A Massive Star Odyssey, from Main Sequence to Supernova
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The stellar wind geometry of η Carinae

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Abstract. *HST*-STIS spectroscopy of the Homunculus reflection nebula around η Carinae provides a rare opportunity to observe a star from more than one direction, and reveals that η Car has an aspherical stellar wind. Relatively high velocities and strong absorption are seen near the polar axis, suggesting *higher mass flux toward the poles*, perhaps resulting from equatorial gravity darkening on a rotating star. The bipolar wind geometry may imply that intrinsically asymmetric ejection helped form the Homunculus. It is also critical for understanding this star's variability and evolution.

1. Introduction

Most of η Car's peculiarities are related in one way or another to its mass loss, either during its mysterious eruptions or its furious stellar wind. Ejecta from its Great Eruption in the 19th century have formed the Homunculus Nebula (Figure 1a), one of the most elegant examples of bipolar structure. The geometry of the Homunculus and various other clues hint that η Car's stellar wind is non-spherical. Reflected light provides a view of the central star from *a range of latitudes*, allowing us to reconstruct the shape of η Car's wind. The ability to observe η Carinae from multiple latitudes yields surprising results; departures from spherical symmetry are usually interpreted as slow equatorial density enhancements. Various models have important discrepancies, and all lack verification by observing wind properties as a function of latitude on a real star.

The long-slit *HST*-STIS spectra were obtained on 2000 March 13, using a $52'' \times 0\farcs2$ aperture centered on the star and oriented as shown in Figure 1a. The case of η Car is unique in astrophysics so far, because the geometry of the bright, hollow reflection nebula is known sufficiently well that we can correlate position in the nebula with stellar latitude. Davidson *et al.* (2001) estimated the shape and orientation of the Homunculus from the same dataset used here, and we use their shape (shown in Figure 1b) to derive the latitude for each position.

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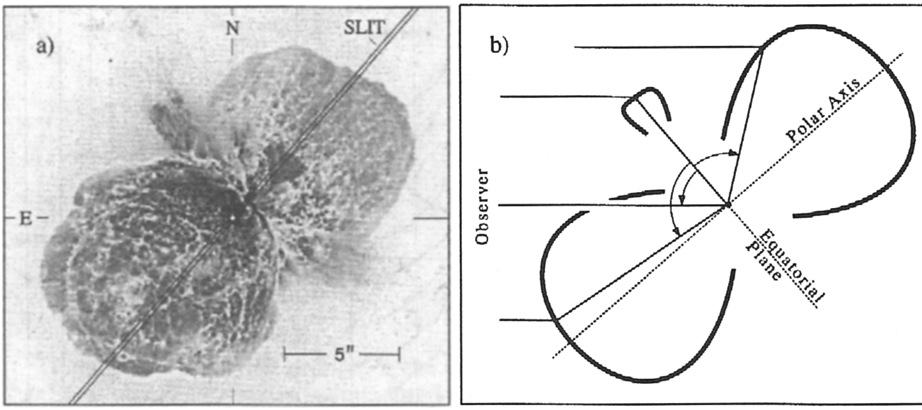

Figure 1. *Left:* orientation and size of the STIS slit used for the March 2000 observations. *Right:* schematic diagram showing the relationship between position and latitude for reflected light in the Homunculus.

2. Hydrogen line profiles

Figure 2 illustrates that reflected line profiles change with position. The primary change occurs in hydrogen P-Cygni absorption, which is strongest 5″ to 6″ SE of the star. It is weak or absent in the reflected spectrum from the NW lobe. Hβ and Hα scattering wings and emission peaks have nearly identical profiles at every position in the SE lobe, but the absorption components differ significantly. Absorption traces a more direct and narrow line of sight between reflecting dust and the star, whereas emission corresponds to a larger region of the wind. Thus, absorption components in Figure 2 give *direct evidence that η Car's current stellar wind is aspherical.* We measured v_∞ and $v_{\rm PCYG}$ for each extraction in Figure 2. Figure 3a shows how we defined these two velocity components, and resulting measurements are plotted in Figure 3b.

1. *Higher velocities near the pole.* Blue-shifted absorption is seen at speeds up to $\sim$1100 km s^{-1}. The observed velocity rises faster than expected if the changes were to due variation in the escape velocity with rotation (see Figure 3b), which signals that the latitudinal dependence of outflow velocity in η Car's wind is influenced by effects other than the simple variation of escape speed. The fastest material between 5″ and 6″ SE of the star coincides with the nebula's polar axis, giving the first direct indication that *the polar axis of the Homunculus is aligned with the rotation axis of the central star.* Any other situation would be alarming. This alignment suggests that axial symmetry and ejection physics during the Great Eruption may be directly linked to the star's rotation.

2. *Deeper absorption near the pole.* Perhaps the most significant result of this investigation is that the deepest P-Cygni absorption is seen at the polar axis, with absorption weakening *progressively* toward lower latitudes (see Figure 2). In dense winds like η Car's, P-Cygni absorption in Balmer lines depends on a precarious balance between ionization and density. A fully ionized wind produces pure emission profiles, but a slight overdensity (perhaps a factor of 2 - 4) may

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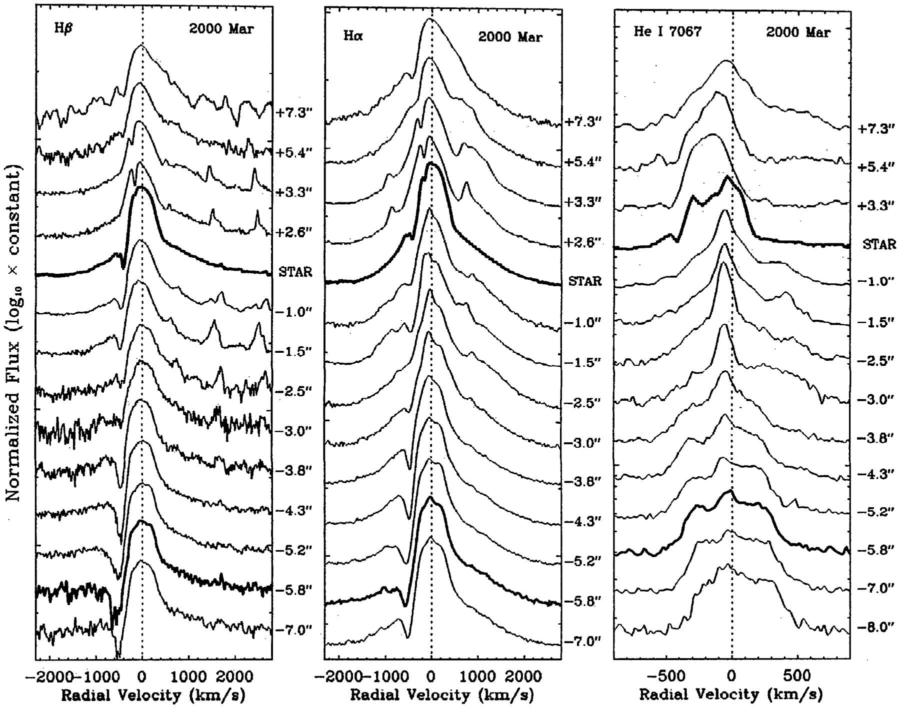

Figure 2. Tracings at several positions along the slit for Hβ, Hα, and He I λ7067 compared to the spectrum of the central star (shown with a thick solid line). Positional offsets are indicated.

be enough to cause the recombination in the outer parts of the wind needed for deep Balmer absorption (see Najarro *et al.* 1997; Hillier *et al.* 2001).

3. *Symmetry about the equatorial plane and polar axis.* Measured values of v_{∞} and v_{P-Cyg} plotted together in Figure 3b follow the same trend, regardless of which polar lobe or which side of the SE polar axis they correspond to, and Hα profiles on either side of the pole are identical. This indicates that the wind outflow pattern is *axisymmetric*, and suggests that the observed wind geometry may result from rotation instead of the direct influence of a companion star.

3. Helium line profiles

Tracings for He I λ7067 at several positions across the nebula are shown in Figure 2. Reflected line profiles in the SE lobe are a combination of central narrow emission from circumstellar gas, plus broad wind emission. At 2″ to 4″ SE of the star, reflected narrow He I λ7067 emission from circumstelar gas is much stronger than at other positions, because the broad component and continuum fade. This suggests that obscuring dust lies along this particular line of sight to the star, projecting *a shadow* onto the SE polar lobe. This same position corresponds to a relatively dark region in *HST* images of the Homunculus (see

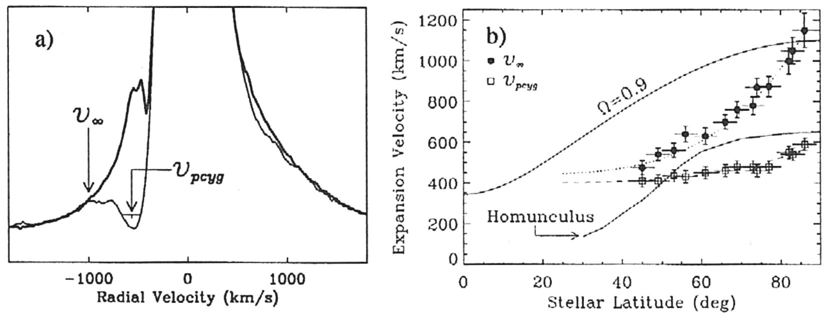

Figure 3. *Left:* Hα profiles of the star (heavy line) and one position in the SE lobe, indicating how we measured v_∞ and $v_{\rm PCYG}$. *Right:* variation of v_∞ and $v_{\rm PCYG}$ for the Hα line as a function of latitude in η Car's wind. The solid line labeled 'Homunculus' corresponds to expansion velocities for the polar lobes. The other solid line shows the expected variation of v_∞ if it is due to changes in escape velocity on a rotating star, for an arbitrary value of $\Omega = 0.9$.

Figure 1a). The obscuring dust would have to be close to the star and compact, because it obscures the star but does not block light from nearby ejecta.

Changes in underlying broad stellar wind profiles are less straightforward to interpret than narrow components. Broad He I λ7067 emission in the SE lobe (see Figure 2) has a nearly symmetric profile. The red side of He I lines disappears in the reflected spectra from the NW polar lobe, and in the spectrum of the star. In other words, low latitudes (below $\sim$50°) seen from the NW lobe have asymmetric profiles with extra blueshifted emission, and high latitudes have symmetric profiles and extra redshifted emission.

4. Geometry of the wind

Latitudinal variations of H and He I lines offer a powerful diagnostic of the 3D ionization and density structure in η Car's stellar wind. The geometry of the wind, in turn, helps us understand the shape of η Car's circumstellar ejecta and their excitation, and the wind is absolutely critical for understanding all aspects of η Car's spectroscopic variability.

Reflected line profiles seen in STIS spectra seem to suggest that η Car's wind has prolate mass flux, with higher velocities, higher densities, and lower ionization toward the pole. This is a surprising result, because conventional wisdom leads one to expect the opposite; for example, rapidly rotating B[e] supergiants are thought to have low-ionization equatorial density enhancements. However, the prolate mass flux we observe in η Car is not without theoretical precedent (see Owocki *et al.* 1996; Maeder & Desjacques 2001).

The proposed wind structure helps solve or mitigate several peculiarities associated with η Car and its ejecta. One major obstacle to understanding η Car is the simultaneous existence of high-excitation circumstellar gas and a dense wind that should absorb all Lyman continuum photons. This is one reason why a binary hypothesis is attractive, as it allows for an external source of the hard photons. The aspherical wind we have proposed has low-density regions that might allow the necessary UV flux to escape, while the dense polar regions incur the high mass-loss rate measured observationally. Most of the high excitation gas around η Car is thought to be in the equatorial plane, in agreememnt with the proposed wind geometry.

5. Wind variability

We must not forget that η Car is a notorious variable star as well. The wind geometry described above has implications for the star's 5.5 yr spectroscopic cycle (Damineli *et al.* 1996), as well as its long-term variability. η Car's most recent 'spectroscopic event' occurred at the beginning of 1998, and STIS data obtained shortly thereafter paint a very different picture of the wind geometry; specifically, low-latitude regions of the wind also had deep P-Cygni absorption in Balmer lines, similar to the polar regions of the wind. In many ways the changes in wind structure during the last event looked like a low-latitude shell ejection, which has important consequences for the roles of rotation and a hypothetical companion star in η Car's 5.5 yr cycle.

Additionally, an extreme mass-loss rate of $10^{-3}\,M_\odot\,yr^{-1}$ concentrated in the polar wind will remove *less than its share* of angular momentum from the star's envelope, and may cause the star to spin up over longer timescales ($\sim$ 100 years). Feast *et al.* (2001) have examined historical spectra of η Car and conclude that its spectroscopic cycle was absent before about 1940, and since then the high-excitation lines have shown a secular increase. If rotation and gravity darkening are needed to direct the mass flux poleward (Owocki *et al.* 1996), then a gradual increase in the star's rotation rate after the Great Eruption may enhance the lower-density zone of the wind near the equator where the essential UV radiation escapes. Rotation may be acting as a valve controlling the escape of Lyman continuum photons at low-latitudes in the wind.

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