THE N II LINES IN ETA CARINAE: A FURTHER EVIDENCE FOR MASS TRANSFER DURING THE 19TH CENTURY GREAT ERUPTION

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ABSTRACT

We argue that the emission and the absorption components of the N II lines recently observed in η Car can originate in the secondary’s wind acceleration zone. We base this claim in part on the presence of these lines in hot nitrogen rich stars, such as WN 8 stars, and on the expected clumpy nature of such winds. The envelope of the secondary star in η Car is expected to be nitrogen rich due to accretion of few × M\textsubscript{☉} of the primary luminous blue variable’s nitrogen rich material during the 19\textsuperscript{th} century Great Eruption. Another argument in support of N II lines origin in the acceleration zone of the secondary wind is the behavior of the emission components. The emission components of the lines show the same Doppler shift variation as that of the absorption components. The secondary’s wind origin of the N II lines is compatible with the binary orientation in which the secondary is closer to us near periastron passage.

Subject headings: (stars:) binaries: general—stars: mass loss—stars: winds, outflows—stars: individual (η Car)

1. Introduction

The origin of the visible He I P Cyg lines (λ7065Å, λ5876Å, and λ4471Å) in the binary system η Carinae is in dispute, with different researchers attributing it to different regions, including the luminous blue variable (LBV) primary star or the winds collision region (Falceta-Gonçalves et al. 2007; Humphreys et al. 2008). In earlier studies (Kashi & Soker 2007, 2008) we attribute the He I P Cyg lines to the acceleration zone of the secondary’s wind. The Doppler shift of the P Cyg absorption component is in agreement with the binary orientation with a longitude angle ω = 90° (Kashi & Soker 2008). Namely, the secondary is closer to us at periastron passage. This orientation, though in dispute, is strongly supported by numerous observations that were discussed in details in Kashi & Soker (2008, 2009b, 2011).

The main arguments for the He I P Cyg lines origin in the secondary wind’s acceleration zone are as follows.

1. The Doppler shift of the P Cyg absorption components follows very well the secondary’s orbit (Kashi & Soker 2007, 2008).

2. The lines are known to originate in stars even cooler than the secondary (e.g., Crowther & Bohannan 1997).

3. The secondary luminosity that is ∼ 20% of the system’s luminosity, is sufficient to account for the depth of the He I lines.

4. The Doppler shift of the emission follows that of the absorption. A model where the Doppler variation of the absorption comes from changes in the radius where it forms within the primary wind, cannot explain the variation of the emission components of the line.

Let us elaborate on the fourth argument. Let us consider an alternative model where the He I lines origin is the acceleration zone of the primary wind, and the change in the Doppler shift of the absorbed part is attributed to a change in the distance from the star where the lines are formed. The Doppler shift changes as the wind velocity inside the acceleration zone is higher at larger distances from the star. In such a model we would expect the width of the emission part of the line to change, but its center to stay at about the primary stellar velocity. These two properties are opposite to observations. Observations show that the Doppler shift of the emission part, e.g., of He I λ7067, follows that of the absorption, and its width does not change much.
N II lines in hot stars

The effective temperature of the secondary is $T_{\text{eff}} \simeq 37-40$ kK (e.g., Verner et al. 2005; Mehner et al. 2010). Mehner et al. (2011) take it that this temperature is too high for the formation of the $\lambda\lambda 5668-5712\,\AA$ N II lines in the secondary’s wind.

This conclusion possibly comes from the fact that observations of the $\lambda\lambda 5668-5712\,\AA$ N II lines in stars with such high effective temperatures are rare, and hard to find in the literature. The natural candidates are WN stars, as they are hot and nitrogen rich. Herald et al. (2001) observed WR 40 and WR 16, classified as WN 8 stars with effective temperatures of $T_{\text{eff}}(\text{WR 40}) \simeq 44$ kK and $T_{\text{eff}}(\text{WR 16}) \simeq 41.7$ kK, respectively.

The presence of $\lambda\lambda 5668-5712\,\AA$ N II lines in hotter stars than the secondary of $\eta$ Car implies that if the wind of the secondary is nitrogen rich and dense, it might produce the N II lines.

Nitrogen-enriched secondary

The N II 5668Å line profile (commonly called the N II 5666Å) in the left panel of figure 1 in Mehner et al. (2011), shows an emission peak that maintains its width across periastron passage and follows the Doppler shift variation of the absorption part. This would not be the case if the emission of this line is an extended region that does not orbit at high velocity around the center of mass.

Though the N II and He I lines intensities behave differently, their Doppler shift is the same. This also shows that the entire lines-formation regions experience the same Doppler shift variation. This cannot be accounted for in a model where the N II and He I lines-formation regions change their location within the primary wind. A change in location within the secondary wind in our model can take place, and it is even expected to occur, but it is not the main effect (it causes deviation from pure orbital motion Doppler shift).

$\eta$ Car is a nitrogen rich system (e.g., Davidson et al. 1986; Dufour et al. 1999; Smith & Morse 2004), and it is accepted that the nitrogen rich gas is formed by the primary. As we propose that the N II lines originate in the secondary wind like the He I lines, the presence of nitrogen rich gas in the secondary wind requires an explanation. The explanation sends us back to the event that made $\eta$ Car a famous star – the 19th century Great Eruption (GE). During the GE the LBV primary has lost $12-40$ M$_{\odot}$ (Smith 2005; Smith & Ferland 2007; Gomez et al. 2010). Most of this mass was expelled to create the Homunculus nebula, but $\sim 3-6$ M$_{\odot}$ from this nitrogen rich material was accreted by the secondary (Kashi & Soker 2011). With the secondary mass loss rate of $\sim 10^{-5}$ M$_{\odot}$ yr$^{-1}$ it would take the secondary $\sim 4 \times 10^5$ yrs to dissipate this mass. According to the accretion model of the GE the present secondary wind is also nitrogen rich.

Nitrogen enrichment by itself is not sufficient in hot star. Herald et al. (2001) could not reproduce in their model the N II lines of the WR 8 stars WR 40 and WR 16. They write: “This problem may be alleviated by a more complex clumping implementation that allows for a range of clump densities at each radius, as the N II features would originate from the densest clumps.” We take this claim, and suggest that the secondary wind is clumpy. The clumps are pronounced in the acceleration zone where the velocity is $\sim 300-400$ km s$^{-1}$, the same general region where we propose the He I lines are formed in the secondary acceleration zone. Probably, in that region some particular processes occur, such as instabilities and shocks, with the possible formation turbulent regions. Skinner et al. (2008), based on analysis of X-ray emission, suggest that shocks occur in the acceleration zone of the wind of $\sigma$ Ori AB (they could not resolve the two stars in X-ray), where the wind velocity is much below the terminal speed. Theoretically, instabilities, with the
formation of clumps, in radiatively driven stellar winds can develop deep in the acceleration zone where the wind is at much below its terminal speed (Runacres & Owocki 2002).

Over all, we suggest that where the wind of the secondary reaches a speed of $\sim 400 \text{ km s}^{-1}$ in its acceleration zone, instabilities that lead to shocks and the formation of clumps cause the formation of some He I and N II lines. Ferland (1999) showed that some lines can be enhanced in turbulent winds. It is possible that the same occurs for the N II lines in the wind of the secondary.

4. Discussion and summary

The Doppler shift variation of some He I lines are quantitatively best explained by the orbital velocity of the secondary star in $\eta$ Carinae (Kashi & Soker 2007), for a semimajor orientation such that the secondary is closer to us at periastron passage ($\omega = 90^{\circ}$). Other arguments that support this orientation are discussed in a previous paper (Kashi & Soker 2008). The attribution of the Doppler shift of the He I lines to the secondary orbital motion explains the observations that the emission components of the lines show the same Doppler variation as the absorption components, a behavior that is in contradiction to models where the lines originate in the primary wind.

Both the absorption and emission components of the N II $\lambda\lambda 5668-5712$ line recently reported by Mehner et al. (2011) show the same Doppler variation as the He I lines observed by Nielsen et al. (2007). For that, we argue here that the N II $\lambda\lambda 5668-5712$ complex, like some He I lines, originates in the acceleration zone of the secondary wind.

Mehner et al. (2011) assume that the N II cannot be formed in the wind of the secondary of $\eta$ Car, and from the similar Doppler shift variation with the He I lines, come to the conclusion that also the He I lines do not originate in the secondary wind. In this short paper we are strongly disputing this conclusion.

For the formation of the N II lines in the hot secondary wind we require (i) that the secondary be nitrogen rich, and (ii) that dense clumps, that have lower ionization parameter, are formed deep in the acceleration zone. These requirements seemed to be fulfilled. (i) The more evolved primary star produces the nitrogen rich gas. The presence of nitrogen rich gas in the outer layers of the secondary are the result of the accretion of $\sim 1 \text{ M}_\odot$ from the primary wind during the 1837–1856 Great Eruption of $\eta$ Car (Kashi & Soker 2010). (ii) There are evidences, theoretically and observationally, that instabilities and shocks, that form clumps, occur in the acceleration zone of winds of O stars, where the wind speed is much below its terminal speed (e.g. Skinner et al. 2008). Such clumps, for example, can account for the N II lines in the hot WN 8 stars WR 16 and WR 40 (Herald et al. 2001).

We can summarize as follows. Our claim that the N II $\lambda\lambda 5668-5712$ complex formed in the acceleration zone of the secondary wind is compatible with other properties of the $\eta$ Car binary system.

1. The Doppler shifts of the N II (reported by Mehner et al. 2011) and some He I lines (reported by Nielsen et al. 2007) are accounted for with the binary orbital motion.

2. The orientation required for the Doppler shift explains other properties, such as the X-ray absorption gas, variation of narrow high emission lines, and more (Kashi & Soker 2008).

3. The clumpy nature of the secondary wind claimed here, as well as of the primary wind argued for by Moffat & Corcoran (2009), facilitate the penetration of one wind through the other (after they are shocked). Such clumps facilitate the accretion of the primary gas onto the secondary near periastron passages (Akashi, Kashi, & Soker, in preparation). The accretion process at each periastron passage seems to be behind the spectroscopic event of $\eta$ Car (Kashi & Soker 2009a).

4. The nitrogen enriched secondary wind is expected from the accretion model for the 19th Great Eruption of $\eta$ Car. In addition, the accreted mass spur-uncup the secondary star. A rapid rotation can make the secondary wind more complicated.

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