Clumping in Hot Star Winds
W.-R. Hamann, A. Feldmeier & L.M. Oskinova, eds.
Potsdam: Univ.-Verl., 2008
URN: http://nbn-resolving.de/urn:nbn:de:kobv:517-opus-13981

On irregular line profiles in the optical spectrum of Eta Carinae

K.E. Nielsen
Catholic University of America, Washington DC 20064, United States &
NASA Goddard Space Flight Center, Code 667, Greenbelt MD 20771, United States

The optical spectrum of Eta Carinae (η Car) is prominent in H I, He I and Fe II wind lines, all of which vary both in absorption and emission with phase. The phase dependance is a consequence of the interaction between the two objects in the η Car binary (η Car A & B). The binary system is enshrouded by ejecta from previous mass ejection events and consequently, η Car B is not directly observable. We have traced the He I lines over η Car's spectroscopic period, using *HST*/STIS data obtained with medium spectral, but high angular, resolving power, and created a radial velocity curve for the system. The He I lines are formed in the core of the system, and appear to be a composite of multiple features formed in spatially separated regions. The sources of their irregular line profiles are still not fully understood, but can be attributed to emission/absorption near the wind-wind interface and/or a direct consequence of the η Car A's, massive, clumpy wind.

This paper will discuss the spectral variability, the narrow emission structure of the He I lines and how clumpiness of the winds may impede the construction of the reliable radial velocity curve, necessary for characterizations of especially η Car B.

1 Introduction

Eta Carinae (η Car) provides a unique opportunity to investigate a massive star in a late evolutionary phase and how CNO processed material is ejected into the ISM. Investigation of the material surrounding η Car is reported to show similar characteristics as Gamma Ray Burst progenitors (Prochaska et al. 2006). Consequently, investigating η Car may provide clues about other extreme objects such as hypernovae and supernova impostors.

Most observations up through the mid-1990s could be interpreted as arising from either a single star or binary system (Davidson 1997). Current consensus favors the binary scenario. However, little is directly known about the companion star. Many indirect signatures of η Car B are observed in the form of periodic behavior.Two X-ray cycles, each characterized by a gradual increase in brightness just before a rapid decline to a low-state, were observed with the *RXTE* and fine-tuned η Car's spectroscopic period to 5.54 yr (Corcoran 2005). The Weigelt condensations follows the 5.54 yr period with emission lines from ionized spectra, such as [Ar III] and [Fe IV], disappearing during the spectroscopic low-state. While the flux of the primary star with $T_{\rm eff}$~15,000 K is sufficient to excite the Weigelt condensations during the spectroscopic low-state (Verner et al. 2002), the flux of an O or WN star with $T_{\rm eff}$~35,000 K is needed to excite the Weigelt blobs during the rest of the period (Verner et al. 2005).

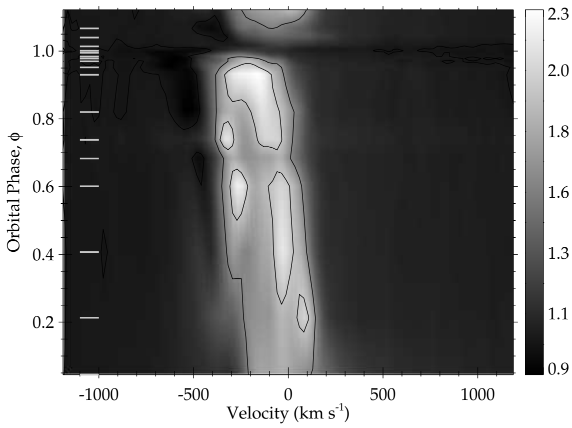

Figure 1: Surface plot for He I λ7067. The line profile's variation with phase is presented with intensity ranging from black to white with increasing line emission. All spectra used in the figure are normalized to the flux level at -1200 km s^{-1}. The observed phases are marked to the left in the figure. Note the structure of the emission at, especially, ϕ=0.6.

Unfortunately, η Car is enshrouded in multiple absorption shells (Gull et al. 2005), associated with the Homunculus and the Little Homunculus, which prevent direct observations of the radiation source in the core of the nebula including η Car A and its hot companion. A hot companion star can usually be detected at short wavelengths. However, the spectrum obtained with *FUSE* (905−1175 Å) is severely blanketed by iron-group resonance and strong interstellar molecular hydrogen absorption. Iping et al. (2005) found potential signatures in the *FUSE* spectrum of a companion star that disappeared just before the X-ray declined in 2003.5, and reappeared after the X-ray low-state. The *FUSE* spectrum does, however, not provide much information about the nature of η Car B. The medium resolution *HST* STIS E140M/E230M spectra (1140−2360 Å) are dominated by ejecta absorption, especially, in the iron-group elements and H_2 in the Homunculus (Nielsen et al. 2005). Longward of 2500 Å the line density decreases and wind lines are easier to identify and analyze. For this analysis we use velocity and intensity variation of spectral features, in the optical wavelength region, formed in the wind-wind interface region between the two massive stars as a proxy for the orbital motion. The data used in this analysis are high angular, medium spectral, resolution *HST*/STIS CCD spectra.

2 Analysis

The He I lines are dramatically blue-shifted with respect to the system velocity over the entire cycle. Their excitation, peculiar line profiles and velocity variation over the spectroscopic period (Fig. 1) suggest that the He I lines are formed in the vicinity of the wind-wind interface region. Consequently, by tracing these lines we can obtain information regarding the orbital parameters of the system including the mass ratio of the objects. The He I lines appear to be a composite of a weak broad P-Cygni wind line, likely formed in η Car A's wind, with narrow emission components superposed on top. The narrow components are likely from spatially separated regions, for example along the two arms of the bow-shock cone. The origin of the He I emission lines is easier to confine to the interface region than the absorption, and would be preferred for deriving a radial velocity curve. However, the complexity of the narrow He I emission, both regarding line profile and number of narrow components, makes the measurements of the radial velocities difficult and inaccurate. The He I absorption is fairly well behaved, easier to measure, and was therefore used to constructed the radial velocity curve (Fig. 2). The velocities were measured through line profile fitting where the absorption and emission were assumed to be decoupled, i.e. originating from different parts of the nebula.

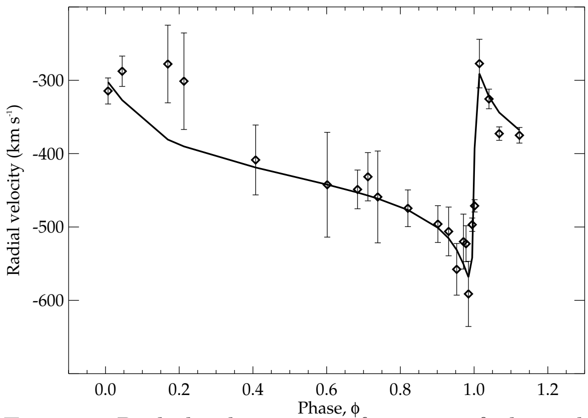

Figure 2: Radial velocity as a function of phase derived from the He I absorption. Solid curve: fit to the data using an eccentricity, e=0.90, velocity amplitude, K=140 km s^{-1} and system absorption velocity, γ=−430 km s^{-1}. The error bars represent estimated uncertainty of the individual fits.

The radial velocity curve is similar to one for a standard binary system, however, the derived parameters from this particular fit, are difficult to interpret. The width of the He I absorption components and their blue-shifts just before periastron indicate that the velocity variations are caused by the motion of η Car A. However, the large velocity amplitude over periastron imply that we are tracing the least massive star of the system. η Car A is more luminous and, therefore, assumed to be the more massive star. The radial velocities are clearly difficult to attribute to the motion of one of the objects alone. The measured velocity are likely the sum of the orbital motion of η Car A and the velocity of the part of η Car A's wind that is ionized by the hot η Car B. To understand how the radiation from η Car B alters the derived radial velocity curve, detailed modeling of the ionization structure in the central parts of the system is required, but even then it is difficult to correct the radial velocities for the ionization in line-of-sight. An accurate radial velocity curve is necessary to derive the relation between the masses, but an alternative method to derive it is necessary. The measurements and the radial velocity curve are discussed in detail in Nielsen et al. (2007).

3 The Next Step

Most of the winds lines in the optical spectrum show asymmetric line profiles with narrow peaks. These profiles are difficult to explain with a spherical symmetric wind model. Their line structure may be caused by a clumpy wind or additional emission from the surrounding nebula in lines-of-sight. The He I lines distinguish themselves from the rest of the wind lines with a larger blue-shift and a much greater velocity amplitude at periastron, indicating that the lines are formed very close to central part of the system (<100 AU). Other observed wind lines can be used to investigate the ionization structure of η Car A's wind. These lines are also used as a comparison to the spectral characteristics in He I. The H I lines are assumed to be formed in a large portion of the primary wind. As demonstrated by Damineli et al. (2000), H I shows spectral variations over the 5.54 yr spectroscopic period but with a smaller velocity amplitude than He I. While H I and Fe II show similar characteristics as the He I lines, they are strongly dominated by the primary stellar wind extending $\sim$1000 AU from η Car (Hillier at al. 2006). Line profiles in Fe II transitions vary considerably due to local physical conditions and population of lower upper energy levels. The intensity variation over the spectroscopic period is likely due to the variation in Balmer continuum from the central source, causing a population shift within Fe^+.

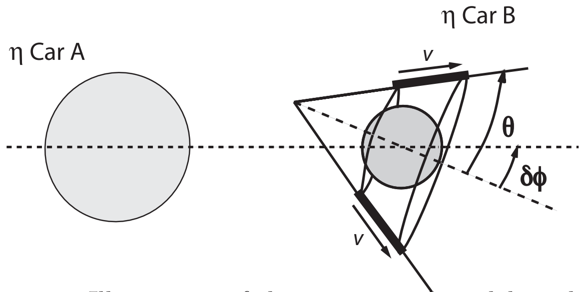

Figure 3: Illustration of the geometrical model used to derive orbital parameters for WR 42 and WR 48. v is the flow velocity along the shock-cone, θ the half-opening angle and $\delta\phi$ is the deviation due to the Coriolis force. The two measurable quantities: the full-width, fw, and the radial velocity, rv, are related to the orbital parameters as $fw = c_1 + 2v \sin\theta \sqrt{1 - \sin^2 i \cos^2 (\phi - \delta\phi)}$ and $rv = c_2 + v \cos\theta \sin i \cos(\phi - \delta\phi)$, respectively, where i is the inclination, ϕ is the orbital phase and c_1, c_2 are constants.

Analysis of the Fe II and H I line profiles will provide valuable information about the excitation conditions in η Car A's wind and the influence by η Car B.

We are confident that the He I emission is formed in the vicinity of the wind-wind interface region. If the lines are formed along the bow-shock then they are dependent on temperature and density along the bow-shock and the momentum ratio of the two objects. The bow-shock can be approximated by a cone (see Fig. 3) with the emission originating at some distance from the apex of the cone. The observed spectrum would be a sum of the emission from the spatially separated arms of the interface region, which would give a double peaked emission feature. Emission features like this have previously been observed in WR star spectrum and have been modeled with simple geometrical models. The model developed by Lührs (1997) can be applied to the narrow components observed in the He I emission profiles to produce a radial velocity curve. This method has a successfully been used in other massive binaries such as WR 42 and WR 48 (Hill et al. 2002).

The next step in our analysis will be to model the He I emission components in a similar way as earlier has been done for the WR spectra. This would provide a radial velocity curve that would be easier to interpret, than the corresponding curve for absorption, and would provide the necessary tool to estimate the mass ratio of the two objects, but also constrain the orbital parameters.

We thank our many collaborators, especially John Hillier (U. Pittsburgh), Ted Gull, Mike Corcoran and Kenji Hamaguchi (NASA GSFC), who share in this major ongoing study. Funding was provided through the *Hubble Space Telescope* Project.

References

Corcoran, M. F. 2005, AJ, 129, 2018

Damineli, A., et al. 2000, ApJL, 528, L101

Davidson, K. 1997, NewA, 2, 387

Gull, T. R., et al. 2005, ApJ, 620, 442

Hill, G. M., Moffat, A. F. J., & St-Louis, N. 2002, MNRAS, 335, 1069

Hillier, D. J., et al. 2006, ApJ, 642, 1098

Iping, R. C., et al. 2005, ApJL, 633, L37

Lührs, S. 1997, PASP, 109, 504

Nielsen, K. E., Gull, T. R., & Vieira Kober, G. 2005, ApJS, 157, 138

Nielsen, K. E., et al. 2007, ApJ, 660, 669

Prochaska, J. X., Chen, H.-W., & Bloom, J. S. 2006, ApJ, 648, 95

Verner, E. M., et al. 2002, ApJ, 581, 1154

Verner, E., Bruhweiler, F., & Gull, T. 2005, ApJ, 624, 973

Moffat: In other WR+O systems with WN component (e.g. V444 Cyg, CQ Cep, CX Cep) we do see blueshifted He I components (in addition to broad components) that vary around the orbit, arising when the curved bow shock passes across the line of sight.

Nielsen: We have, so far, not found a WR system where the absorption variations are comparable with what we see in the η Car spectrum. However, it is worth the effort to investigate this further.

Ignace: Can the variations in [Fe II] and [Fe III] lines be used with your He I data to resolve some of the radial velocity issues?

Nielsen: Likely, but not in a straightforward way, since the lines presumably are formed in different parts of the wind. The [Fe II] and [Fe III] lines will help us to understand the ionization structure of the winds, and especially the influence of the hot companion star.

Sonneborn: Could you explain again the interpretation of the very large negative radial velocity curve of η Car?

Nielsen: Since we are measuring radial velocities in the absorption component, we will get a significantly larger negative velocity compared with corresponding values derived with the emission component. The measured velocity is consistent with the terminal velocity for η Car A's wind.

Owocki: As I understand it, your "light curve" is not of a fixed object/star but of an outflowing wind that is tied, in some complex way, to an orbiting star. But now that we have 3D hydrodynamic simulations of the wind interaction, I think it should be possible to correct for the various dynamic and projection effects to derive an orbital solution for the wind's source.

Nielsen: Correct, we interpret the radial velocity curve as sum of the orbital motion of the primary star (η Car A) and the velocity of the absorbing part of the primary wind in the line of sight. The contribution of the latter is very difficult to derive, and new 3D hydrodynamic simulations will be a valuable tool for understanding how the hot companion influences the ionization structure in the central parts of the system. However, one concern may be that the 3D simulations include too many "unknowns", especially since we have very little information about the geometry of the bow shock.

Hillier: Augusto Damineli has a paper in preparation which discusses ground-based optical data obtained through the last two cycles. There are differences in the time behavior of lines throughout the 5.5 year cycle, and particularly around periastron. These variations tell us much about the interaction between the companion star and η Carinae and the circumstellar material. Additional comment: the major difficulty in interpreting the radial velocity light curve is that the orbit is highly eccentric. As a consequence there are complicated changes in the bow shock structure around periastron, as nicely illustrated by the movie of Atsuo Okazaki shown by Ted Gull. Unfortunately this (i.e. periastron) is where most of the radial velocity changes occur.