originates from the OB association Vel OB1; then, the kinematical age of the system is 2 to 3 Myr years, which would be consistent with the expected time interval between the supernova explosion of the primary and the subsequent evolution of the secondary into a supergiant (Van Rensbergen *et al.* 1996). The *Hipparcos* measurements confirm this result: the space velocity of the system is about $35\,\mathrm{km\,s^{-1}}$ with respect to the OB association (which is less than the $90\,\mathrm{km\,s^{-1}}$ quoted in Kaper *et al.* 1997).

Chevalier & Ilovaisky (1998) report on the *Hipparcos* results of a sample of HMXBs; Blaauw's scenario predicts that they should all be runaway systems. The peculiar tangential velocity and distance above the galactic plane

Table 1. Peculiar tangential (and radial, when available) velocity of a sample of high-mass X-ray binaries, corrected for the solar peculiar motion and galactic rotation (see also Chevalier & Ilovaisky 1998). The systems are ordered according to their spectral type; the top 6 HMXBs are OB supergiant systems, the bottom 11 are Be/X-ray binaries. The z distance above the galactic plane is listed as well.

system	name	sp. type OB comp.	d (kpc)	z (pc)	v_{tan} ($\mathrm{km\,s^{-1}}$)	v_{rad} ($\mathrm{km\,s^{-1}}$)
1700-377	HD 153919	O6.5 Iaf+	1.7	62	58	−49
1119-603	Cen X-3	O6.5 II-III	7.9	42		+26
1956+350	Cyg X-1	O9.7 Iab	2.5	132	47	−15
1538-522	QV Nor	B0.5 Iab	5.5	202		−85
0114+650	V662 Cas	B0.5 Ib	3.8	170	26	−18
0900-403	Vela X-1	B0.5 Ib	1.8	124	34	−10
0352+309	X Per	O9.5 IIIe	0.8	253	27	−26
0535+262	V725 Tau	B0 IIIe	2.0	8	97	−12
1249-637	BZ Cru	B0 IIIe	0.3	1	14	
0521+373	HD 34921	B0 IVpe	1.05	14	23	−17
0236+610	LSI+61 303	B0 Ve	1.8	36	9	−37
1145-619	Hen 715	B1 Ve	1.1	5	6	
1036-565	HD 91188	B4 IIIe	0.5	6	20	
1255-567	μ^2 Cru	B5 Ve	0.11	11	13	
0739-529	HD 63666	B7 IV-Ve	0.52	126	12	
1253-761	HD 109857	B7 Ve	0.24	53	24	
0749-600	HD 65663	B8 IIIe	0.40	117	10	

are listed in Table 1 for all HMXBs observed with *Hipparcos*. The peculiar velocity is obtained after subtraction of the velocity of the local standard of rest (*cf.* Comerón *et al.* 1998). The values differ somewhat from those quoted by Chevalier & Ilovaisky (1998); this might be due to: *(i)* a different model for the galactic rotation; and *(ii)* a different adopted distance for some systems (*cf.* Steele *et al.* 1998). The OB-supergiant systems have high tangential velocities ($\langle v_t \rangle = 42 \pm 14\,\mathrm{km\,s^{-1}}$), while the Be/X-ray binary systems have on average lower tangential velocities ($\langle v_t \rangle = 23 \pm 24\,\mathrm{km\,s^{-1}}$; note, however, the large peculiar velocity of 0535+262). This difference in runaway speed can be well explained by the different evolutionary history of these systems (van den Heuvel, priv. comm.). The average z distance above the plane for OB stars in clusters and associations is -5 ± 70 pc, for the field population -50 ± 213 pc (Gies 1987). For the OB-supergiant systems in Table 1 $\langle z \rangle = +122$ pc; for the Be/X-ray binaries $\langle z \rangle = -45$ pc, which is in agreement with the OB supergiant systems having larger runaway velocities.

We have searched for the presence of wind bow-shocks around other HMXBs using *IRAS* high-resolution maps, *ISO*-CAM images, and narrow-band imaging (in [OIII] and Hα). Our preliminary results indicate that only a minor fraction of HMXBs is associated with a bow-shock. In fact, Vela X-1 is the only system clearly showing a bow-shock, both in the optical and in the infrared, and for Wray 977 (GX 301-2) and LMC X-1 we only find marginal observational evidence for the presence of a wind bow shock.

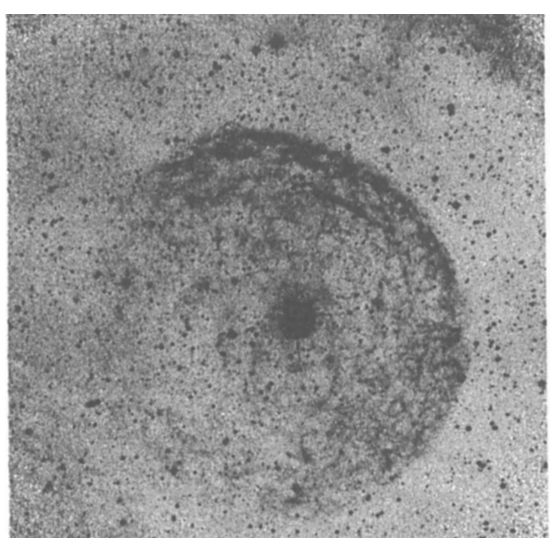

Figure 3. A narrow-band Hα image obtained by us with the *ESO* 1.5m Danish telescope showing the ring nebula around WR16 (HD 86161). The field measures $11'.5 \times 11'.5$; north is up and east is to the the left. The brightening of the nebula at one side might be due to the large peculiar velocity ($v_t = 130\,\mathrm{km\,s^{-1}}$, Moffat *et al.* 1998) of WR 16 in that direction.

5. Discussion

When the system is located in a region where the ambient medium has a relatively low density and high temperature (such as inside a superbubble surrounding a massive OB association), the local speed of sound might be so high (of the order of $100\,\mathrm{km\,s^{-1}}$) that the space velocity of the system is subsonic. This situation most likely applies to the case of *e.g.*, Cyg X-1 and LMC X-4 for which we could not detect a wind bow-shock. Cyg X-1 is located at the edge of the Cygnus superbubble, a region of very hot gas emitting in X-rays, centered on Cyg OB2 (Comerón *et al.* 1998). LMC X-4 resides inside the LMC4 supergiant shell filled with tenuous hot gas (Bomans *et al.* 1996).

Moffat *et al.* (1998) show that several WR stars are moving towards recognized/potential bow-shock structures. These structures might, however, be due to ring nebulae resulting from the interaction of the fast WR-star wind with the slow wind of its red-supergiant progenitor (Marston, these Proceedings). A large space velocity might give rise to a partial brightening of the ring nebula, such as observed for WR 16 (Fig. 3).

Acknowledgments. LK acknowledges financial support from the Royal Netherlands Academy of Arts and Sciences and the Leids Kerkhoven-Bosscha Fonds. We thank Tony Moffat for carefully reading the paper.

References

Blaauw, A. 1961, Bull. Astr. Inst. Neth. 15, 265

Blaauw, A. 1993, in: J.P. Cassinelli & E.B. Churchwell (eds.), Massive Stars: Their Lives in the Interstellar Medium, ASP-CS 35, 207

Bomans, D.J., de Boer, K.S., Koornneef, J., Grevel, E.K. 1996, A&A 313, 101

Chevalier, C., Ilovaisky, S. 1998, A&A 330, 201

Comerón, F., Kaper, L. 1998, A&A 338, 273

Comerón, F., Torra, J., Gómez, A.E. 1998, A&A 330, 975

Gies, D.R. 1987, ApJS 64, 545

Gies, D.R., Bolton, C.T. 1986, ApJS 61, 419

Hansen, B.M.S., Phinney, E.S. 1997, MNRAS 291, 569

Kaper, L., van Loon, J.Th., Augusteijn, T. *et al.* 1997, ApJ 475, L37

Moffat, A.F.J., Marchenko, S.V., Seggewiss, W., van der Hucht, K.A., *et al.* 1998, A&A 313, 949

Philp, C.J., Evans, C.R., Leonard, P.J.T., Frale, D.A. 1996, AJ 111, 1220

Poveda, A., *et al.* 1967, Bol. Obs. Ton. y Tac. 4, 860

van Rensbergen, W., Vanbeveren, D., de Loore, C. 1996, A&A 305, 825

Steele, I.A., Negueruela, I., Coe, M., Roche, P. 1998, MNRAS 297, L5

Stone, R.C. 1991, AJ 102, 333

Van Buren, D., McCray, R. 1988, ApJ 329, L93

Van Buren, D., Noriega-Crespo, A., Dgani, R. 1995, AJ 110, 2914

Wilkin, F.P. 1996, ApJ 459, L31

Discussion

Nolan Walborn: The WN7 star HD 92740 is an 80-day spectroscopic binary with a radial-velocity amplitude of the order 100 $\mathrm{km\,s^{-1}}$. Could *Hipparcos* have measured the transverse component of the orbital motion? On the other hand, it is also located near the western edge of the Carina nebula, relatively far from the rest of the ionizing cluster Trumpler 16. What is the direction of the proper-motion vector? The WN6 star HD 93131 is also located at the edge of the nebula, to the south.

Lex Kaper: A sinusoidal motion with 100 $\mathrm{km\,s^{-1}}$ amplitude and 80-day period yields an amplitude in the radial excursion with respect to the barycenter of the system of 0.73 AU which, at the distance of 2.63 kpc given by Moffat *et al.* (1998) for this star, would subtend an angle of 0.28 mas. That would be of order of the standard error in parallax, rendering the orbital motion undetectable in practice for this system. Interestingly, this may not be so for more nearby systems with comparable orbital velocities. For WR stars whose radial velocities are so difficult to measure, the *Hipparcos* intermediate data could be a very valuable resource in finding astrometric evidence for massive companions. The proper-motion vector of HD 92740 is (Moffat *et al.* 1998): $\mu_\alpha \cos\delta = -7.81 \pm 0.56$ and $\mu_\delta = 2.58 \pm 0.44$ arcsec/yr, resulting in a peculiar tangential velocity of 38 $\mathrm{km\,s^{-1}}$. For HD 93131: $\mu_\alpha \cos\delta = -6.55 \pm 0.60$ and $\mu_\delta = 2.03 \pm 0.46$ arcsec/yr with velocity $v_t = 26\,\mathrm{km\,s^{-1}}$.

https://doi.org/10.1017/S0074180900205585 Published online by Cambridge University Press