THE ORIGIN OF STRUCTURES IN WOLF-RAYET WINDS: FUSE OBSERVATIONS OF WR 135

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1. INTRODUCTION

All massive ($M_{\text{ms}} \sim 20–100 \ M_{\odot}$) stars drive strong winds. These stars spend most of their lifetimes in the hot part of the H-R diagram, either as O (H-burning) or Wolf-Rayet (W-R, mainly He-burning) stars. Although hot-star winds were suspected to be inhomogeneous (e.g., Cherepashchuk et al. 1984), truly direct evidence came only from the detection of stochastic, systematically moving subpeaks on the strong emission lines of W-R stars (Moffat et al. 1988). This profoundly changed the approach in atmospheric modeling of W-R stars (e.g., Hillier 1991; Hamann & Koesterke 1998; Hillier & Miller 1999) and resulted in a substantial reduction, by a factor 2–5, of predicted mass-loss rates. A similar factor may also apply to O star winds (e.g., Eversberg et al. 1998; Donati et al. 2002; Fullerton et al. 2006). Since the evolution of massive stars is heavily affected by mass loss, such a significant reduction in mass-loss rate called for a major revision in models of massive stars and stimulated further research (see Meynet & Maeder 2005 and references therein).

Although the consequences of wind inhomogeneities for mass-loss estimates are understood, the origin of the clumps is not. It is almost certain that radiative instabilities (e.g., Owocki 1994) must ultimately lead to supersonic, compressible turbulence (Henriksen 1994). Then it is reasonable to assume that the resulting shocks will generate the X-ray fluxes seen emanating (e.g., Berghöfer et al. 1997; Wessolowski 1996) from all hot-star winds. Linking shocks to X-rays, one should look for a stochastic variability of X-ray flux, expecting that the resulting shocks will generate the X-ray flux seen to propagate outward toward the edges of strong emission lines. These peaks are interpreted as density enhancements emitting excess recombination-line radiation, propagating, on average, along with the general wind outflow. In WR 135 the moving subpeaks typically range up to 0.2%–2.0% of the underlying emission-line strength, have a radial velocity dispersion $\sigma \approx 175 \ \text{km s}^{-1}$, and last for 7.5 hr on average (Lépine et al. 2000). The spectrum of WR 135, leaving aside the prominent O vi feature, can be modeled with $t_{\text{off}}(T_{\text{off}} = \frac{1}{2}) = 2.7 \times 10^{4} \ \text{K}$ (Dessart et al. 2000). On the other hand, the O vi doublet, the central subject of our discussion, peaks in strength at $T \sim 3 \times 10^{5} \ \text{K}$ (Zsargó et al. 2003; Sembach et al. 2004). This high ionization, two stages above the dominant level (Cassinelli & Olson 1979), is explained by Auger ionization in the presence of X-rays generated in numerous wind-embedded shocks.
Here we report the simultaneous appearance of short-lived (hours) absorption features in the high-velocity, blueshifted flanks of all major P Cygni emission profiles (O vi included) in the FUSE range. We link these absorption features to strong, highly supersonic shocks embedded in the wind of WR 135.

2. FUSE OBSERVATIONS

We observed WR 135 with FUSE (Moos et al. 2000; Sahnow et al. 2000) in 2004 October, starting at HJD 2,453,287.5930 (UT = 02:11, October 9) and ending at HJD 2,453,288.8483 (UT 08:19, October 10), thus following the star for more than 30 hr practically nonstop. The spectra were obtained in histogram (HIST) mode, with the medium-resolution (MDRS; 4° × 20°) aperture, covering 910–1185 Å. Initially, 59 exposures (root name D0440101*) were scheduled back to back over 18 consecutive orbits. However, for technical reasons, only 42 spectra were obtained, with a particularly large, ~4 hr gap during planned exposures 15–29, when detectors autonomously shut down. Exposures 5 and 55 were skipped because of acquisition problems. Exposures 15–29, when detectors autonomously shut down. Exposures 15–29, when detectors autonomously shut down. Exposures 30–39 (HJD 2,453,288.1803), and 40–59 (HJD 2,453,288.3598), were obtained, with a particularly large, ~4 hr gap during planned exposures 15–29, when detectors autonomously shut down. Exposures 5 and 55 were skipped because of acquisition problems. Exposures 15–29, when detectors autonomously shut down. Exposures 15–29, when detectors autonomously shut down. Exposures 30–39 (HJD 2,453,288.1803), and 40–59 (HJD 2,453,288.3598), and UT 20:34 – 08:11 (next day, exposures 40–59, red lines), i.e., with time progressing from black to red.

3. RESULTS AND DISCUSSION

Despite the overall improvement in S/N, our detection limits do not exceed 5%–10% (referring to the ambient continuum), depending on the spectral range, in any individual exposure. The fixed-pattern noise (small-scale and fairly stable, within a few hours, noise patterns) is mainly responsible for the problem. These detection limits are approximately a factor of 2 lower in the grouped exposures. Within these limits, the emission parts of all major transitions can be considered as constant. Let us recall that in the optical lines, the variability does not exceed ~2% (Lépine et al. 2000). In Figure 1 we show the major variable part—that of the absorption troughs of the P Cygni profiles. To normalize the velocities, we used the terminal wind velocity $v_w = 1479$ km s$^{-1}$ from Willis et al. (2004), which fits the data better than $v_w = 1343 ± 496$ km s$^{-1}$ from Niedzielski & Skorzynski (2002).

Finally, we converted the detected variations to the differences of apparent optical depths, $d = \ln \left( F_2/F_1 \right)$ (Savage & Sembach 1991), where $F_1$ is an average of exposures 1–14 and $F_2$ is either an average of exposures 30–39 or an average of exposures 40–59 (see Fig. 1). To reduce the noise, we removed all artefacts introduced by the saturated features (literally, the results of 0/0 division) and smoothed the $F_2/F_1$ ratio using a Gaussian filter with FWHM = 15 pixels. The smoothing does not change the original FWHM values of the features; however, it slightly (≤10%) reduces their depths. One immediately notices (Fig. 2, exposures 1–14 vs. exposures 40–59) the high-velocity, $v \approx -1.5 v_w$ to $-1.0 v_w$ feature seen in all well-developed P Cygni profiles across the spectrum. The excellent match between these features seen in both components of the S iv doublet lends additional credibility to the result. This absorption component appears to be much wider in the C iii line, which can be explained by the multiplet nature of this transition, with contributing components being separated by as much as $\sim 0.1 v_w$. While preparing Figure 2, we tentatively assigned $\lambda_0 = 1175.7$ Å to C iii, noticing that the components are spread between 1174.93 and 1176.37 Å. Another prominent feature at $v \approx -0.8 v_w$ to $-0.2 v_w$ is seriously affected by saturation (O vi, S iv, and C iii profiles), which causes the displacements or even near disappearance of this feature. However, this absorption com-
by any detectable changes in the $-0.4v_c < v < -0.1v_c$ part of the profile (Fig. 2).

There are two possible explanations for the detected blue-edge ($v > v_c$) variability: discrete absorption components (DACs) and fairly localized, wind-embedded shocks. The DACs are thought to be related to the corotating interaction regions (CIRs; Cranmer & Owocki 1996), the zones where high-speed streams generated by disturbances at the base of the wind collide with the relatively slower parts of the wind. One should notice the high incidence of DACs in the winds of OB stars (Kaper et al. 1996) versus relative rarity of these large-scale, spatially coherent structures in the W-R winds (see Marchenko 2003 and references therein).

Have we captured a single, isolated, stochastically appearing shock or a CIR-like structure that periodically crosses the line of sight? We favor the former, as there is no trace of any large-scale, coherent structures in the optical (Lépine et al. 2000). Plus, the wind of WR 135 is not flattened, contrary to all the CIR-bearing examples: WR 6, WR 134, and WR 137 (see Lefèvre et al. 2005 and references therein). In OB stars, any CIR-related variability takes place in a wide velocity range, $-v_c < v < v_c$, practically never exceeding $v_c$ (rather, slightly modulating the blueshifted absorption edge; Kaper & Henrichs 1994). In WR 135 we see a clear dominance of variability that goes far beyond $-v_c$, by as much as 50%. And we see no signs of variability exceeding the 5%-10% detectability levels in the “traditional” CIR domain, $-v_c < v < v_c$ (cf. the well-studied case of WR 6; St-Louis et al. 1995). In WR 135, rather than modulating the $-v_c < v$ edge, as usually attributable to CIRs, the short-living additional absorption is perceived as an isolated feature (cf. S iv λ1073 in Fig. 1) with no signs of a gradual shift to higher velocities (cf. C iii λ1175.7 in Fig. 1). In addition, the timescales of the detected UV variability, ~0.5–1.0 days, correspond reasonably well to the average “survival” times of blobs in the optical region, ≤0.5 days (Lépine et al. 2000). And the FWHMs of the features seen in Figure 2, FWHM ≈ 400 km s$^{-1}$, closely match the observed value of the radial velocity dispersion in the blobs seen in optical emission lines, $a = 175$ km s$^{-1}$. The synchronized appearance of the absorption features in all major P Cygni profiles across the FUSE spectrum mimics the general correlation in the behavior of blobs observed in different lines in the optical (Lépine et al. 2000; Lefèvre et al. 2005). Hence, one may relate the observed traces of shocked, and rapidly cooling (thus getting denser), gas to the incidence of numerous overdense clumps (blobs) in the wind of WR 135. Of course, the great spatial coherence of a DAC-related structure may facilitate detection. On the other hand, while adopting the model of a structured (clumpy) W-R wind, one must count on the presence of a large amount of profile-forming, overdense structures (e.g., Lépine et al. 2000). The sheer number of stochastically distributed inhomogeneities leads to a high probability of seeing, at any given moment, such a structure in absorption (i.e., projected on the optically thick part of the wind).

One may provide additional arguments favoring the “shock” scenario over DAC (CIR)–related variability. There are numerous examples of $v > v_c$ variability in W-R stars observed by IUE: WR 136 (St-Louis et al. 1989) and WR 6 (St-Louis et al. 1995), to name a few. An extensive search for O vi variability in the winds of OB stars (Lehner et al. 2003) shows that a solid majority, at least 64% of the O3-B1 targets, can be considered as variable. However, none of the surveyed objects showed $v > v_c$ variations in O vi, despite the tendency of stronger shocks to occur more frequently near $v_c$ and despite the tendency of more than 80% of O stars (Howarth & Prinja

![Fig. 2.—Top panel: Differences of apparent optical depths of the variable details in the profiles of O vi (solid line), S iv at 1062.7 Å (dotted line), and S iv at 1073.0 Å (dashed line). Bottom panel: Si iii λ1108.4 (solid line) and C iii λ1175.7 (long-dashed line).](Image 47x342 to 289x726)
1989) to show DACs in their spectra. Hence, the O vi line seems to be less sensitive to the DAC-related phenomena than other strong UV transitions. The only notable exception is α Cam, where the detected variability in UV resonance lines (Lamers et al. 1988) extends far beyond the derived $v_{\infty} = 1550 \text{ km s}^{-1}$ (Repolust et al. 2004).

If we are to interpret the variability as some kind of relaxation of the initially “unperturbed” profile (red line in Fig. 1), then the O vi profile has the highest restoration pace. This could be related to fast cooling of the shocked gas. Also, note that in the C iv and S iv profiles, the higher velocity (thus presumably higher temperature) region is restored much faster. Adopting the C iv related to fast cooling of the shocked gas. Also, note that in the O iv transitions, the only notable exception is O p vii (Lamers et al. 1988) extends far beyond the derived other strong UV transitions. The only notable exception is seems to be less sensitive to the DAC-related phenomena than space.

From our simultaneous detection (both in time and in velocity space) of a short-lived (hours) absorption feature in the $v > v_{\infty}$ parts of the emission profiles of lines with a wide range of ionization potentials, including the shock-sensitive O vi doublet, we conclude that:

1. Inn the winds of hot, massive stars, the highly blueshifted, $|v| > v_{\infty}$ parts of the P Cygni profiles may originate in high-speed, shocked regions of the winds.

2. Considering the enormous, $\sim 1/4 v_{\infty}$ FWHM of the features (Fig. 2), one can safely assume that a network of shocks, each with an adequate azimuthal extension, may create a flow with a highly nonmonotonic velocity field, thus resulting in a completely saturated P Cygni trough—a hypothesis voiced a long time ago by Lucy (1983; with further developments in Puls et al. 1993) but never proved with any certainty.

3. The observed shocks may be responsible for the relatively soft X-ray flux from OB/W-R winds, with relative (to an unperturbed flow) velocities of the shocked gas reaching $\pm 500 \text{ km s}^{-1}$, thus providing $kT \approx 0.5 \text{ keV}$, in good agreement with the characteristic X-ray temperatures of single OB stars (Berghöfer et al. 1996).

4. If shocks and blobs are related, then, considering the propagation of reverse/forward shocks (now the same as blobs) in the wind, we cannot expect them to follow the velocity law of an unperturbed wind. This may explain the seemingly low acceleration of blobs in the W-R winds (see the discussion in Koesterke et al. 2001).

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Facilities: FUSE

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