Clumping in Hot Star Winds
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Eta Carinae viewed from different vantages

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The spatially-resolved winds of the massive binary, Eta Carinae, extend an arcsecond on the sky, well beyond the 10 to 20 milliarcsecond binary orbital dimension. Stellar wind line profiles, observed at very different angular resolutions of VLTI/AMBER, HST/STIS and VLT/UVES, provide spatial information on the extended wind interaction structure as it changes with orbital phase. These same wind lines, observable in the starlight scattered off the foreground lobe of the dusty Homunculus, provide time-variant line profiles viewed from significantly different angles. Comparisons of direct and scattered wind profiles observed in the same epoch and at different orbital phases provide insight on the extended wind structure and promise the potential for three-dimensional imaging of the outer wind structures. Massive, long-lasting clumps, including the nebular Weigelt blobs, originated during the two historical ejection events. Wind interactions with these clumps are quite noticeable in spatially-resolved spectroscopy. As the 2009.0 minimum approaches, analysis of existing spectra and 3-D modeling are providing bases for key observations to gain further understanding of this complex massive binary.

1 The Eta Carinae System

Eta Carinae is a very luminous binary stellar system near the end of its hydrogen-burning phase (Davidson & Humphreys, 1997). It experienced two major events seen by astronomers: in the 1840s, a major brightening accompanied by ejection that we see as the dusty, neutral Homunculus, a bipolar shell thought to contain at least 12 $M_\odot$(Smith et al., 2003a); and in the 1890s a lesser event with ejecta that we see as the interior, ionized Little Homunculus which contains about 0.5 $M_\odot$(Ishibashi et al, 2003). The central source is a massive wind that enshrouds two massive stars with a 5.54-year spectroscopic and X-ray period (Damineli, 1996, Corcoran, 2006). Beginning with the 1998.0 minimum with particular focus on the 2003.5 minimum, several campaigns were conducted to observe the X-ray, visible and UV changes of Eta Carinae including the accompanying responses of the immediately surrounding ejecta. A large number of atlases and papers have been published derived from these observations. Analysis is continuing along with increasingly detailed models to explain the observations and to predict phased behavior of Eta Carinae leading to crucial tests to differentiate between various models of this massive binary system.

The massive ejecta are very rich in nitrogen and helium, very poor in oxygen and carbon. Indeed the N/O and N/C ratios seen by Verner et al., 2002 and Verner, Bruhweiler & Gull, 2005 are consistent with models of evolved massive stars with high angular rotation at the end of their CNO cycle (Meynet & Maeder, 2003).

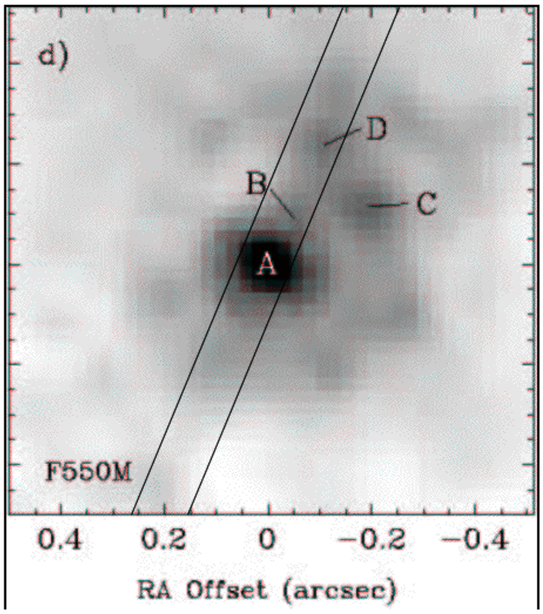

Figure 1: Eta Carinae and its wind/ejecta structure imaged by HST at 5500Å. Spatially-resolved HST/STIS spectra indicate that the interacting winds extend out to 0.4”. Weigelt B, C, and D are very luminous narrow-line emission structures located in the downwind cavity carved by the hot secondary and are directly excited by the hot companion. Other clumps complete a ring around Eta Carinae (A) but are shielded by the massive primary stellar wind.

An evolved, massive star is well past the H-burning phase, moving into the He-burning phase that ultimately leads to C and O overabundances at late stages. Recently Smith & Owocki, 2006 pointed out that, with the lowered mass loss rate for an O star during its main sequence lifetime, most mass lost before the supernova event must occur through multiple major ejection events. Eta Carinae, with its N-rich ejecta appears to have just begun a series of major ejections that C- and O-rich Wolf Rayet stars have progressed beyond. Given the transient nature of the Homunculus, historically recent ejecta of Eta Carinae, and the accessibility to studying the material as it responds to the periodically variable FUV and X-ray excitation by the central source, we can learn much about this early phase of massive stellar evolution.

2 Observations

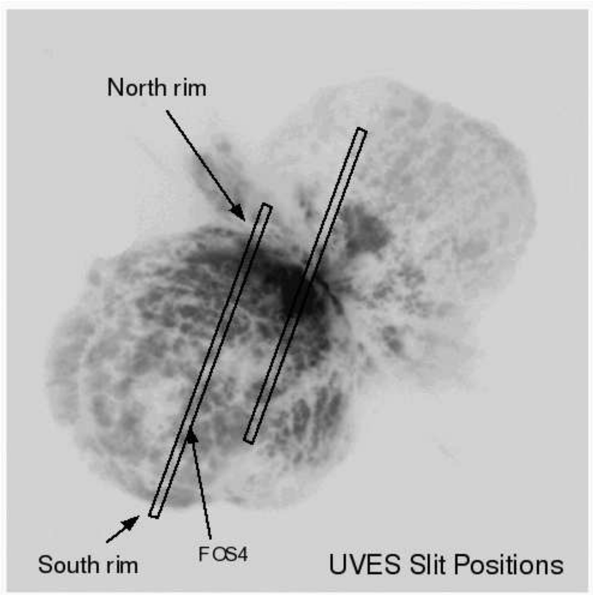

Figure 2: Eta Carinae and the Homunculus as imaged by HST. FOV is about 20". The UVES slit positions for Eta Carinae and for the nebular observations (FOS4) are overlaid. The foreground lobe scatters starlight off the cap and the background wall, resulting in a double-velocity profile. However along the rim, nebular absorption lines and the stellar wind profiles indicate scattering primarily at a single velocity. We use this (see Figure 3) to view the central source from a very different viewing angle relative to line of sight.

Direct imagery of Eta Carinae and the Homunculus (Figures 1 and 2) show extensive structure in the dusty, bipolar and disk ejecta. Figure 1, which is of the central 1" field, includes a number of condensations. The three labeled B, C and D are the Weigelt blobs (Weigelt & Ebersberger, 1986)Spatially resolved spectroscopy at varying angular and spectral resolutions tell much additional detail.

Smith et al., 2003b, using HST/STIS spatially-resolved spectra with $\delta\theta \approx 0.1$" and spectral resolving power, R = 8000, noticed that the hydrogen Bα line terminal wind velocity in the scattered starlight off the center of the foreground Homunculus lobe is greater than that measured in line of sight. We suggested a latitudinal wind dependence especially across the broad spectroscopic maximum of the 5.5-year period. Weis et al, 2005, Stahl et al., 2005 and Davidson et al., 2005, used VLT/UVES observations with seeing-limited angular resolution, $\theta \approx 1$–2" and R≈80,000, to monitor changes across the 2003.5 spectroscopic minimum. They confirmed that the wind lines seen by scattered starlight in the center of the foreground lobe, labeled FOS4 in Figure 2 showed higher terminal wind velocities. They also noted that the wind profiles seen directly in line of sight and scattered off the foreground lobe included temporal bumps and wiggles that were not easily explained by a single wind that varied uniformly by latitude.

The highest angular resolution currently possible is with the VLTI/AMBER at 2 microns at 4 mas and 1500 or 12,000 resolving power (Weigelt et al., 2007). Comparison of the hydrogen Bγ and He I 2.06μ line profiles and visibilities with continuum visibilities led to a model wind structure in the shape of a prolate spheroid with major axis aligned with the bipolar axis. The dominant source of continuum in the infrared is the extended primary, thought to be at least 200 times brighter at those wavelengths that the secondary, which, if a normal O or WN star, dominates in the FUV. Current VLT/AMBER measures place an upper limit of the secondary at 1/50th the flux of the primary.

AMBER measures a FWHM continuum diameter of 4.2 mas (10 AU at 2300 pcs). The wind line FWHM diameters are 6.5 mas for the He I 20.6 μ and 9.6 mas for the H Brγ line, consistent with the more extended optical depth of line transitions and decreasing excitation requirements. The He I line profiles originate from singlet and triplet levels requiring much higher temperatures and/or excitation/ionizing photons that does the H Brγ transition. One peculiar aspect was that the He I profile, most noticeably the absorption component was measured to be blue shifted by several hundred km/s relative to the H I profile.

The HST/STIS medium dispersion, long slit spectra (0.1" angular resolution with R=8000) recorded from 1998.0 to 2004.3 across the 2003.5 minimum provides insight to the velocity shift.

(Nielsen, et al., 2007). The model, discussed by Nielsen, 2007 suggests that while the H I wind lines, along with Fe II wind lines, originate from the overall wind, dominated by the massive, cooler primary wind, the He I wind line originates in the wall of the cavity carved out of the primary wind by the less massive, energetic secondary wind. However, the FUV radiation from the hot secondary penetrates the wall for a significant distance into the primary wind. The blue-shifted He I profile indicates that the secondary star, in the highly elliptical orbit, spends most of the orbit on the near side of the primary.

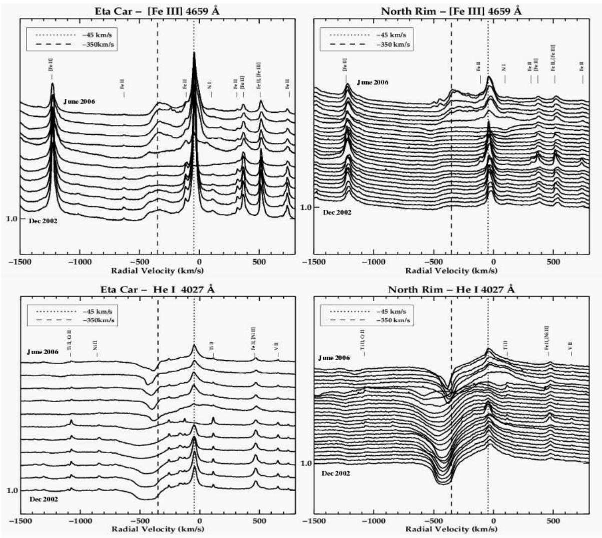

Figure 3: VLT/UVES line profiles recorded from December 2002 through June 2006 (K. Weis, PI). Top row: [Fe III] 4659Å. Bottom row: He I 4027Å. Left: Line profiles direct from of Eta Carinae. Right: Line profiles scattered off of the northern rim. Both [Fe III] and He I emission disappear during the 2003.5 minimum.

We learn much about the wind interaction by probing the scattered starlight at different positions across the Homunculus. The wall of the foreground lobe, in line of sight, registers strong absorption lines at −513 km/s (Gull et al., 2005). We have identified over two thousand metal and molecular absorption lines in the STIS UV ($\delta\theta \approx$.06", R≈110,000) and VLT/UVES ($\delta\theta \approx$1-2", R≈80,000) spectra. Many of these lines, while smeared out in the center of the lobe are still observed in the rim structures.

We compare windline profiles in line of sight and scattered off the northern rim (Figure 3). He I and [Fe III] lines originate from two very different regions: He I from the wind-wind interaction region as discussed above and [Fe III] from the outer, lower density regions, photo-excited by the FUV emission of the secondary star. Careful examination of the two sets of spectra indicates that 1) the narrow emission component of [Fe III] is much weaker in the view seen from the northern rim and 2) the He I absorption is significantly more robust in the northern rim view compared to direct line of sight.

3 Discussion & Conclusions

The wind line profiles are very different when viewed at different angles due to the extended, veiling wind-wind interaction. The wind line profiles change with time, primarily due to binary orbital motion and their interacting winds. However irregular features appear and disappear at shorter intervals. Some may be due to long term changes of the wind opacity, but much is likely due to clumping within the massive winds. With appropriate angular and spectral resolutions, the opportunity is available to get information leading to that a 3-D image of the near side wind structure. Data from these instruments provide very complimentary information that will lead not only to gross properties of the winds but also of the massive clumps ejected during major outbursts.

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Cassinelli: You have been discussing the disk wind. Is this related to the "extended skirt" seen off to the side of Homunculus?

Weis: Across the skirt there is low energy X-ray emission.

Gull: The [Fe III], [Ar III], [S III], [Ne III] emission appears to come from the interior disk edge, but this region is photoionized by the hot secondary companion.

de Koter: You showed that you probed the iron lines on many positions in the Homunculus, also quite far out. Do you have any information on the abundances of iron? This may be very important in better understanding the dust formation (or subsequent destruction/re-formation).

Gull: Hillier's models of the primary star assume normal abundances. As to nebular abundances, Verner et al. (2001,2003) demonstrate He/H ~ 1, N/O, N/C ~ 100. In the line of sight, the Homunculus shows Ti/Ni, etc. to be large. The metal-ionized nebula (Sr-Filament) has Ti/Ni ~ 80 solar and Cr/Ni ~ 20 solar. We suspect these strange abundance ratios to be caused by low C, O abundances leading to many metals, ordinarily formed as oxides and precipitated on dust grains, to be trapped in the gaseous phase. Ti, V, Sc, Sr, Y have been identifed in emission in the Sr filament and in absorption at -513 km/s in line of sight (Homunculus).

Moffat: I really admire your and others' work! But we will not understand what is going on until we actually resolve and track (spatially or spectroscopically) both stars. One clearly needs high spatial resolution and the "right" spectral window.

Gull: Gerd Weigelt and team place an upper limit to the secondary of 1/50 of the primary. Models suggest an O star would be 1/200. Recent improvements in VLTI/AMBER with the auxiliary telescopes should reach to 1/300. In the UV, FUSE observations do detect flux that disappears during the minimum (Iping et al. 2005), but foreground absorption and wind scattering prevents wind line identification.