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WOLF-RAYET STARS BEFORE AND AFTER *HIPPARCOS*[1]

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RESUMEN

La misión *Hipparcos* ha producido una base de datos homogénea de observaciones *astrométricas* de alta precisión: posiciones, paralajes, movimientos propios y *fotometría* de banda ancha de alta calidad, para 67 estrellas Wolf-Rayet (WR), es decir, para la mayor parte de las estrellas WR Galácticas más brillantes que v = 12 mag. Los principales resultados son: (1) *Hipparcos* ha descubierto dos nuevas binarias visuales cercanas de tipo WR. (2) La medición de paralaje para la estrella WR más brillante que se conoce, γ^2 Velorum, arroja una distancia sorprendentemente pequeña, llevando a consecuencias destacables. (3) Los movimientos propios de *Hipparcos* revelan que, en general, las estrellas WR siguen la rotación del disco Galáctico, aunque 8 estrellas presentan definitivamente características de “desbocadas”, debido a sus grandes velocidades tangenciales peculiares. (4) Aproximadamente el 60% de las estrellas WR observadas muestran variaciones de luz detectables. Además de las variables conocidas, se han encontrado estrellas WR con variaciones irregulares y de largo período. La estrella WR121, de tipo WC9, exhibe un espectacular mínimo de luz tipo R CrB, resultante de un episodio de formación de polvo.

ABSTRACT

The *Hipparcos* mission has provided a homogeneous data base of high precision *astrometric* observations: positions, parallaxes, and proper motions; and high-quality broad-band *photometry*, for 67 Wolf-Rayet (WR) stars, i.e., for the bulk of the Galactic WR stars brighter than v = 12 mag. The main results are: (1) *Hipparcos* has discovered two new, close visual WR binaries. (2) The parallax measurement of the brightest known WR star, γ^2 Velorum, gives a surprisingly small distance, leading to remarkable consequences. (3) The *Hipparcos* proper motions reveal that WR stars in general follow the rotation of the Galactic disk, although 8 stars show definite runaway character on account of their large peculiar tangential velocities. (4) About 60% of the observed WR stars show detectable light variations. Besides the known variables, WR stars with irregular as well as long-term variations have been detected. The WC9 star WR121 displays a spectacular R CrB-like light minimum resulting from a dust formation episode.

Key words: **GALAXY: KINEMATICS AND DYNAMICS — STARS: INDIVIDUAL: (γ^2 VELORUM = HD 68273 = WR 11) — STARS: MASSIVE — STARS: WOLF-RAYET**

1. INTRODUCTION

Since their discovery in 1867 by two members of the Paris Observatory, Wolf-Rayet (WR) stars have attracted the scientific ambitions of several generations of astronomers. The common goal of all investigations has focussed mainly on three points:

- The explanation of the extremely broad emission lines, which correspond to velocities in the range of v = 700–3200 km s^{-1}.
- The determination of the physical stellar characteristics, especially masses, temperatures, chemical abundances, and the fitting of the stars into the theoretical scheme of general stellar evolution.

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[1] Based on data from the ESA *Hipparcos* astrometry satellite.

- The discussion of the WR stars in relation to their parent galaxies: in the first place, of course, with our Galaxy, then with the Magellanic Clouds, and finally with a fair number of galaxies in the Local Group and now far beyond.

The fruit of most studies on WR stars is nowadays regularly collected in symposia of the International Astronomical Union (IAU), the last one held in 1994 on the island of Elba, Italy (van der Hucht & Williams 1995), the next one proposed for the end of 1998 in Puerto Vallarta, Mexico. In addition, a number of reviews has appeared on short intervals; see e.g., van der Hucht (1996, with further references).

Now, 130 years after the recognition of the WR star phenomenon, the release of a wealth of data from the *Hipparcos* satellite necessitates a new discussion of all astrometric aspects of WR star research: positions, parallaxes, proper motions. Since *Hipparcos* also provides very precise, repeated broadband photometry, a new stimulus is also given for the study of WR star light variability.

2. WR STAR ASTROMETRY AND PHOTOMETRY BEFORE *HIPPARCOS*

It is impossible to review all observational and theoretical work so far performed on WR stars. Here we restrict ourselves to topics which are related to the type of data obtained with *Hipparcos*.

2.1. Astrometry

- *Positions*

Angular positions are known with an accuracy of, e.g., $0\overset{''}{.}5$ in the SAO Catalogue (SAO 1966) or, more precisely, down to $0\overset{''}{.}07$ for a number of bright WR stars in the PPM Catalogue (Röser & Bastian 1991). But even the less precise SAO positions are good enough to study the two-dimensional Galactic distribution of WR stars on the sky.

Sometimes, researchers are interested in very precise, but relative positions. This is the case for close visual binaries and the cores of compact young clusters. For the Galactic starburst cluster NGC 3603 with the "stellar" core HD 97950 (=WR 43, WN6+O5) speckle techniques (Hofmann, Seggewiss, & Weigelt 1995) and the *HST* (Moffat, Drissen, & Shara 1994) have resolved the cluster core down to about $0\overset{''}{.}08$ into more than 30 individual stars, among them 3 WR stars of WN type.

- *Parallaxes*

All WR stars are too far away to measure parallaxes by ground-based techniques. Even the brightest WR star, γ^2 Velorum, should have a parallax of $\pi = 2.2$ mas (milliarcsec) for a supposed spectroscopic distance of 450 pc (but see § 4.2).

- *Proper Motions*

Proper motions are also difficult to determine, because of large stellar distances. For bright WR stars, values are given in the PPM Catalogue, all at the limit of the standard errors and too few for meaningful investigations. But especially proper motions would be very useful to study WR tangential motions, both systematic in the Galaxy and peculiar, since reliable systemic radial velocities are almost impossible to secure for WR stars.

2.2. Photometry

Broad-band photometric data are difficult to interprete for WR stars because of the contribution of the strong wind emission lines to the photospheric continuum. Therefore, narrow-band photometry of emission lines and essentially emission-free continuum regions has widely been used to determine intrinsic colours, interstellar reddening, and absolute magnitudes of WR stars (e.g., Smith 1968; van der Hucht et al. 1988). Broad-band (UBV) photometry has served mainly for the study of various kinds of light variability, like eclipses, ellipsoidal variations, or optical outbursts.

A special sub-category of photometry, polarimetry, has contributed substantially to our knowledge of mass loss in WR + O binary systems (see e.g., St-Louis et al. 1988). This type of photometry is not complemented by *Hipparcos* observations.

3. THE *HIPPARCOS* ASTROMETRY SATELLITE MISSION

The somewhat revolutionary design of an astrometry satellite was initiated in 1967 by P. Lacroute of the Observatoire de Strasbourg, at the IAU General Assembly, held in Prague (see Lacroute 1982). He proposed to mount a rigid system of two plane mirrors into the entrance of an orbiting telescope so that two fields of the sky, differing by a constant, fixed angle, could always be recorded simultaneously.

In 1977, the European Space Agency (ESA) completed a phase A study of such a project. The plans showed two entrance mirrors, which image two fields with a relative separation of 58°, into a 29 cm f/4.8 Baker-Schmidt telescope. The field of view (FOV) was $0\overset{\circ}{.}9$ x $0\overset{\circ}{.}9$. The detector was an Image Dissector Tube (IDT) behind a modulating grid with 2688 slits (slit width corresponding to $1\overset{''}{.}208$ on the sky).

A call for scientific proposals was made as early as 1982. The satellite was launched in August 1989 and finally switched off in August 1993. 13 million data points (positions and brightnesses) of about 120,000 preselected stars collected by the satellite within 3.5 years were reduced simultaneously. Finally, in the beginning of 1997, i.e., 15 years after the deadline for the proposals, the full set of data was released by the European Space Agency (ESA 1997).

Despite the fact that the satellite did not reach the foreseen geostationary Earth orbit, but rather occupied an extreme ellipse with a perigee distance of only 500 km, the mission was a splendid success: all 120,000 stars of the input catalogue have been measured with an accuracy (mean error) of about ±1 mas in position and parallax, and ±1 mas per year in proper motion.

4. WR STAR ASTROMETRY AND PHOTOMETRY AFTER *HIPPARCOS*

In 1982 the programme committee of the *Hipparcos* mission approved three proposals dealing with WR star observations with the following applicants:

30: K. A. van der Hucht (P.I.), W. Sutantyo, J.-P. de Cuyper, E. P. J. van den Heuvel.

49: B. Stenholm (P.I.), I. Lundström.

78: M.-C. Lortet (P.I., meanwhile retired), A. F. J. Moffat (new P.I.), W. Seggewiss, A. Gómez (S. V. Marchenko joined later).

The groups decided to work together with an 'esprit de corps'.

In total, 67 WR stars were observed by the *Hipparcos* telescope, i.e., the bulk of Galactic WR stars brighter than $v = 12$ mag (see the list in Moffat et al. 1998). Unfortunately, a few important WR stars are not included in this sample, e.g., WR 25 (= HD 93162), the WR star with the largest known X-ray flux. For proposal #30, 70 O-type stars with previously known runaway character (from radial motions only) were also observed.

4.1. Positions

First of all, *Hipparcos* provided new positions of the 67 WR stars. The mean standard errors are ±1.2 mas in right ascension and in declination. This value is about 20 % larger than the overall mean standard error of the *Hipparcos* positions.

The very precise WR star positions will receive unprecedented significance when follow-up astrometric space missions, like DIVA (Röser et al. 1997) or GAIA (Lindegren & Perryman 1997), will use them as first-epoch positions for proper motion determinations early in the next millenium.

Of interest are precise *relative* positions in close visual binary systems. *Hipparcos* discovered two new very close binaries: WR 31 and WR 66 (see Table 1). WR 86 was already discovered as a close double via visual observations by Rositter in 1935. Recent speckle observations of WR 86 at the Kitt Peak 4-m telescope (Hartkopf et al. 1996) gave a separation of $0\overset{''}{.}236$, in close agreement with the *Hipparcos* value. Even more recently, *HST* imaging gave a separation of $0\overset{''}{.}286 \pm 0\overset{''}{.}039$ (Niemela et al. 1998).

4.2. Parallaxes

We cannot expect that the *Hipparcos* parallaxes of WR stars would give new insight into distances and hence absolute magnitudes of our sample, though the mean standard error σ is close to ±1 mas. Indeed, one third of all parallaxes are negative. Only for 4 stars in our sample does the measured value exceed $2\,\sigma$, but for three of them the parallax is not meaningful —in accordance with statistics.

We are left only with the brightest known WR star having a reliable parallax, γ^2 Velorum (=WR 11 = HD 68273), with $\pi = (3.88 \pm 0.53)$ mas ($\pi \approx 7\,\sigma$!), corresponding to a distance of $d = 258$ pc (+41/−31 pc). This is really a surprise, because most astronomers had agreed previously that γ^2Vel's distance was $d = 450$ pc. The problem with the parallax is that the star is a spectroscopic binary (WC 8 + O9 I, period 78.5 days) whose orbital elements lead to a projected semi-major axis of about 4 mas, using the *Hipparcos* distance. Of course,

TABLE 1

CLOSE WOLF-RAYET VISUAL BINARIES OBSERVED BY *HIPPARCOS*

WR	HD	spectral-type	separation	ΔH_p [a]
31	94546	WN4o + O8V (+ ...)	$0\farcs635$	$2\fm52$
66	134877	SB2, 4.8 d WN8(h) (+ ...)	0.396	1.05
86	156327	WC7 (+B0III)	0.230	0.27

[a] H_p is the broad-band *Hipparcos* magnitude; see § 4.4.

this value is reduced to a center-of-light variation of the WR and the O-type star of ~ 1.3 mas. A new reduction of the original *Hipparcos* data by F. Mignard and J. L. Falin, taking into account the superimposed orbit of the center of light, confirms the new published parallax from *Hipparcos*.

On the one hand, the new distance of γ^2 Vel goes a fair way to solving the problem of the mass loss rate derived from radio data (van der Hucht et al. 1997): Applying the new distance, the radio rate is scaled down to $\dot{M} = 3.5 \cdot 10^{-5}$ $\mathrm{M}_\odot$ yr^{-1} and is now in better agreement with the value derived from polarization measurements (St-Louis et al. 1988; although another factor 3 may be necessary if clumping is important: Moffat & Robert 1994) and recent *ASCA* X-ray spectra (Stevens et al. 1996). On the other hand, with the new distance γ^2 Vel can no longer be considered a member of the association Vela OB2, like its famous neighbour ζ Puppis (= HD 66811, O4 I(n)f), with its *Hipparcos* distance of $d = 429$ pc. To complete the irritation, its visual companion γ^1 Vel (= HD 68243, B1 IV) was *not* measured by *Hipparcos*.

Detailed discussions of the surprising *Hipparcos* parallax of γ^2 Vel and its consequences are given by van der Hucht et al. (1997) and Schaerer et al. (1997).

4.3. Proper Motions

Remarkable progress in WR star research was provided by *Hipparcos* through the large, systematic data base of high-precision proper motions. In contrast, systemic radial velocities of WR stars are biased by line blending and uncertainties arising from the formation of lines in a rapidly expanding wind.

On the basis of the new *Hipparcos* data, Moffat et al. (1998) studied the motions of the WR stars —both systematic (Galactic rotation) and peculiar. First, the differential *angular* rotation was examined by plotting the longitudinal and latitudinal components μ_l and μ_b of the proper motion (after subtracting off the Solar motion) versus Galatic longitude. It is apparent that the WR stars follow the rotation of the Galactic disk when using a flat rotation curve. But 5 stars deviate from the expected rotation by more then $10\,\sigma$ in at least one of the components. Moreover, in the Galactic longitude range $l = 260° - 300°$ one notes a coherent deviation in μ_b. Moffat et al. (1998) conclude that this may be due to large-scale deviation from the assumed circular rotation towards the Carina region. Secondly, peculiar velocities of the WR stars are derived from the *absolute* tangential motion (in km s^{-1}). Unfortunately, photometric distances, often with relatively large errors, had to be brought into play to calculate the peculiar tangential velocities $(v_t)_{pec}$ from known standard equations. The values are plotted versus Galactic longitude in Fig. 1.. For the selection of stars with abnormally large peculiar motions, i.e., *runaway stars*, a base limit of 42 km s^{-1} was chosen (in accordance with the RV criteria of Cruz-Gonzáles et al. 1974). Then, the criterion

$$(v_t)_{pec} > 42 + \sigma(v_t)_{pec} \ \mathrm{km\ s}^{-1}$$

led Moffat et al. (1998) to the selection of 8 WR stars with runaway character (see the identifications in Fig. 1). The data give no clear answer to the question which mechanism may be operating to produce the WR runaways: the binary supernova scenario (Blaauw 1961) or the cluster ejection mechanism (Poveda, Ruiz, & Allen 1967). Kinematical ages based on displacement and motion away from the Galactic plane slightly favour the cluster ejection hypothesis.

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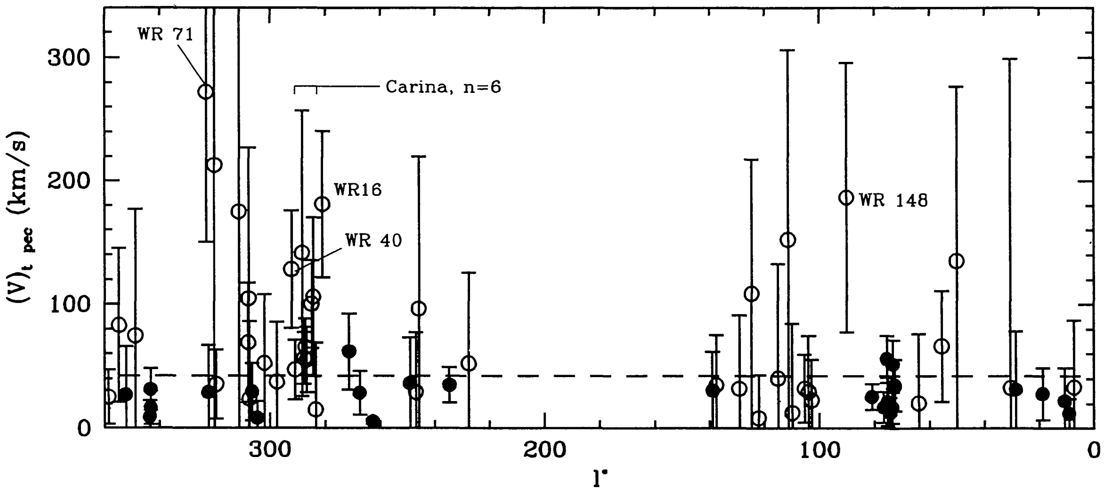

Fig. 1. Peculiar tangential velocities of *Hipparcos* WR stars versus Galactic longitude. Filled symbols are for distances $d \leq 2.5$ kpc, open sysmbols are for $d > 2.5$ kpc. The dashed horizontal line refers to the base limit of 42 km s^{-1}.

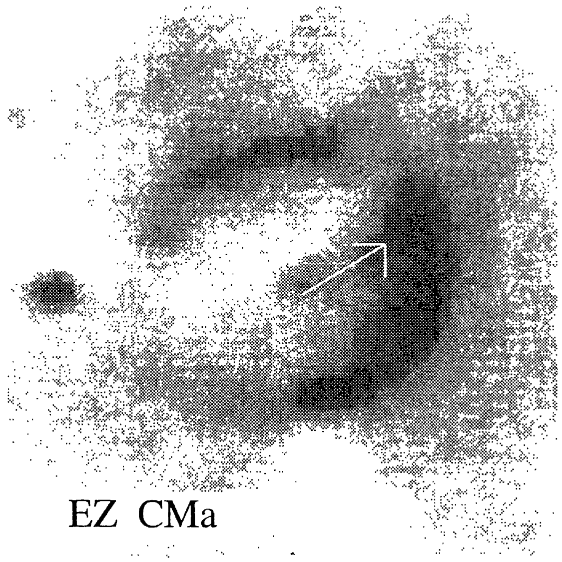

Fig. 2. Ring nebula arround WR6 (EZ CMa) with superposed proper motion vector. The map is taken from Van Buren, Noriega-Crespo, & Dgani (1995).

Finally, Moffat et al. (1998) argued that, if $(v_t)_{pec}$ is supersonic with respect to the surrounding interstellar medium, a bow shock should occur in the direction of motion of the WR star. Therefore, they scanned the literature for enhanced emission in the direction of the peculiar tangential motion around the WR stars of the sample and found 11 candidates with recognized or potential bow shock structures. As an example, Fig. 2 shows the star WR6 (= HD 50896 = EZ CMa), which is moving right toward the brightest part of the surrounding ring nebula.

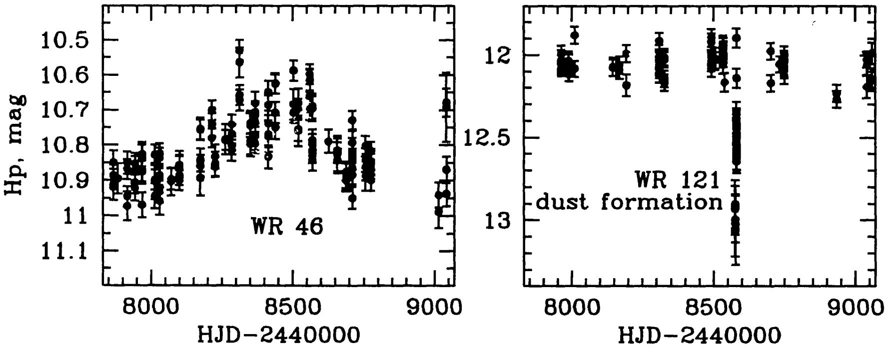

Fig. 3. *Left:* Light curve of the long-term variable WR46 (= HD 104994, WN3p). *Right:* The dust formation episode of the WC9 star WR121 (= AS320).

4.4. Photometry

Though primarily an astrometry mission, *Hipparcos* also provided 13 million photometric observations for the 120,000 input stars, i.e., one measurement per scan, resulting in a mean number of 110 data points per star. The disadvantage of the *Hipparcos* magnitude, named H_p, is that the spectral pass-band is very broad, FWHM $\cong$ 2200 Å. The peak transmission is near 4500 Å. It is practically impossible to transform the *Hipparcos* H_p into any known photometric system. But the individual data points are sufficiently precise: the standard error is about ±0.02 mag for the majority of the WR stars.

A detailed survey of the *Hipparcos* photometry for the WR star sample (as well as 70 O-type stars) is given by Marchenko et al. (1998). About 60% of the observed WR stars can be classified as variable. An extensive search for *periodic* light variations was performed (see the light curves with and without folded periods in Marchenko et al. 1998). A short summary of the results is given here:

- The light-curves of the known eclipsing binaries WR139 (= V444 Cyg) and WR155 (= CQ Cep) pass the test for the stability and reliability of the *Hipparcos* observations. The eclipsing system WR153 (= GP Cep) displays the complicated superposition of at least two periods; a rigorous analysis is in progress (Panov & Seggewiss 1999).
- Most of the massive WR+O SB2 binaries display atmospheric eclipses, when previously known spectroscopic periods are applied.
- For the presumably single WR stars, the candidate runaways appear to be more variable than the stars with small peculiar velocities.
- Four WR star light curves show irregular variations. WR40 (= HD 96548, WN8) has the largest amplitude, with 0.15 mag. Six stars exhibit long-term light variations. This is most pronounced for WR46 (= HD 104994, WN3p), for which the light curve is shown in Fig. 3. A most remarkable event happened in the light of WR121 (= AS320, WC9): The *Hipparcos* data show an R CrB-like light minimum more than 1 mag deep (Fig. 3). The star is a known dust maker (Williams, van der Hucht, & Thé 1987; see in particular Veen et al. 1998), for which this event is the signature of another dust formation episode.

5. SUMMARY

(1) The precise *Hipparcos* positions will gain their real importance when they will serve as first-epoch observations for proper motion determinations with space missions in the next millenium. At any rate, two very close visual WR binaries have been discovered, and precise separations and position angles for several known visual WR binaries provided.

(2) *Hipparcos* parallaxes are meaningful only for the nearest WR star, γ^2 Vel. But the new, large parallax was a surprise and has been discussed extensively.

(3) The most important progress is provided by the *Hipparcos* proper motions of the WR star sample. The study of the longitudinal and latitudinal proper motion components show that the WR stars follow Galactic

rotation for a flat rotation curve. But in the Carina region there is a coherent deviation from circular rotation. In addition, at least 8 WR stars can be regarded as candidates for runaways because of their high peculiar tangential velocities. Some of them tend to form bow shocks in the direction of the motion.

(4) Many kinds of light variability are inherent in the photometric data base. Among the most interesting cases are the apparently irregular variations of WR40, WR138, and WR148; long-term variability of WR7, WR18, WR46, WR66, and WR71; and, as the signature of a dust formation episode, an R CrB-type eclipse of the WC9 star WR121. Detailed analyses of all light curves should be a major objective of future investigations.

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