Wolf-Rayet Stars
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The impact of rotation on the line profiles of Wolf-Rayet stars

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The distribution of angular momentum in massive stars is a critical component of their evolution, yet not much is known on the rotation velocities of Wolf-Rayet stars. There are various indications that rapidly rotating Wolf-Rayet stars should exist. Unfortunately, due to their expanding atmospheres, rotational velocities of Wolf-Rayet stars are very difficult to measure. In this work, we model the effects of rotation on the atmospheres of Wolf-Rayet stars by implementing a 3D integration scheme in the PoWR code. We further investigate whether the peculiar spectra of five Wolf-Rayet stars may imply rapid rotation, infer the corresponding rotation parameters, and discuss the implications of our results. We find that rotation helps to reproduce the unique spectra analyzed here. However, if rotation is indeed involved, the inferred rotational velocities at the stellar surface are large ($\sim 200\,\mathrm{km/s}$), and the implied co-rotation radii ($\sim 10R_*$) suggest the existence of very strong photospheric magnetic fields ($\sim 20\,\mathrm{kG}$).

1 Introduction

The rotation rates of Wolf-Rayet (WR) stars are crucial in the context of the evolution of massive stars (e.g. Meynet & Maeder 2005; Georgy et al. 2014). Rotation dramatically affects the chemical stratification of the star due to rotationally induced mixing (e.g. Heger & Langer 2000), surface deformations (von Zeipel 1924; Bjorkman & Cassinelli 1993), and may provide extra driving of the stellar wind (Friend & Abbott 1986). Furthermore, WR stars with rapidly rotating cores have been proposed as progenitors of long-duration gamma-ray bursts (LGRBs) by various authors, relying on the collapsar model of Woosley (1993).

Recent spectroscopic studies performed with the non-LTE Potsdam Wolf-Rayet (PoWR) model atmosphere code potentially imply the existence of rapidly rotating WR stars. Hamann et al. (2006) and Hainich et al. (2014), who performed extensive spectroscopic studies of a total sample of ~ 180 WN stars, made use of a flux-convolution with a rotation profile in order to reproduce the broad and round emission lines of a few WR stars in their samples. The sample of WN stars portraying these unique broad profiles composes a galactic WR star, WR 2, and four WR stars residing in the Large Magellanic Cloud (LMC): BAT99 7, 51, 88, and 94. To emphasize the striking uniqueness of these spectra, we show a comparison (Fig. 1) between the observed spectra of two WN4b stars residing in the LMC: BAT99 7 (solid blue line), which is in the round-lined star sample, and BAT99 134 (dashed green line). Note the distinct qualitative difference between the two spectra – and this despite their identical spectral class! Out of hundreds of WR stars previously analyzed, only a handful exhibit such exceptional features. We note that Chené et al. (in prep.) claim to have been able to reproduce the spectrum of WR 2 without assuming any rotation.

A few WR stars have been observed to show periodic photometric variations which may be attributed to so called co-rotating interaction regions (CIRs) in the wind (Marchenko & Moffat 1998; Cranmer & Owocki 1996; Chené & St-Louis 2005). Rotation may also lead to a the departure from spherical symmetry which can be detected with polarimetry via the so-called line effect (e.g. Harries et al. 1998), i.e. an enhanced polarization of the continuum radiation relative to that of emission lines. Yet rotational broadening of spectral lines remains the most direct method to detect and calculate rotational velocities of stars. Alas, a simple flux convolution of rotation profiles cannot be applied to WR spectra because they are formed in extended atmospheres. To model rotation in expanding atmospheres, an accurate, 3D integration of the emerging intensities is needed. In these proceedings, which are heavily based on published results by Shenar et al. (2014), we shortly describe the modeling of rotation in expanding atmospheres, and discuss the modeling results.

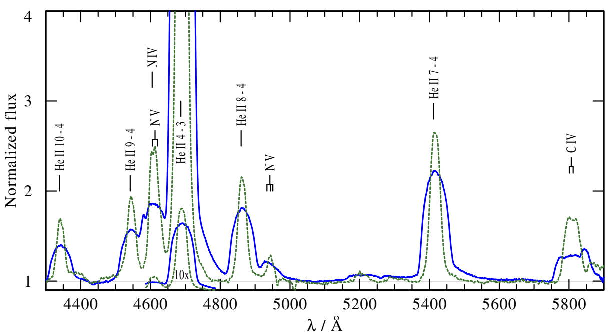

Fig. 1: Comparison between the observed optical spectra of two WN4b stars in the LMC: BAT99 134 (dashed green line), and BAT99 7 (solid blue line).

2 Modeling the effect of rotation on WR spectra

The modeling in this work is performed using the non-LTE model atmosphere PoWR code. A description of the assumptions (spherical symmetry, stationary mass-loss) and methods used in the code is given by Gräfener et al. (2002) and Hamann & Gräfener (2004). The rotational velocity field adopted here is divided into two radial domains: (a) the co-rotating domain $r \leq R_{\rm cor}$, where we postulate the existence of a radius $R_{\rm cor}$ larger or equal to the stellar surface R_*, up to which the wind co-rotates with the star (constant angular velocity), and (b) the outer domain $r > R_{\rm cor}$, where the only forces present are radial, and where the angular momentum is therefore conserved.

Rotation is modeled here only during the formal integration of the emergent intensities, i.e. any possible effect of rotation on the population numbers of the wind plasma are ignored. A thorough discussion of the assumptions and their justifications can be found in Shenar et al. (2014). The structure of the assumed velocity field implies a linear increase of the ϕ-component of the wind velocity up to $r = R_{\rm cor}$, and a sharp decrease of $1/r$ beyond the co-rotation radius due to angular momentum conservation.

3 Results and discussion

A systematic test of the influence of the two free parameters, $v \sin i$ and $R_{\rm cor}$, reveals that even rapid rotation bears no notable influence when no co-rotation of the stellar wind is assumed (i.e. $R_{\rm cor} = R_*$.). The reason is that the majority of lines are formed far above the stellar surface ($r \sim 10\,R_*$), where the rotational velocity becomes very small due to angular momentum conservation. This is thoroughly illustrated in Sect. 4.2 in Shenar et al. (2014).

Generally, the co-rotation radii are found to be of the order of $10\,R_*$, and the co-rotation velocities of the order of 2000 km/s. The implied rotation velocities at the surface of the stars are therefore of the order of 200 km/s. In Fig. 2, we show an example for the effect of rotation for two stars in our sample, BAT99 94 (upper panels) and 88 (lower panels). The model including rotation (dotted red lines) is compared to the non-rotating model (dashed black line) and to the observations (solid blue lines). Generally, suitable rotation parameters help to reproduce the round and broad appearance of the spectral lines. The detailed results of the rotation parameters are given in Shenar et al. (2014). Below, we discuss the general character of the results, their implications, and their plausibility.

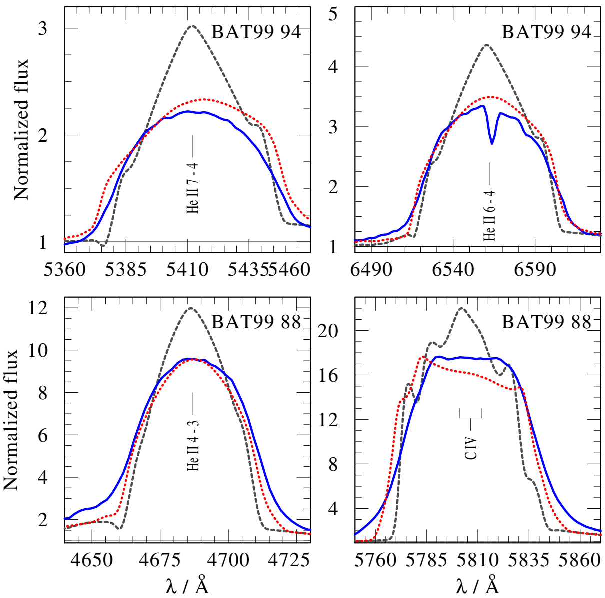

Fig. 2: Comparison between synthetic spectra calculated with rotation (dotted red line) and without rotation (dashed black line) with the observations (solid blue line) for two He II lines belonging to BAT99 94 and 88.

3.1 Rapid rotation

While it conceivable that the WR stars would rotate with velocities of the order of 200 km/s at their surface, the velocities found at the co-rotation radii exceed the local escape velocities by far. One would thus expect to be able to observe significant deviations from spherical symmetry in our sample.

A common method to detect asymmetry in stellar winds is by searching for the so-called line effect (e.g. Schulte-Ladbeck et al. 1991; Harries et al. 1998). Chené et al. (in prep.) extensively analyzed polarimetric data of WR 2 and did not find any linear line depolarization down to the 0.05% noise level, and attribute the 3% linear polarization detected by Akras et al. (2013) to scattering off grains in the interstellar matter. The non-detection of the line effect in WR 2 thus challenges its rapid rotation suggested in this work. As thoroughly discussed in Sect. 5.3 in Shenar et al. (2014), although relatively little scattering occurs in the outermost wind layers, their asymmetry is likely to cause a net continuum polarization to a certain extent. However, the net polarization is very hard to estimate without consistent modeling, and it is not a-priori clear that the resulting asymmetries would have measurable consequences. We therefore stress the need for modeling polarized radiative transfer in co-rotating atmospheres. Whether an obvious contradiction between the polarimetric data and the rotation hypothesized here arises remains to be seen.

3.2 Large co-rotation radii

The postulated co-rotation of the wind is motivated by the possible existence of strong magnetic fields in WR stars. Using some simple assumptions on the postulated magnetic field geometry, is possible to estimate the stellar magnetic field B_* necessary to confine the matter up to a given co-rotation radius (see Sect. 5.4 in Shenar et al. 2014). The magnetic field estimates turn out to be very large, of the order of 20 kG at the photosphere ($\tau_{\rm Ross} \sim 2/3$).

Admittedly, the inferred magnetic fields are very strong. Nevertheless, a couple of OB stars were observed to exhibit strong magnetic fields of several kG (see Nazé 2013, for a review on the topic), with one star even reaching a value of ~ 20 kG (cf. Wade et al. 2012). Since these stars are recognized as progenitors of WR stars, it is plausible that some WR stars can have photospheric magnetic fields of at least this order of magnitude. Taking this reasoning one step further, magnetic fields of magnetars, recognized to be the descendents of WR stars (e.g. Gaensler et al. 2005), often reach values of $10^{14} - 10^{15}$ G (e.g. Esposito et al. 2009). However, to date, any attempts to detect global magnetic larger than several 100 G fields in WR stars have failed (e.g. Kholtygin et al. 2011; de la Chevrotière et al. 2013).

4 Summary

To summarize, among the ~ 180 WN stars analyzed in the Galaxy and in the LMC, we identified five stars (one galactic, four LMC) whose spectra exhibit exceptionally broad and round emission line profiles. It has been suggested that these profiles might indicate rapid rotation (Hamann et al. 2006). Motivated by this and by the lack of alternative explanations, we extended our code to properly handle rotation in expanding atmospheres of hot stars. The modeling of rotation in expanding atmospheres can have a variety of applications, as illustrated by Hillier et al. (2012) for the case of O stars and by Hainich et al. (2015) for the case of WR stars.

We find that rotation helps to reproduce the unique spectra analyzed here. However, the plausibility of the implied rotational velocities and magnetic fields is challenged by other studies. Future observations of the remaining stars in our sample, especially spectropolarimetric ones which could potentially detect the existence of magnetic fields in the sample stars, could help to support, or disprove, the hypothesis brought to test here.

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Philip Massey: Some WRs have intrinsic absorption lines, such as HD 193077 (WR 138), a star that has very high $v \sin i$ (500 km/s) as shown from a Fourier analysis of the absorption (Massey 1980, ApJ, 236, 526). Do these stars help at all?

Tomer Shenar: WR 138 has reported low-amplitude radial velocity measurements, suggesting it may be an eccentric, long-term WR+B binary (Lamontagne et al. 1982, ApJ, 253, 230, and following studies). Hamann et al. (2006, ApJ, 457, 1015) associate the He I absorption lines in the star with a companion, so there is a good chance the measured rotation corresponds to the companion (but this requires further study). Generally, absorption lines intrinsic to a WR star are natural candidates for probing rotation at the surface, but given that these lines will probably be associated with H I / He II, pressure-broadening, in combination with the very uncertain gravities of WR stars, may cause problems here.

Philip Massey: There is a nice summery of the history of RV studies of WR 138 by Palate et al. (2013). There is evidence of a 1550 day period (see the discussion by Palate et al. 2013, A&A, 560, A27) in the emission line velocities, but the amplitude is low and the radial velocities have not been measured consistently. I now have data on this star extending over a decade, the results of which will be discussed elsewhere. In the meanwhile it is worth noting that if the punitive companion is an OB star, its $v \sin i$ of 500 km/s is uniquely high. That seems quite a coincidence, doesn't it?

Tomer Shenar: This is indeed a challenge, but there are resolutions that come to mind. (Perhaps the companion is a binary itself?) It won't be necessarily easier to account for such a high rotation velocity in a single WR star, and it would be even harder to explain the presence of He I lines in its spectrum. I'm expecting those new results which will be discussed elsewhere!

Dominik Bomans: How rare are these round emission line WR stars?

Tomer Shenar: 1 out of the 63 Galactic WNs analyzed by Hamann et al. (2006, A&A, 457, 1015) and 4 out of the 102 LMC WNs analyzed by Hainich et al. (2014, A&A, 565, 27) are found to show these unique profiles (WR 2, BAT99 7, 51, 88, and 94). Sander et al. (2012, A&A, 540, 144) reported roundish profiles for two out of the four Galactic WO stars (WR 102 and 142), but the profiles are not as extreme, and Frank Tramper could reproduce them using standard assumptions in his PhD thesis. So, pretty rare!

Anthony (Tony) Moffat: In fact Chené et al. did find low-level, but clear spectral variation due to clumping, pointing to a high terminal velocity in WR 2 that is not compatible with your much lower value.

Tomer Shenar: Admittedly, the soon-to-be-published study by Chené et al. poses many challenges to the hypothesis of rotation in WR 2, and I wouldn't like to continue backing this hypothesis if Chené et al. do indeed manage to reproduce the profiles using standard assumptions, as they claim in their paper. I'm not sure about this specific argument though: It seems that the derivation of clump velocities performed by Chené et al. is heavily based on the assumption that the velocity field in the wind consists solely of a radial outflow (as implied by their Eq. 4).

Tomer Shenar (with microphone) asking a question. Also visible in this picture are A. Liermann (left, standing), A. E. Lynas-Gray (left, sitting), and H. Todt (right, sitting).