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Are the O stars in WR+O binaries exceptionally rapid rotators?

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ABSTRACT

We examine claims of strong gravity-darkening effects in the O-star components of WR+O binaries. We generate synthetic spectra for a wide range of parameters, and show that the line-width results are consistent with extensive measurements of O stars that are either single or are members of 'normal' binaries. By contrast, the WR+O results are at the extremes of, or outside, the distributions of both models and other observations. Remeasurement of the WR+O spectra shows that they can be reconciled with other results by judicious choice of pseudo-continuum normalization. With this interpretation, the supersynchronous rotation previously noted for the O-star components in the WR+O binaries with the longest orbital periods appears to be unexceptional. Our investigation is therefore consistent with the aphorism that if the title of a paper ends with a question mark, the answer is probably 'no'.

Key words: binaries: spectroscopic – stars: early-type – stars: rotation.

1 INTRODUCTION

Rotation is known to be a significant factor in massive-star evolution, giving rise to internal mixing (Eddington 1925) which has consequences both for directly observable quantities, such as luminosity and surface abundances (e.g. Sweet & Roy 1953; Heger & Langer 2000), and for the stars' lifetimes and ultimate fates (e.g. Maeder & Meynet 2012; Langer 2012).

The most rapid rotators are expected to exhibit gravity darkening: a reduction in local surface temperature (and hence flux) that is proportional to local effective gravity (von Zeipel 1924), resulting in the equatorial regions being cooler than the poles. This expectation has been substantiated indirectly, through spectroscopy (e.g. Walker 1991; Howarth & Reid 1993), and directly, through optical long-baseline interferometric imaging, which additionally reveals the distortion in surface shape arising from centrifugal forces (e.g. Domiciano de Souza et al. 2003).

Recently Shara et al. (2017, hereinafter S17) have published an analysis of good-quality echelle spectroscopy of a number of Galactic binaries each composed of a Wolf–Rayet (WR) and an O-type star, with the aim of measuring rotational velocities for the O-star components. The challenges of such measurements are demonstrated by the fact that prior to their study results had been published for only two such systems; S17 were able to extend the sample to eight targets. For all systems investigated, they found the O-star He I absorption lines to be systematically broader than their He II counterparts, in terms of both directly measured line widths, and inferred rotational speeds. They interpreted this result in the context of strong gravity-darkening effects arising from rapid rotation, such that He II line formation largely arises in hot polar caps while He I lines are formed at equatorial latitudes.

Such rapid rotation would have significant implications for angular momentum transfer in massive binary systems, for (orbital) circularization and (rotational) synchronization, and hence for binary evolution, as well as having broader ramifications on the interpretation of rotation in currently, or effectively, single O stars. If validated, the S17 inferences would therefore have important consequences; this alone is sufficient to motivate subjecting them to further scrutiny. Additionally, however, there are some apparently anomalous aspects of their conclusions which prompt caution.

First among these is simply the magnitude of the reported effects, reaching up to a factor of ∼two difference in apparent projected velocities for the He I and He II lines. This is considerably larger than the ∼10 per cent effects predicted for Be stars (see e.g. Townsend, Owocki, & Howarth 2004), or observed in the most rapidly rotating single Galactic O stars (e.g. Howarth & Smith 2001). Furthermore, although the projected equatorial speeds inferred by S17 are reasonably large, they are in all cases thought to be substantially subcritical, with angular rotation rates reported to be typically only ∼65 per cent of the critical value at which the effective gravity is zero at the equator,

$$\omega_c = \sqrt{(GM_*)/(1.5R_p)^3} \quad (1)$$

(for a star of mass M_* and polar radius R_p). Consequently, it is surprising that dramatic gravity-darkening effects should be manifest in these systems, when such strong signatures have not been found in well-studied single stars.

To explore these issues, we have calculated synthetic spectra for a grid of model rotating stars (Section 2) and compared these to a range of observations (Section 3). The results of this comparison are

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discussed in Section 4, along with an indication of how the inferred results for the WR+O systems may be reconciled with expectations.

2 MODELS

2.1 Basic assumptions

The geometry is that of a rotationally distorted (Roche-model) stellar surface, divided into a large number of 'tiles'. The specific intensity (or radiance) for each tile is interpolated from a pre-computed grid of model-atmosphere results, as a function of wavelength λ, viewing angle μ,[1] local effective temperature $T^{\ell}_{\rm eff}$, and local effective gravity $\log g^{\ell}$, Doppler shifted according to the line-of-sight velocity. Results for all tiles are summed, weighted by projected area, in order to generate a synthetic spectrum. The model is described in greater detail by Howarth & Smith (2001; see also Howarth 2016).

The use of specific intensities means that limb darkening is taken into account in a fully wavelength-dependent manner. Gravity darkening is modelled in the 'ELR' formalism (Espinosa Lara & Rieutord 2011), which gives results close to traditional von Zeipel gravity darkening (von Zeipel 1924), but which leads to better agreement with, in particular, interferometric observations (e.g. Domiciano de Souza et al. 2014).

The model-atmosphere intensities were computed on a dense wavelength grid, resolving intrinsic line profiles, by using Hubeny's SYNSPEC code,[2] starting from the atmospheric structures of the TLUSTY OSTAR2002 and BSTAR2006 grids (Lanz & Hubeny 2003, 2007); abundances and microturbulence parameters were as discussed by Reeve & Howarth (2016). The models are line-blanketed, non-LTE, steady-state, plane-parallel, and hydrostatic. The hydrostatic approximation may be questioned for hot low-gravity atmospheres; Lanz & Hubeny (2003) address this issue at some length, concluding that TLUSTY models give a satisfactory representation of most spectral lines in the UV–IR regime, and that line blanketing is the more important consideration. For the most rapid rotators other factors (particularly gravity darkening) are likely to dominate.

2.2 Parameters

Given the abundances, microturbulence, and input physics, standard model spectra may be fully specified by two parameters describing the atmosphere (normally $T_{\rm eff}$ and $\log g$) and one describing the rotation (normally $v_{\rm e}\sin i$, the maximum magnitude of the projection of the equatorial rotation velocity onto the line of sight). For a gravity-darkened, rotationally distorted model star we may equivalently specify the corresponding global effective temperature,

$$T_{\rm eff} = \sqrt[4]{\int \sigma (T^{\ell}_{\rm eff})^4 \, {\rm d}A \Big/ \int \sigma \, {\rm d}A}$$

(where σ is the Stefan–Boltzmann constant and the integrations are over surface area), and the base-10 logarithm of the polar gravity in c.g.s. units, $\log g_{\rm p}$. However, we additionally require *three* rotational parameters because, for a rotationally distorted star, the equatorial rotation speed and the axial inclination become separable, while the magnitude of the gravity darkening depends on $\omega/\omega_{\rm c}$, the ratio of the rotational angular velocity[3] to the critical value (equation 1).

[1] Where $\mu = \cos\theta$ and θ is the angle between the surface normal and the line of sight.
[2] http://nova.astro.umd.edu/Synspec49/synspec.html
[3] Assumed to be independent of latitude in the models discussed here.

Table 1. Summary of model grids ; note that $T_{\rm eff}$ is in units of kK throughout this table.

Parameter		Range	Interval	Unit
$T_{\rm eff}$		32:42	1	kK
$\cos i$		0:1	0.1	–
$\log_{10}(1-\omega/\omega_{\rm c})$		−2:0	0.2	–
$\log g_{\rm p}$	(V)	3.92		dex cgs
	(III)	$3.70 - 0.016 \times (40 - T_{\rm eff})$		
$R_{\rm p}$	(V)	$(0.4T_{\rm eff} - 5)$		$\mathcal{R}_\odot$
	(III)	$15.5 - 0.2 \times (40 - T_{\rm eff})$		

The physical parameters of the O-star components in the WR binaries studied by S17 are poorly determined; in most cases, even the spectral types are only approximate. Rather than pursue 'custom' models, we therefore generated a grid of synthetic spectra to explore the parameter space of interest.

The spectral types compiled by S17 for the O-star companions in their sample range from O4–O6 to O8–O9 IV, with near-main-sequence luminosity classes. On that basis, we ran two series of models approximating main-sequence and giant stars, adopting the parameters summarized in Table 1. The dependences on effective temperature of polar gravity, $\log g_{\rm p}$, and polar radius, $R_{\rm p}$, are rough approximations guided by the Martins, Schaerer, & Hillier (2005) calibration of O-star parameters as a function of spectral type (their tables 1 and 2). The precise choices for these parameters are not critical; ratios of line widths are fixed for given $\log g_{\rm p}$, $T_{\rm eff}$, $\omega/\omega_{\rm c}$, and i (although the overall scaling of the system – and hence the equatorial rotation velocity – scales linearly with $R_{\rm p}$).

3 RESULTS

The procedure adopted by S17 was to rectify their spectra using low-order polynomial fits to the continua in the region of features of interest, followed by least-squares Gaussian fits to characterize the full width at half maximum (FWHM) depth of the absorption lines. These FWHM values were then converted to measures of rotational speeds by using the polynomial FWHM–$v_{\rm e}\sin i$ relationships published by Ramírez-Agudelo et al. (2015).

[Consequently, S17 tabulate their velocity measurements as '$v_{\rm e}\sin i$' values. However, given the systematic differences between results from He I and He II lines they report, these measures are clearly not intended to be interpreted as actual projected equatorial rotation speeds. To avoid potential confusion, we will refer to these interpreted quantities as $v_{\rm m}\sin i$ (where the 'm' subscript may be taken to indicate 'measured'), reserving $v_{\rm e}\sin i$ for the true projected equatorial rotation speed.]

To characterize the model results in a manner as similar as possible to the observational results presented by S17 (and by Ramírez-Agudelo et al. 2015) we simply fitted Gaussians (plus a constant) to the helium lines of interest in the model spectra, following rectification with matched continuum models. Particularly at high rotation speeds, the lines can be shallow as well as broad, so in order to eliminate 'wild' solutions (normally arising from blends with very weak helium lines) fits were rejected which yielded normalized central line depths of greater than 0.99 or central wavelengths more than 1 Å from the laboratory value. For He I λ4922, this limited the models to $T_{\rm eff} \leq 38$ kK.

We can circumvent issues associated with the intermediate calibrations of $v_{\rm e}\sin i$ as a function of line width, and thereby more easily scrutinize the S17 line-width measurements, by consider-

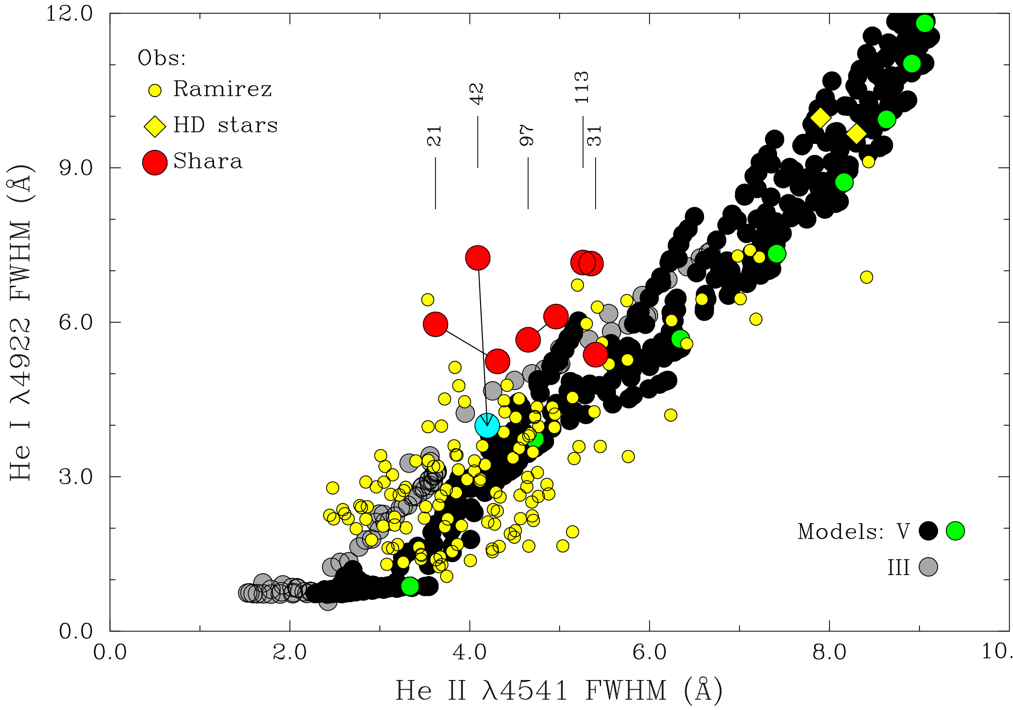

Figure 1. Summary of FWHM results for the He I λ4922 and He II λ4541 lines. Models are as discussed in Section 2; green dots identify main-sequence models at $T_{\mathrm{eff}} = 33$ kK, $i = 90°$, to indicate the trends of projected equatorial rotation velocities ($v_{\mathrm{e}} \sin i = 0$, 141, 240, 313, 368, 410, 443, and 468 km s^{-1}). The 'Ramirez' observations are FWHM measurements used by Ramírez-Agudelo et al. (2015), which are unpublished results from Sana et al. (2013). 'HD' shows new measurements of line widths in echelle spectra of the rapid rotators HD 93521 and 149757. The Shara et al. (2017) measurements are identified by WR catalogue number (van der Hucht 2001); multiple measurements of the same star are joined by solid lines, with the leftmost observation labelled. The arrow indicates the remeasurement of WR 42 discussed in Section 4.

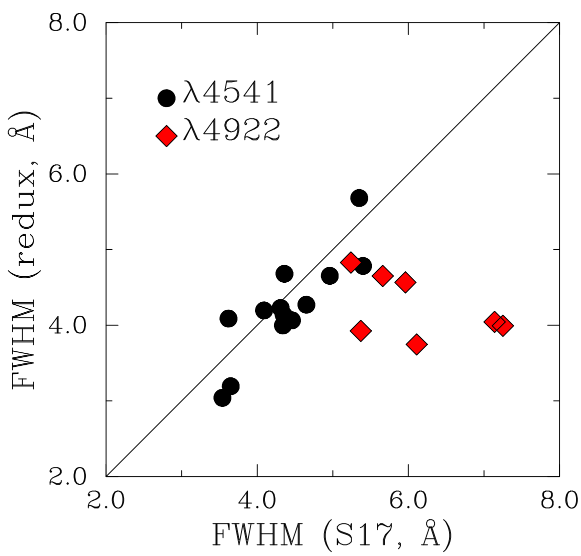

Figure 2. Full widths at half maximum depth of Gaussian fits to helium absorption lines; the diagonal line is the 1:1 relationship. The λ4922 line widths measured here are systematically smaller than those reported by S17.

ing directly the helium-line full widths at half maximum depth. The only He II line calibrated by Ramírez-Agudelo et al. (2015) is He II λ4541, while of the He I lines they considered only λ4922 is reasonably straightfoward to measure in most of the S17 spectra. Consequently, S17 concentrated on the λλ4541, 4922 lines – as shall we.

Model results for these lines are plotted in Fig. 1, along with measurements reported by S17 and by Ramírez-Agudelo et al. (2015; single stars and primary components of binaries). We also include measurements for the late-O main-sequence stars HD 93521 and HD 149757 (ζ Oph), obtained from the echelle spectra presented by Howarth & Smith (2001); these are among the most rapidly rotating stars known ($v_{\mathrm{e}} \sin i \gtrsim 400$ km s^{-1}), and are believed to have $\omega/\omega_{\mathrm{c}} \gtrsim 0.9$.

4 DISCUSSION

It is apparent from Fig. 1 that the models are in broad agreement both with the extensive Ramírez-Agudelo et al. results and with observations of the well-established rapid rotators HD 93521 and ζ Oph. The S17 measurements, however, are mostly offset to larger values of the λλ4922/4541 line-width ratio than either the models or the bulk of other observations.

While it is possible that this circumstance arises because the models omit some relevant physics, or that the O stars in WR binaries occupy a region of parameter space not populated by other results, Fig. 1 suggests a more prosaic alternative – that the S17 measurements of the helium absorption lines may not all be reliable. This would be perfectly understandable: the absorption lines are wide and shallow (being both rotationally broadened and diluted by emission from the companion), and are normally set within strong WR emission lines that are likely to give rise to relatively steep and structured pseudo-continua, with associated challenges to rectification.

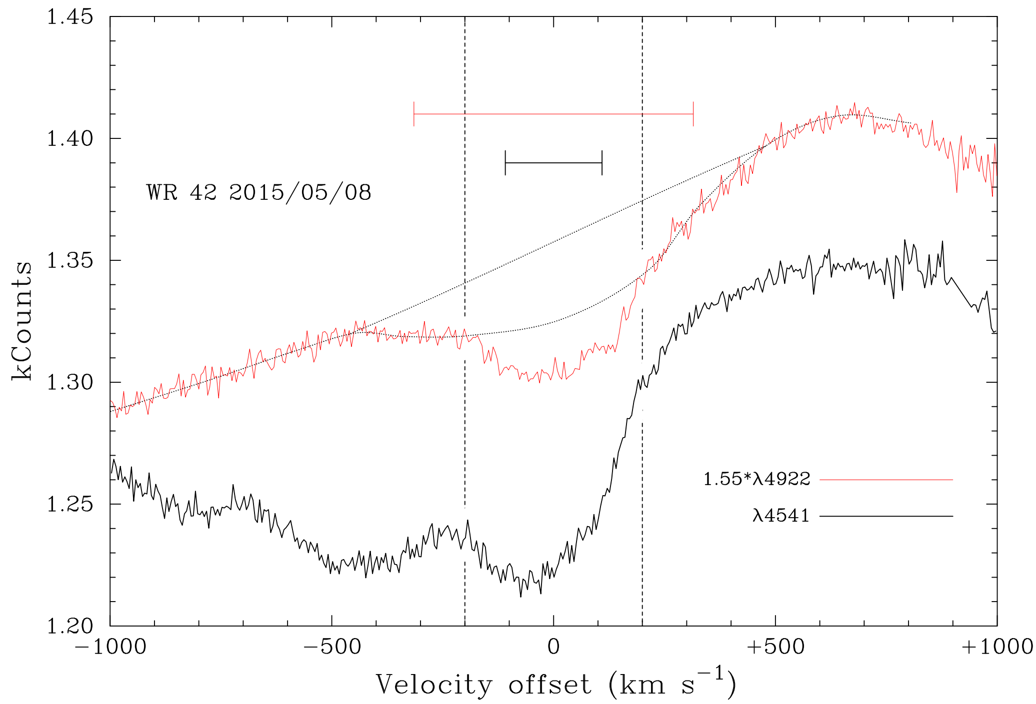

Figure 3. The He II λ4541, He I λ4922 lines in one of S17's observations of WR 42, in velocity space. The λ4922 counts have been multiplied × 1.55 for display, and a small, ad hoc, global velocity shift has been applied to bring the absorption lines close to zero velocity. Vertical dashed lines at ±200 km are intended only to facilitate comparison, and have no physical significance. Dotted lines, discussed in this section, show two possible interpretations of the pseudo-continuum level appropriate to λ4922. The horizontal bars represent the $\pm v_{\rm m}\sin i$ values found for each line by S17, demonstrating the factor of two difference they inferred for these lines from this spectrum.

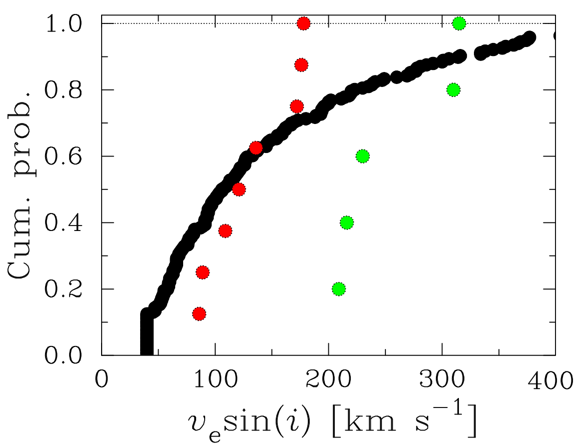

Figure 4. Cumulative probability distribution functions of projected rotational velocities. Black dots: $v_{\rm e}\sin i$ measures for single O stars, from Ramírez-Agudelo et al. (2013; the cut-off at $v_{\rm e}\sin i = 40\,{\rm km\,s^{-1}}$ is observational, not astrophysical). Red [green] dots: He II λ4541 [He I λ4922] $v_{\rm m}\sin i$ measures for O stars in WR binaries (from S17); where multiple measurements are available for a given system, the value with the smallest error was used.

To explore this possibility, we have carried out independent measurements of the line widths in the *SALT* spectra used by S17,[4] following their procedures except that, instead of approximating the pseudo-continua by low-order polynomials, we fitted Hermite splines to continuum points selected by eye, which affords rather more flexibility in accommodating the WR emission-line structure. Results are summarized in Fig. 2. While our measurements of λ4541 are in general agreement with S17's, our λ4922 FWHM values are systematically smaller, by up to almost a factor of two.

Fig. 3 illustrates the probable cause for these differences, using observations of one of the most discrepant cases, WR 42. The figure emphasizes the importance of continuum placement for these shallow absorption features (typical depths 2–3 per cent of local pseudo-continuum levels). In this case a 'high' continuum for λ4922 was reconstructed by dividing the observed spectrum by the S17 Gaussian fit, and consequently should be a reasonably close match to their choice. Our alternative 'low' continuum is, we suggest, at least equally plausible from a purely empirical perspective, and leads to a line width that is, in practice, indistinguishable from that for λ4541. Thus, while there is no fully objective way of deciding which (if either) of the proposed continua is 'correct', we believe that Fig. 3 demonstrates that exceptionally strong gravity-darkening effects are not necessarily required in order to explain the observations; and that a conservative interpretation of the results therefore is that they are consistent with model-based expectations.

A consequence of this is that the $v_{\rm e}\sin i$ value for each of the O-star components could be at the lower (He II λ4541) end of the $v_{\rm m}\sin i$ values reported by S17, rather than the high-end (He I λ4922) values they adopt. In that case, based on the synchronous rotation rates compiled by S17, most – though now not all – of the O-star rotation speeds remain supersynchronous. However, it is unclear if this requires any special spin-up mechanism, as suggested by S17. Fig. 4 compares the cumulative probability distribution functions of inferred rotational velocities for the S17 sample ($v_{\rm m}\sin i$ values) with the $v_{\rm e}\sin i$ measurements reported by

[4]The reduced spectra originally used by S17 have been mislaid; we are very grateful to Steve Crawford for providing re-reduced data to us.

Ramírez-Agudelo et al. (2013) for a sample of apparently single O stars. If we adopt the He II λ4541 $v_m \sin i$ values as more representative of the projected equatorial velocities than are the He I λ4922 values, then it appears plausible that the supersynchronous rotation in wide binaries could arise simply through initial conditions that are unexceptional – in fact, it is the *absence* of very rapid (and very slow) rotators that now stands out in Fig. 4.

A Kuiper test confirms the qualitative impression that, even for the small-number statistics that apply here, the null hypothesis that CDFs for the single and S17 O stars are drawn from the same parent populations can be rejected with ∼99 per cent confidence. Of course, the comparison made in Fig. 4 is subject to many caveats, and the S17 and Ramírez-Agudelo et al. samples are, in several respects, not directly comparable; but again, a conservative interpretation allows for the possibility that there is no strong a priori case for suggesting that the WR+O systems require special consideration in the context of current tidal-braking theory (nowithstanding its other shortcomings; see e.g. Khaliullin & Khaliullina 2010).

5 CONCLUSIONS

We have re-examined the rotational velocities of O stars in WR+O binaries. New model calculations and analyses of large samples of 'normal' stars are in good mutual agreement, but published measurements of the WR+O systems are discrepant with both. We have shown that this discrepancy can reasonably be explained by the choice of pseudo-continuum levels, particularly for the shallow He I λ4922 line. Consequently, we suggest that the observations demand neither implausibly large gravity-darkening effects nor novel mechanisms to sustain supersynchronous rotation.

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