FIRST VISITOR EXPERIENCE WITH PISCO:

Phase Dependent Polarization Variations of Southern Galactic WR + O Systems

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Scientific Rational

Wolf-Rayet (WR) stars are the likely descendents of the most massive stars before they explode as supernovae. Their distinguishing features are their extremely intense, broad emission lines of high ionization level. These lines arise in hot, fast, dense winds, which are rich in the products of centrally burned Hydrogen and Helium.

Three ionization sequences are encountered. From hot to "cool", these are: WN2 . . . WN9, in which the products of CNO-cycle H-burning appear in the winds; WC4 . . . WC9, in which the products of He-burning appear; and WO1 . . . WO4, a rarely observed stage of He-burning, in which Oxygen becomes enhanced. Although several unsolved, fundamental problems relating to WR stars remain, the relatively simple task of determining the absolute masses (as well as the mass loss rates) is tractable now, thanks to the advent and perfection of precision polarimeters.

Polarization arises in WR stars via the basically simple process of scattering of photons off free electrons, which abound in the hot, highly ionized winds of these stars. However, in the case of a single WR star with a homogeneous, spherically symmetric wind, the polarization due to electrons on any one side is expected to cancel with the polarization of similar electrons located at right angles to this. The net polarization is therefore zero (cf. Fig. 1a).

In the case of a binary star (or some other asymmetry, either in the light source or electron distribution), full cancellation does not occur and we expect to see some level of net non-zero linear polarization, which varies systematically with orbital phase (cf. Fig. 1b). This has indeed been seen in several *bright* WR + O binary systems:

V444 Cygni (Rudy and Kemp 1978; Robert et al. 1987);

CQ Cep (Drissen et al. 1986);

γ^2 Vel, HD 97152 and HD 152270 (St-Louis et al. 1987a; Luna 1982, 1985).

The full amplitudes of the phase-dependent variations in the degree of polarization range from about 0.2 to 0.8 %. The remaining 99.2 to 99.8 % of the light is unpolarized, i.e. the vibration direction of the electric vectors of individual photons are completely uncorrelated.

Typically in a binary, the degree of polarization varies mainly in a double wave per orbit as the cloud of fleeing electrons around the WR star scatters and polarizes the light from the O-type companion. Note that the wind of the O-type star is normally at least a factor ten weaker than the WR wind and can essentially be neglected. The reason for the double wave is simple: scattering electrons around the WR star when it is on one side of the O-star will produce the same polarization as when the the WR star is located on the diametrically opposite side (cf. Fig. 1b).

It can be easily shown that the manner in which the polarization varies depends, among other parameters, on the inclination of the orbital plane in the sky, i (cf. Brown, McLean and Emslie 1978). For orbits seen edge-on ($i = 90°$), the intrinsic polarization angle remains constant with orbital phase, while the amplitude varies from a maximum at quadrature, when scattering tends to occur at right angles, to zero at conjunction, when forward or back scattering occurs. For the other extreme, $i = 0°$, the polarization angle oscillates through 360° per orbit, while the amplitude remains constant. In general, one will, of course, find intermediate values of i. Once the value of i is known, one can then calculate the true stellar masses from the spectroscopic radial velocity orbits, which yield $M \sin^3 i$ only, i.e. one gets

$$M = (M \sin^3 i)_{spectrosc.} / (\sin^3 i)_{polarim.}$$

The mass is clearly the most fundamental parameter of a star. Unless the systems eclipses, it appears that the variation of polarization is the most reliable way to obtain i and hence M.

From the amplitude, A, of the phase-dependent polarization variations, one can also obtain a reliable estimate of the mass loss rate $\dot{M}$ of the WR star. It can be shown that A depends mainly on the total number of scatterers located in the WR wind out to near the orbit of the O-type star. Assuming total ionization of the dominating element, Helium, in the WR wind, as well as a simple wind law, one can use A to derive $\dot{M}$ (cf. St-Louis et al. 1987b). The mass loss rate is also a very important parameter for WR stars, which are able to expose more and more exotic products of nuclear burning, the higher $\dot{M}$ is. This gives us a good view of the processes that take place deep inside the stellar interior.

Use of the Instrument

In order to increase our sample of objects, we decided to request the use of the ESO polarimeter at the 2.2-m Max-Planck telescope. The instrument is fondly known as PISCO – "Polarization with Instrumental and Sky Compen-

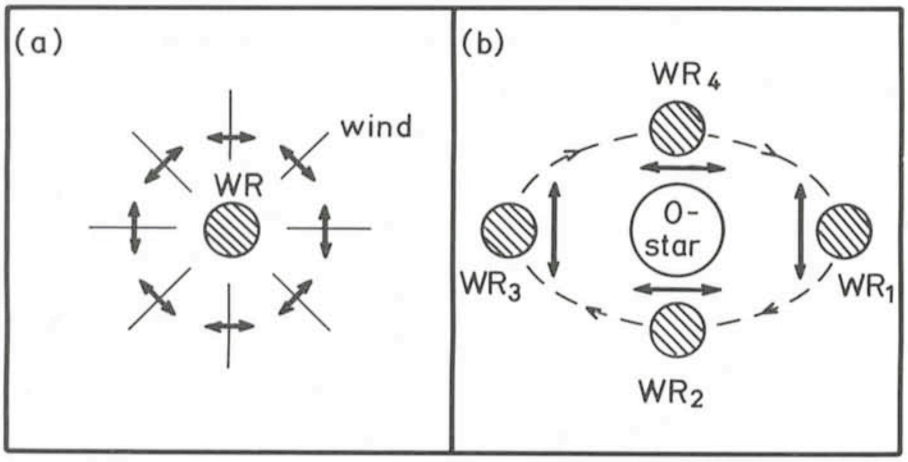

Figure 1: *Electric vectors of polarization seen*
(a) simultaneously in a spherically symmetric wind and
(b) in succession in a WR + O binary system.
Note that in reality both stars in (b) will orbit about a common centre of mass.

sation". For a more detailed description of PISCO, we refer to last December's *Messenger* (Stahl et al. 1986).

We used PISCO during six nights in early May 1987 to observe a half dozen southern Galactic WR + O systems below the 9th magnitude limit of a previous more general polarization variability survey of southern WR stars (cf. St-Louis et al. 1987a and Drissen et al. 1987). For the latter work, it was much easier to obtain a much longer run on a smaller telescope! Later, we hope to be able to study WR + O binaries in the Magellanic Clouds in order to test the effect of lower metallicity on the mass loss rates.

Since electron scattering is wavelength independent, we decided to save an enormous amount of time by monitoring for polarization variation in *one* bandpass only. We chose the *visual* broad band in order to reduce the effects of moonlight and wavelength-dependent atmospheric extinction, compared to, say, the broad *blue* band. We used PISCO in its full sky and instrumental compensation mode for observing linear polarization, i.e. with a rotating half-wave plate as variable retarder and a Foster prism as analyzer. A double diaphragm with 10 arcsecond holes allowed us to keep the bright moonlit sky to a tolerable level, while capturing most of the starlight.

As usual, we had to calibrate the efficiency of measuring the polarization. From observations of bright non-polarized stars through a 99.99 % polarizer, as well as from direct observations of standard stars, we found an efficiency factor of 90.4 % ± 0.4 %. While quite good, we wonder if this could not be improved to the *upper* 90 %!

From observation of various non-polarized stars, we found and eliminated a residual telescope polarization of $P_{tel} \simeq 0.056$ % in a direction $\theta_{tel} \simeq 99°$ (angles here are expressed in the conventional way from celestial north through east). The zero-point of the polarization angle was established on the basis of polarized standard stars. The zero-point tended to drift in one sense by about 1° each night at the beginning of the run, but remained constant later.

Since the expected amplitudes of orbital polarization modulation are small (< 1 %), it is necessary to obtain high precision for each data point. From previous experience, a scatter of $\sigma_{pol} \lesssim 0.02$ % per observation is necessary. To reach this level, one must collect about 25 million photons. This is based on Poisson statistics; the real errors are always somewhat larger due usually to hidden systematic effects. Exposure times of 30 minutes were necessary to

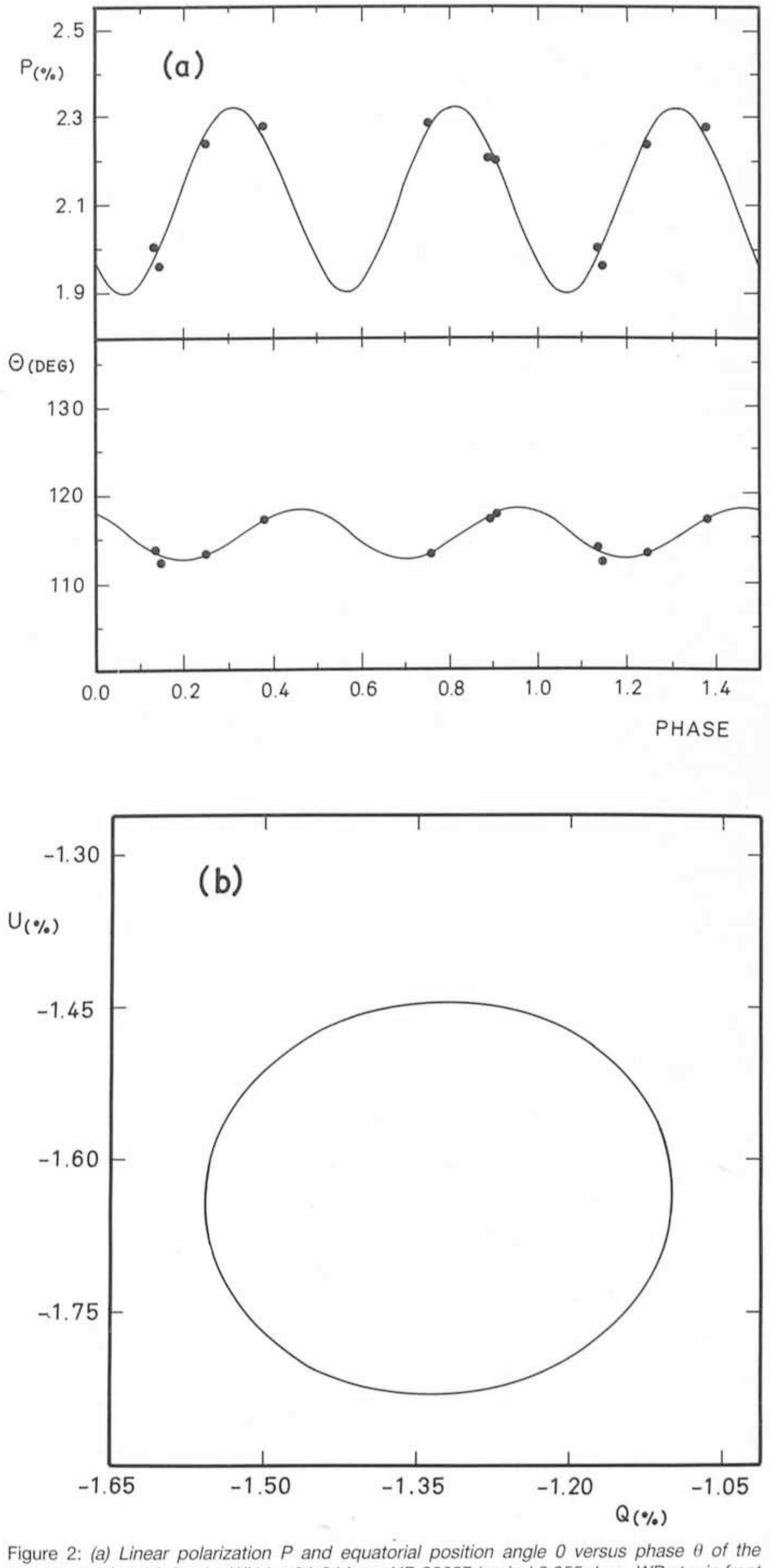

Figure 2: *(a) Linear polarization P and equatorial position angle θ versus phase θ of the spectroscopic orbit for the WN4 + 04-6 binary HD 90657 (period 8.255 days, WR star in front at JD = 2443923.7). The curve is a forced double-wave sinusoidal fit made to the Stokes parameters Q(θ) and U(θ). Note that Q = P cos 2θ and U = P sin 2θ.*
(b) The Q-U locus from the double-wave fit for HD 90657. The curve results in the orbital inclination i = 56°.5 ± 6°.3 and the position angle of the line of nodes Ω = 5°.4 ± 16°.3.

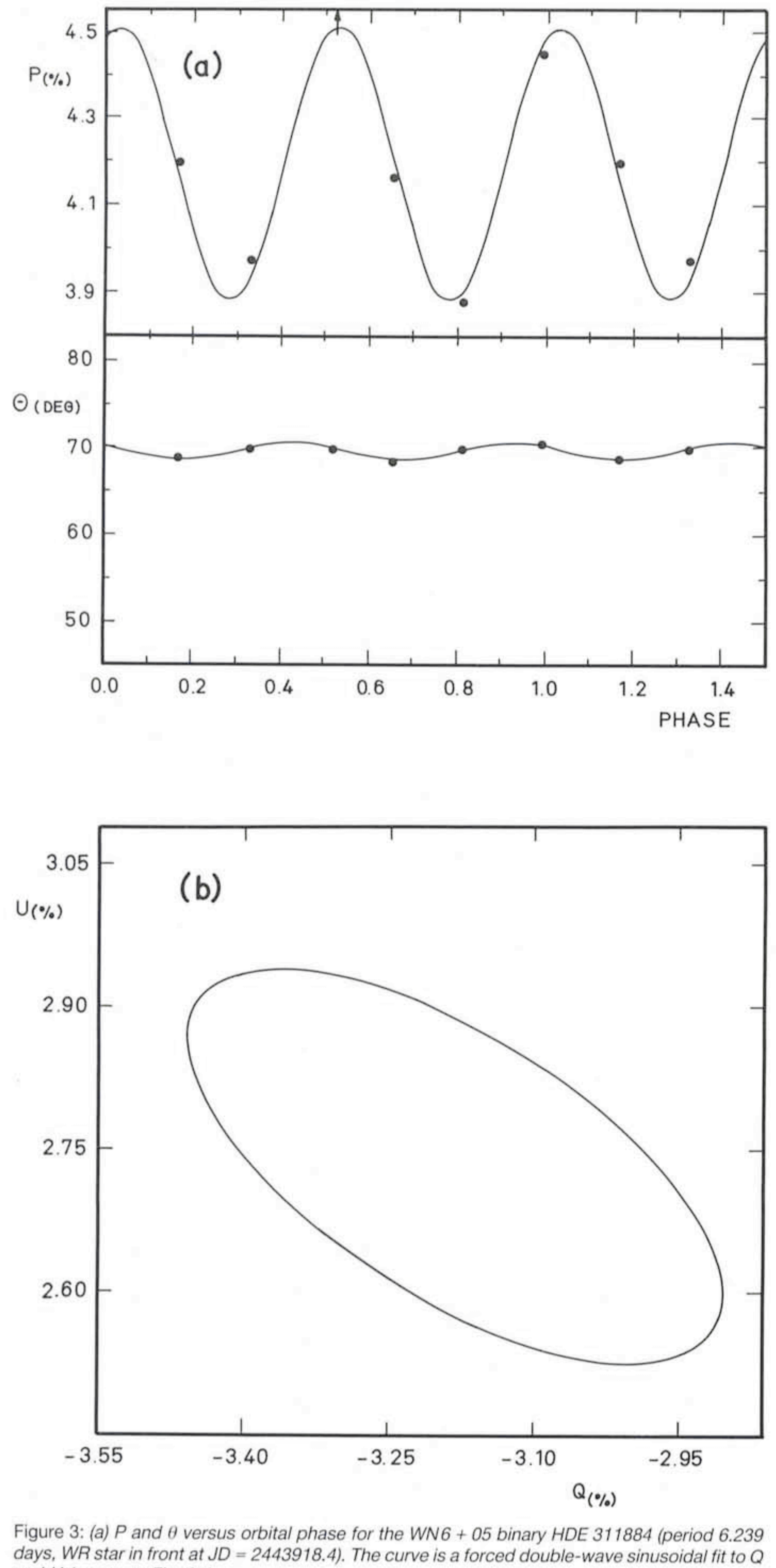

Figure 3: *(a) P and θ versus orbital phase for the WN6 + 05 binary HDE 311884 (period 6.239 days, WR star in front at JD = 2443918.4). The curve is a forced double-wave sinusoidal fit to Q and U (compare Fig. 2a).*
(b) The Q-U locus from the double-wave fit for HDE 311884. The results are $i = 76^{\circ}\!.9 \pm 1^{\circ}\!.7$ *and* $\Omega = -32^{\circ}\!.8 \pm 4^{\circ}\!.0$*. Note how the more elongated shape here compared to the curve of Fig. 2b leads to a higher orbital inclination.*

reach this precision at $V \simeq 11$ mag. The brightest star observable without adding a neutral density filter had $V \sim 7.8$ mag, yielding a mean count rate of ~ 300,000 counts per second in one of the channels; the other channel counted photons at only slightly more then half this rate.

Luckily, about 80 % of the six nights were clear. The data were completely reduced at La Silla before departure. (It appears that AFJM now owes Hugo Schwarz a bottle of Champagne because of this.) This required some extreme effort to modify and debug the reduction programme; we are very grateful to the ESO mountain staff for this, as well as for their help at the telescope.

For the most part, PISCO works very well. The only major problem remaining in our view is the inadequacy of the on-line reduction during the night. This allowed us to get barely a rough feeling for the real quality of the data as they were being obtained. If not already done, the efficiency of using PISCO could be considerably enhanced if one could walk away from the telescope each morning with definitive (or nearly so) data!

Some Results

We wish to terminate this brief exposé by illustrating the results for some of the six WR + O binaries and one test O + O binary that were observed. The WR + O systems ranged in brightness from $V \simeq 9$ to 11 mag. An additional WR + O system at $V = 11.2$ mag turned out to be unmeasurable due to the proximity of the full moon ($\lesssim 30^{\circ}$). This sample of stars is complete as far as southern WR + O binaries of $V \lesssim 11$ mag are concerned, although a six-night run is only a start especially for the systems with longer periods ($P \gtrsim 10$ days).

In Figures 2 and 3 we show plots of P and θ versus spectroscopic orbital phase, and the Stokes parameters $Q = P \cos 2\theta$ versus $U = P \sin 2\theta$ for two WR + O systems:

(1) HD 90657, WN4 + O4-6, P = 8.255 d (Niemela and Moffat 1982), and

(2) HDE 311884, WN6 + O5, P = 6.239 d (Niemela 1987; Niemela, Conti and Massey 1980).

Note the double wave per orbit. The observed modulation in θ is considerably reduced due to the dilution from a moderately strong but constant component of interstellar polarization. From the shape of the Q-U figures traced out during the orbit we deduce $i = 56^{\circ}\!.5 \pm 6^{\circ}\!.3$ and thus $M_{WR} = 9\ M_{\odot}/\sin^3 i = 16\ M_{\odot}$ for the first system and $i = 76^{\circ}\!.9 \pm 1^{\circ}\!.7$ and hence $M_{WR} = 40\ M_{\odot}/\sin^3 i = 43\ M_{\odot}$ for the second

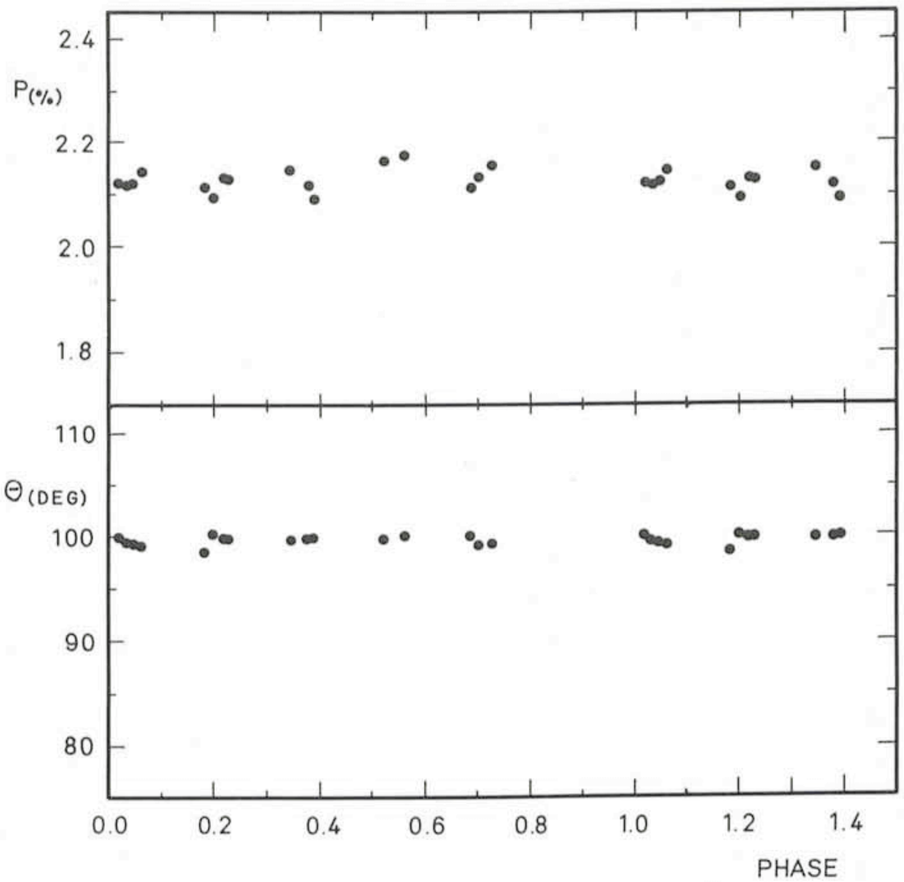

Figure 4: *P and θ versus orbital phase for the 03 V +08 V binary HD 93205 (period 6.0810 d). Periastron passage occurs at phase 0.0 ± 0.1.*

system. These masses are in line with previous suspicions that the hotter WN stars tend to be less massive on the average than the cooler ones. In fact, HDE 311884 is the most massive known WR star. We will save deriving mass loss rates $\dot{M}$ for these stars until we have a more substantial data base with more stars.

For the sake of comparison, we show similar observations for a double O-type binary, HD 93205, in the central part of the bright Carina Nebula (cf. Conti and Walborn 1976). This system, of type O3 V + O8 V, with a period of 6.0810 d in an eccentric orbit (e = 0.49), contains the earliest main-sequence star known in a binary. It is of great importance to estimate its mass. Our results, shown as plots of P and θ versus spectroscopic orbital phase in Figure 4, were somewhat disappointing to say the least, since they failed to reveal a significant modulation. Contrast this with the WR binary HDE 311884 in Figure 3, of similar period and thus similar orbital separation! In retrospect however, it may not be too surprising that the amplitude of HD 93205 is so small, since O-type stars (even the hottest ones) especially near the main sequence, are known to have mass loss rates that are generally a factor ≳ 10 less than the mass loss rates of WR stars. Our polarization data here confirm this. Hence, the mass of the O3 V star must remain as a lower limit on the basis of the spectroscopic orbit: $M^{x}_{O3V} \sin^3 i = 39\,M_\odot$.

Acknowledgements

We wish to congratulate K. Metz and his team for the fine work in constructing such a superb instrument. We are very grateful to ESO for observing time, and to the ESO mountain staff, especially our introducing astronomer Hugo Schwarz, for able assistance at the telescope and the reduction terminal. AFJM acknowledges financial support from the Natural Sciences and Engineering Research Council of Canada, WS from the Deutsche Forschungsgemeinschaft.

References

Brown, J.C., McLean, I.S. and Emslie, A.G.: 1978, *Astron. Astrophys.* **68,** 415.
Conti, P.S. and Walborn, N.R.: 1976, *Astrophys. J.* **207,** 502.
Drissen, L., Moffat, A.F.J., Bastien, P., Lamontagne, R. and Tapia, S.: 1986, *Astrophys. J.* **306,** 215.
Drissen, L., St-Louis, N., Moffat, A.F.J. and Bastien, P.: 1987, *Astrophys. J.* (in press).
Luna, H.C.: 1982, *Publ. Astron. Soc. Pacific* **94,** 695.
Luna, H.C.: 1985, *Revista Mexicana Astron. Astrofis.* **10,** 267.
Niemela, V.S.: 1987, priv. comm.
Niemela, V.S.: Conti, P.S. and Massey, P.: 1980, *Astrophys. J.* **241,** 1050.
Niemela, V.S. and Moffat, A.F.J.: 1982, *Astrophys. J.* **259,** 213.
Robert, C., Moffat, A.F.J., Bastien, P., St-Louis, N. and Drissen, L.: 1987 (in prep.).
Rudy, R.J. and Kemp, J.C.: 1978, *Astrophys. J.* **221,** 200.
Stahl, O., Buzzoni, B., Kraus, G., Schwarz, H., Metz, K. and Roth, M.: 1986, *The Messenger* **46,** 23.
St-Louis, N., Drissen, L., Moffat, A.F.J., Bastien, P. and Tapia, S.: 1987a, *Astrophys. J.* (in press).
St-Louis, N., Moffat, A.F.J., Drissen, L., Bastien, P. and Robert, C.: 1987b (in prep.).

HR 4049: an Old Low-Mass Star Disguised as a Young Massive Supergiant

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Preface

Scientific collaborations can be triggered by fortuitous circumstances. The common project we report on here started in a bizarre way. Two of the authors (HL and CW) first met during a third-cycle course in Han-sur-Lesse in the south of Belgium, where HL was lecturing on mass loss in massive stars. During a conversation it turned out that we were both puzzled by results we had obtained on a southern late-B super-