HD 192641 AND HD 193077: TWO SINGLE, HYDROGEN-RICH WOLF-RAYETS?

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As recently as six years ago it was generally agreed that all Wolf-Rayet (WR) stars were the product of mass loss induced by Roche lobe over-flow (RLOF), and that thus they were all members of binary systems. In particular, the presence of absorption lines in the spectrum of a WR star was taken as a definitive indicator that the star was a binary, as it was well known that emission alone (other than the absorption present in P Cygni profiles) was a WR characteristic. However, Niemela (1973) showed that in the WN 7 binary HD 92740 that the absorption and emission lines move in phase, proving that in at least one case the absorption spectrum originates in the WR star itself. Conti (1976) has meanwhile suggested that WR stars could form by mass loss due to a stellar wind rather than RLOF. Obviously it is well worth examining the belief that all (or even most) WR stars are binaries. The currently popular feeling is that the late WN stars (WN 7, 8, and 9) are the only possible exceptions to the traditional picture, while the members of the other subclasses are all hydrogen-poor and probably members of binaries. I hope to convince you today that this is not the complete story.

For the past two observing seasons I have been obtaining coude spectrograms (10 Å/mm) at KPNO of the northern WR stars with absorption lines but no orbit solutions. The naive motivation for this project was to determine more orbits and hence masses, since the masses of WR stars are poorly determined. The first two stars studied have been HD 192641 (WC 7) and HD 193077 (WN 5). Both show the upper Balmer lines in absorption plus the emission lines appropriate to their subclasses. I obtained ~1-2 plates each night for a week once a month for six months, and have additional material. The plates were all traced on a PDS microphotometer and radial velocities were

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produced using an objective criteria to define line-center. The high dispersion material combined with this reduction procedure resulted in very good velocity measurements for even the broad emission lines.

Much to my surprise neither of these stars showed any trace of radial velocity variations. The scatter in the velocities are 20 km s^{-1} for the "best" emission lines, and so any orbital motion must be such that the semi-amplitude, K_{EM}, of the WR star is less than 30 km s^{-1} for periods less than a few years. Bracher (1966 and private communication) reports measurements of plates that she obtained in 1964 and 1966 of HD 193077; her velocities agree with mine.

Low orbital inclinations or extremely long periods cannot be ruled out for HD 192641, but for HD 193077 neither is likely. The absorption lines in HD 193077 are incredibly broad, with v sin $\underline{i}$ = 500 km s^{-1}, greater than that known for any other early-type star. A Fourier analysis of the absorption lines shows that they are broadened by rotation, and not by turbulence or electron scattering. (The strengths of the absorption lines are normal for an O star, however.) Therefore, if these lines originate in an OB companion its rotation axis must be inclined less than 45° to our line of sight or the equatorial rotation velocity would tear the star apart. If the rotation axis of this alleged companion is aligned with the orbital axis, then this constraint on the orbital inclination, combined with the limit on K_{EM}, demands that the period must be greater than ~1000 days if the system consists of a 10 $M_\odot$ WR and a 30 $M_\odot$ OB star. This is 10 times longer than the longest known WR binary period.

If HD 193077 is single, then the absorption lines must be formed in the WR star. This interpretation is supported by two indirect pieces of evidence. There is hydrogen present in the WR envelope, as inferred by the odd-n vs. even-n Pickering emission line fluxes [implying N(H)/N(He) ~ 0.8]. Furthermore, the emission line strengths in HD 193077 are weak compared to some other WN 5 stars. Although small emission line strengths were mentioned by Kuhi (1973) as possible evidence of a companion (which would contribute to the continuum flux), the argument can be made that weak emission lines indicate that the envelope is not very extensive and hence one may actually see down to the absorption-line forming region rather than only part way into the wind.

Vanbeveren and Conti (1979) have argued that at most 40% of the galactic WR stars have massive (uncollapsed) companions, where they have accepted the presence of absorption lines as sufficient evidence of duplicity. They suggest that this number possibly should be doubled to account for the WR plus collapsed companion systems, but that 20% must then be single. If more systems like HD 192641 and HD 193077 are found not to have velocity variations then the percentage of actual single WR stars could be substantially higher.

The details on HD 193077 may be found in Ap. J. (in press). The work on HD 192641 is still in progress.

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COMMENTS FOLLOWING MASSEY

Webbink: Geoff Bath isn't here, but I feel confident that if he were, he would express grave doubts that one can attribute the observed spectral features to a rotating hydrostatic stellar surface. Could not the breadth and Fourier structure of the absorption lines be produced in an optically thick outflowing wind?

Massey: Hardly. I would be pretty amazed if you could produce these higher-order Balmer lines (H8-H13) and He I λ3820 in absorption in a stellar wind.

Zuiderwijk: From the upper limit of 30 km/s you can hardly conclude that the star is not a binary; there is still room for a lower mass companion like a neutron star. If this should be the case one could expect some type of periodic variations in several spectral lines. Did you look in your spectra for such variations?

Massey: Yes, there are no profile changes observed in any of the emission lines I studied. The limit that the emission-line K must be less than 30 km s^{-1} places very strong constraints on sin *i* and P for a canonical WR binary ($30M_\odot + 10M_\odot$). While it is true that a low mass companion (or a hundred low mass companions) cannot be excluded, the only reason for believing the star was a binary was the presence of absorption, which cannot be attributed to a low mass companion.

Mayo: Re Webbink's comment that these broad (500 km/sec) higher Balmer absorption lines may arise not in stellar photosphere but in optically thick stellar wind. Another non-stellar interpretation may be possible--namely that these lines arise in an optically thick accretion disc. Such a disc can easily give rise to lines rotationally broadened by 500 km/sec, (whereas you say 500 km/sec rotational velocities are not observed in "normal" O-stars). Also in the discs in cataclysmic variables we see higher order Balmer and He I lines in absorption. However the disc would have to be pretty luminous to show up against such a luminous star as the W-R.

Massey: The line strengths of H9, H10, H11 and He I λ3820 are normal for an O star. I am extremely dubious you could get these lines that strong in anything other than a stellar photosphere. That would have to be some disk!

Seggewiss: I like to add to the paper of Massey that there are at least two Wolf-Rayet binaries in which the central absorption lines originate in the WR atmosphere, because the radial velocities of the absorptions vary in phase with the WR emission lines: HD 92740 and HD 197406, both of spectral type WN 7 (Moffat and Seggewiss, Astron. & Astrophys. 70, 69, 1978 and in press).

Massey: Yes, as I mentioned in my talk, Virpi Niemela (PASP, 85, 220, 1973) showed that in HD 92740 the emission and absorption move in phase, and this has now been confirmed by Conti, Niemela, and Walborn (Ap. J., 228, 206, 1979) and your own work with Moffat. I was unaware that HD 197406 has absorption lines: Bracher did not find any in her comprehensive study (Univ. of Indiana thesis, 1966; PASP, 1979, in press), so I look forward to your paper with considerable interest.

We know of several WN 7-8 systems which have absorption and appear to be single--but I hope I've convinced you that this is not the entire story. There are members of the other subclasses which have absorption lines present but appear to be single.

Collins: I would like to second Ron Webbink's concern about interpreting the hydrogen line profiles as arising from uniformly rotating hydrostatic atmospheres since those used to generate the Fourier transform you used for reference are totally inappropriate for such large velocities.

Massey: Since there are no hydrostatic plane parallel non-LTE calculations available (rotating or non-rotating) for the upper Balmer lines on HE I λ3820, I used the observed lines of the slowly rotating O-star 10 Lac convolved with 500 km s^{-1} rotation and 500 km s^{-1} turbulence for comparison. The value 500 km s^{-1} for v sin *i* is derived from the locations of the cusps in the transform of the observed profiles, and are not "generated" from atmosphere calculations. While the Fourier technique is not strictly applicable since there is no intrinsic profile when there is an expanding, rotating atmosphere (see Mihalas, Ap. J., 1979, submitted) the method certainly is sufficient to show that the dominant broadening mechanism is rotation. There for large values of v sin *i*, what to use for the "intrinsic profile" matters very little, since broadening swamps the "intrinsic" shape. There is a 5-10% uncertainty in the derived value of v sin *i* due to the question of how to treat limb darkening (I have used $\varepsilon = 0.6$ for the continuum), and I have ignored any gravity darkening effects. I expect that the value of v sin *i* = 500 km/s is in error by 10-20 %, but the point is that the absorption broadening is due to rotation, not electron scattering or turbulence.

Kuzma: Was the v sin *i* $\approx$ 500 km sec^{-1} obtained from only the hydrogen lines, or were similar values obtained from the other absorption lines?

Massey: The value was derived from H11 and He I λ3820.

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