Modelling the Colliding-Wind Spectra of WR+OB Binaries

G. M. Hill[1]

1. W.M. Keck Observatory, 65-1120 Mamalahoa Hwy, Kamuela HI, 96743, USA

Striking line profile variations can be visible in the spectra of massive star binaries where wind-wind collisions are thought to occur. The study of these systems is fascinating in their own right, but modelling these profiles also opens up the exciting possibility of learning much more about these important objects, including basic parameters such as their stellar masses and wind characteristics.

1 Introduction

Massive stars, including their formation, evolution, basic physical characteristics, and ultimate demise as supernovae, continue to fascinate us and inform numerous areas of astrophysics. Even prior to their explosive death, their powerful stellar winds and high luminosity drive significant chemical enrichment and energy deposition within their host systems. To better understand the assembly and evolution of these systems over cosmic time we must also better understand massive stars. Recent decades have shown steady progress, but significant uncertainties still remain in our knowledge of massive stars, including even some of their basic stellar and wind characteristics and how those evolve with time.

Stellar astrophysics has long benefited from the study of binaries, both in their own right and as a way to learn more about stars in general. Massive star binaries are no different, and when we are able to measure and study the effects of wind-wind collisions in these objects, the potential increases. The production of x-rays, excess line emission, photometric variations, non-thermal radio emission, etc., supply a rich banquet of observational diagnostic tools. From them we can potentially learn basic quantities like the orbital inclination and investigate fascinating physics such as the shocks, dust creation, etc., that arise from the colliding winds.

When the winds from two massive stars collide, a region of shocked gas is created which will tend to envelope the star with the weaker wind. Figure 1 presents an artist's depiction of such a system where the wind from a Wolf-Rayet star collides with that from its OB companion and forms a shock-cone around it. To be more precise, there are actually two regions of shocked gas corresponding to each wind separated by a contact discontinuity. A schematic illustration of this is also presented in Fig. 1 of Lamberts et al. (2017).

Among the numerous phenomena mentioned above that result from wind-wind collisions, we will focus here on excess line emission. As the shocked gas streams away from the head-on collision region, it cools and line emission can arise, especially in transitions which are particularly density sensitive. As the stars orbit each other, the viewing angle towards the shock-cone varies. In turn, as a result, the shape and position of the excess line emission depends on orbital phase and inclination, along with the shape of the shock-cone. With this then comes the possibility of

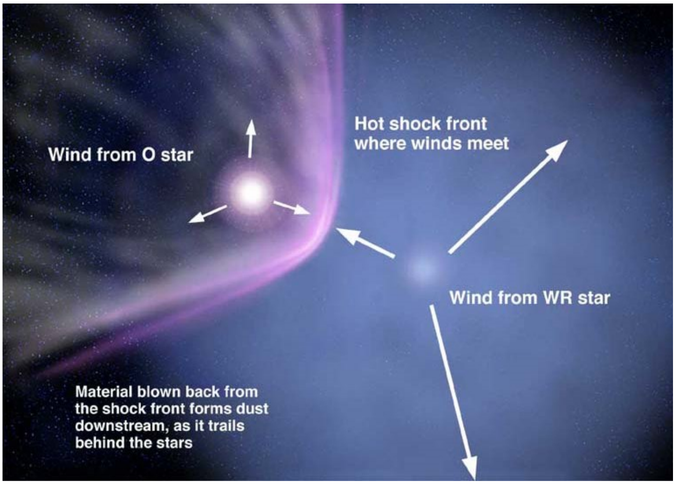

Fig. 1: Artist's depiction of a WR+OB collding wind system. Artwork by Jon Lomborg, courtesy of Gemini Observatory.

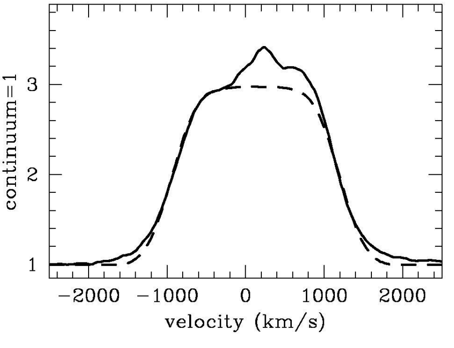

Fig. 2: C III λ5696 emission line of WR 113. The dashed line indicates the nominal underlying profile expected in the absence of excess emission from a wind-wind collision region.

determining a host of useful and fascinating physical characteristics of the stars, their winds, and the wind-wind collision region itself.

As an example, Fig. 2 shows the C III λ5696 emission line as observed from the WR+OB colliding wind binary WR 113 and also indicates how it appears to be composed of a symmetrical, flat-topped, underlying line profile typical for this line in single WC stars and additional emission. Indeed the underlying component (like other lines) shifts back and forth as one would expect, with orbital phase, while the excess component changes both in position and shape. This behaviour is readily explained by the assumption that the underlying profile arises from the undisturbed Wolf-Rayet wind and the excess emission originates in the shock-cone. That this behaviour is so obvious with C III λ5696 is consistent with the transition's sensitivity to density.

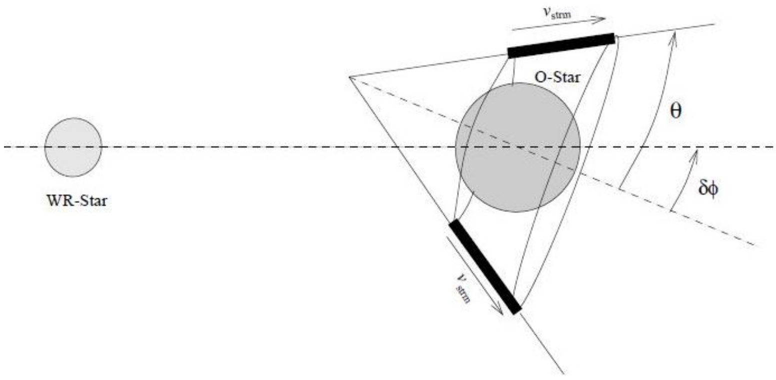

Fig. 3: Cartoon of the simple geometry used in early versions of line profile modelling code.

2 Modelling the line profiles

As noted above, an exciting possibility arises to model these changing line profiles and derive a number of parameters related to the orbit, the stars, their winds and the physics of the wind-wind collision. One notable example amongst these is the orbital inclination so that absolute masses are derived without the complication of a $\sin^3 i$ factor. Some of the early efforts to do this, either analytically or via numerical integration, are Luehrs (1997), Stevens & Howarth (1999), and Hill et al. (2000). The approach I will describe here has been used to study half a dozen WR+OB systems so far and is described in detail in Hill et al. (2018). In brief though, synthetic line profiles are generated by numerical integration over two source volumes. These are a spherical, expanding shell which gives rise to the underlying profile and a cone shaped shock region wich produces the excess emission. The numerical integration is embedded within a χ^2 minimization algorithm which then works through parameter space to match the synthetic profiles to observed ones.

Early versions of the code assumed a fairly simple geometry. Figure 3 shows how at first the shock-cone was modelled as a simple straight cone with only a half a dozen free parameters for the cone and two for the spherical, expanding shell representing the undisturbed WR wind. For the cone, these were the opening angle of the cone, its thickness, a Coriolis-induced turning angle, and the streaming and turbulence velocities of plasma in the cone. For the shell, they were just the streaming and turbulence velocities. In both cases the turbulence was considered to be isotropic. Despite the simplicity, very good fits to the line profiles were obtained for WR 42, WR 48, and WR 79 (Hill et al., 2002).

In subsequent years, the code has been applied to other spectral lines, such as He I λ10830 (Hill, 2007), used to study WR 104, a possible GRB progenitor (Hill, 2009), and gradually evolved in complexity (Hill et al., 2018). At the time of this writing, work is being extended to a binary with an eccentric orbit that has been visually resolved (γ^2 Vel) which will allow a direct test of how well the orbital inclination is found. The eccentric case is challenging, though, as it breaks a number of symmetries, thus complicating the physics. On the plus side though, it permits a direct probe of how some parameters, such as excess emission, strength vary with stellar separation.

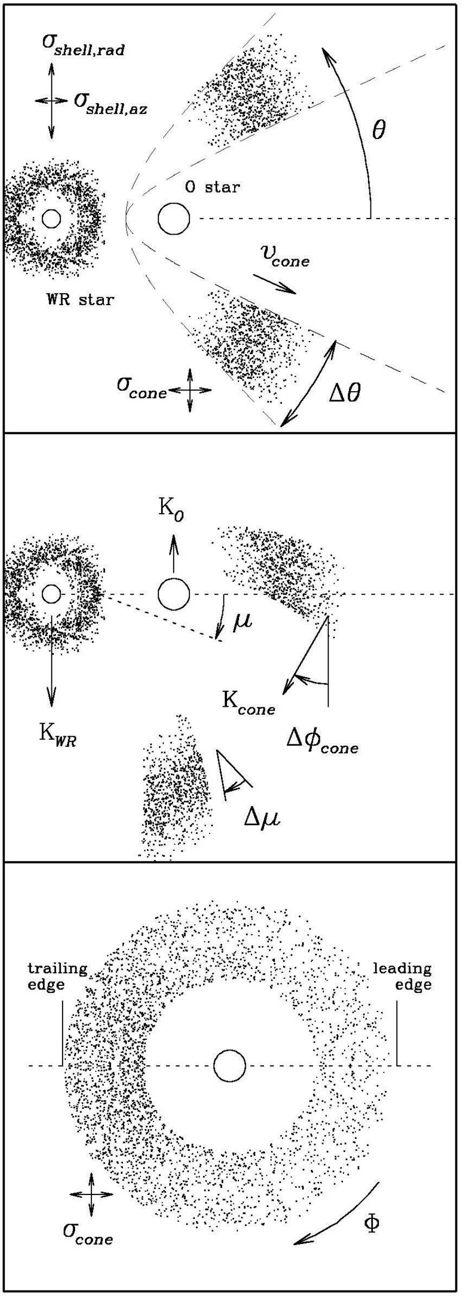

Fig. 4: Cartoon illustration (not to scale) of the parameters used in the current version of the colliding wind line profile modelling code. The small dots depict the line emitting regions in the undisturbed WR wind and in the shock-cone. See text for further details.

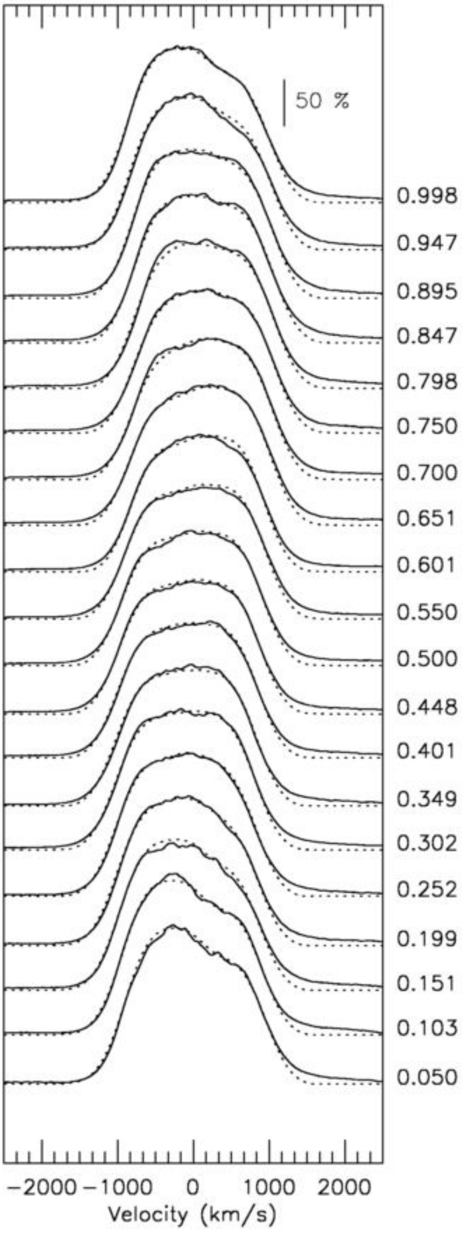

Fig. 5: Fit of synthetic profiles (dotted) to γ^2 Vel C III λ5696 emission lines (solid). Spectra are labelled according to true anomaly instead of phase.

Figure 4 provides an updated set of cartoon illustrations of the free parameters now used in the line fitting code. The top panel is a plane view without any parameters related to orbital motion. Turbulence is no longer assumed to be isotropic. The middle panel adds in some effects that result from orbital motion. These include (for example) curvature of the shock-cone and "memory" of the plasma's origin from the WR star in the form of an orbital component of its velocity (K_{cone}) but with a phase delay ($\Delta\phi_{cone}$) related to the flow time from the shell's line-forming region to that of the shock-cone. One effect not indicated in Fig. 4 is related to the motion of plasma in the shock-cone. Rather than streaming through the cone's line-forming region with constant velocity, the modelling code permits acceleration. The bottom panel of Fig. 4 depicts an edge-on view of the orbit, looking down a straight shock-cone with the OB star in the distance and showing how the code allows the density of line-emitting plasma to vary around the cone. This permits more (or less) emission to arise from the trailing edge versus the leading edge of the shock-cone.

Figure 5 shows the fits achieved with the code for γ^2 Vel. Although the excess emission is obvious near periastron, it is barely visible near apastron. Although results are still preliminary, it appears the modelling code is able to recover the interferometric orbital inclination to within 5 or 10 degrees.

3 Future work

The extension of this work to the He I λ10830 line represents a particularly exciting avenue of pursuit. Unlike C III λ5696 which is only present in WC spectra, it is visible in WN stars as well. In addition, it tends to form farther out in the wind and will allow the study of the shock-cone farther along. At nearly twice the wavelength, it will also be easier to observe for highly reddened systems.

Another desirable direction is to continue the study of systems which allow comparison with orbital inclinations found via other methods. Besides resolved orbits, this might also include polarimetry, eclipsing binaries, resolved dust spirals, etc.

Acknowledgements. I thank my collaborators in these efforts, Tony Moffat and Nicole St-Louis. I particularly want to thank the honoree of this symposium, John Landstreet. It was John that instilled in me a love of exactly the kind of work described here... modelling spectra to study the physics of the source.

References

Hill, G. M., in American Astronomical Society Meeting Abstracts #209, *American Astronomical Society Meeting Abstracts*, volume 209, 254.20 (2007)

Hill, G. M., in American Astronomical Society Meeting Abstracts #213, *American Astronomical Society Meeting Abstracts*, volume 213, 341.03 (2009)

Hill, G. M., Moffat, A. F. J., St-Louis, N., *MNRAS* **335**, 4, 1069 (2002)

Hill, G. M., Moffat, A. F. J., St-Louis, N., *MNRAS* **474**, 3, 2987 (2018)

Hill, G. M., Moffat, A. F. J., St-Louis, N., Bartzakos, P., *MNRAS* **318**, 2, 402 (2000)

Lamberts, A., et al., *MNRAS* **468**, 3, 2655 (2017)

Luehrs, S., *PASP* **109**, 504 (1997)

Stevens, I. R., Howarth, I. D., *MNRAS* **302**, 3, 549 (1999)

Véronique Petit.

John Landstreet, Gregg Wade, and PhD grads and candidates from the RMC/Queen's school.

Group photo from the outing to Pinery Provincial Park.