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The Stellar Wind Geometry of η Carinae

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Abstract. The Homunculus reflection nebula around η Carinae provides a rare opportunity to observe a star from more than one direction. For η Car, the nebula's geometry is known well enough to infer how wind profiles vary with latitude. STIS spectra of the Homunculus show directly that η Car has an aspherical stellar wind. P Cygni absorption in Balmer lines depends on latitude, with relatively high velocities and strong absorption near the polar axis. Stronger absorption at high latitudes is surprising, and it suggests *higher mass flux toward the poles*, perhaps resulting from equatorial gravity darkening on a rotating star. Reflected profiles of He I lines are more puzzling, and offer clues to η Car's circumstellar structure. 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

η Carinae is one star (or two) that may be overqualified for inclusion in a discussion of exotic objects that pose challenges to stellar evolution. 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 (Fig. 1*a*), one of the most elegant examples of bipolar structure. Although its mass-loss rate today is a factor of 10^2 smaller than during the Great Eruption, η Car still has one of the densest stellar winds of any evolved star, with $\dot{M} \sim 10^{-3} M_{\odot}$ yr^{-1} (Hillier et al. 2001). The geometry of the Homunculus and various other clues hint that η Car's stellar wind is non-spherical.

Reflected light from various positions in the nebula 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 sur-

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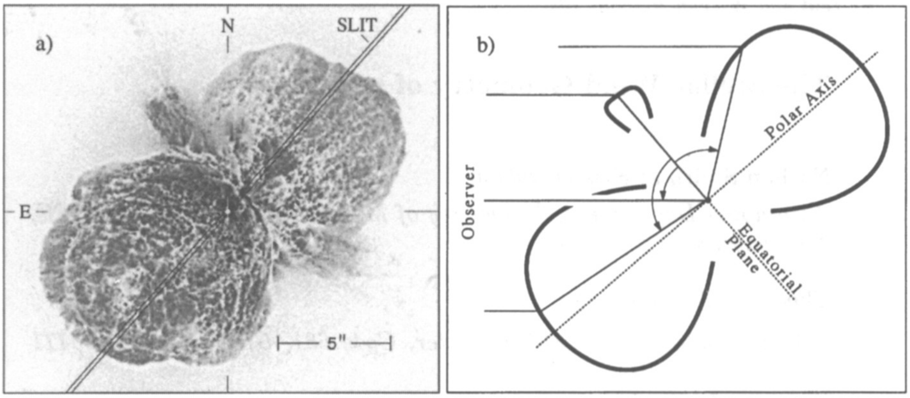

Figure 1. (a) Orientation and size of the STIS slit used for the March 2000 observations. (b) Schematic diagram showing the relationship between position and latitude for reflected light in the Homunculus. The vertical axis is distance along the slit and the horizontal axis is distance perpendicular to the plane of the sky.

prising results in the context of current models for asymmetry in rotating stellar winds, especially with regard to the expected latitudinal density distribution; departures from spherical symmetry are usually interpreted as slow equatorial density enhancements. Various models have important discrepancies, and all lack direct observational verification by measuring wind properties as a function of latitude on a real star.

We have observed η Carinae several times over the past few years using *HST*/STIS to document variability in η Car's spectrum during its 5.5 year cycle. The long-slit *HST*/STIS spectra discussed here were obtained on 2000 March 13, using a $52'' \times 0\farcs2$ aperture centered on the star and oriented at position angle $138\fdg9 \leftrightarrow 318\fdg9$, as shown in Fig. 1*a*. Fig. 2 shows examples of long-slit STIS spectra for a few reflected lines in η Car's stellar wind. 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 Fig. 1*b*) to derive the latitude for each position.

2. Hydrogen Line Profiles

Fig. 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,

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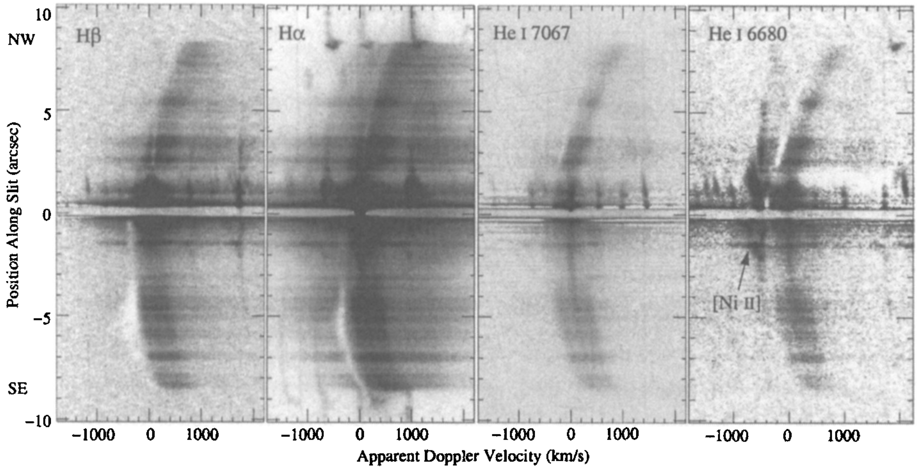

Figure 2. Continuum-subtracted long-slit STIS spectra (March 2000) of a few of the brightest reflected emission lines in η Car's stellar wind, using the 0.″2-wide long-slit aperture shown in Fig. 1*a*.

absorption components in Fig. 2 give *direct evidence that η Car's current stellar wind is aspherical.* We measured v_∞ and v_{pcyg} for each extraction in Fig. 3. Fig. 4*a* shows how we defined these two velocity components, and resulting measurements are plotted in Fig. 4*b*.

1. *Higher velocities near the pole.* Blueshifted absorption is seen at speeds up to $\sim 1100\,\mathrm{km\,s^{-1}}$, much faster than values usually quoted for η Car's wind. The observed velocity rises faster than would be expected if the changes were to due variation in the escape velocity with rotation (see Fig. 4*b*), 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. Good candidates are gravity darkening or magnetic fields.

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. The alignment of these axes suggests that axial symmetry and ejection physics during the Great Eruption may be directly linked to the star's rotation. Values for v_∞ at high latitudes are almost twice the expansion velocities for the Homunculus (see Fig. 4*b*). Therefore, we might expect to see shock-excited emission inside the polar lobes, such as the H_2 and [Fe II] lines described by Smith & Davidson (2001).

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 Fig. 3). 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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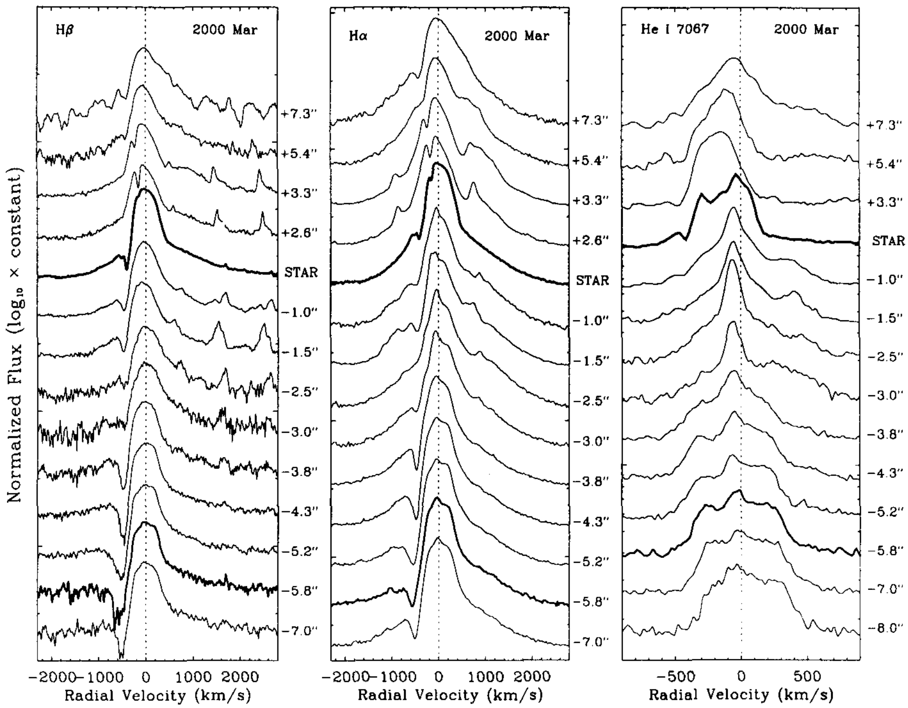

Figure 3. Tracings at several positions along the slit for Hβ, Hα, and He I λ7067 compared to the spectrum of the central star (shown with a thick solid line). Positional offsets are indicated.

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

3. *Symmetry about the equatorial plane and polar axis.* Measured values of v_∞ and v_{pcyg} plotted together in Fig. 4*b* 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*. A hot companion star with a fast wind might give rise to high-velocity blueshifted absorption projected in one direction, but not toward both poles symmetric about the equator. This suggests that the observed wind geometry may result from rotation instead of the direct influence of a companion star.

3. Helium Line Profiles

Fig. 2 shows the long-slit spectrum across the major axis of the Homunculus for He I lines as well. Tracings for He I λ7067 at several positions across the nebula are shown in Fig. 3. Reflected line profiles in the SE lobe seem to have three velocity components in Fig. 2, caused by a combination of central narrow

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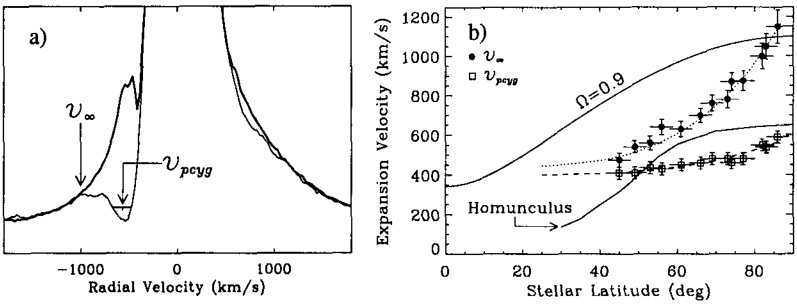

Figure 4. (a) Hα profiles of the star (heavy line) and one position in the SE lobe, indicating how we measured v_∞ and v_{pcyg}. (b) Variation of v_∞ and v_{pcyg} for the Hα line as a function of latitude in η Car's wind. The solid line labeled "Homunculus" corresponds to expansion velocities for the polar lobes. The other solid line shows the expected variation of v_∞ if it is due changes in escape velocity on a rotating star, for an arbitrary value of $\Omega = 0.9$.

emission from circumstellar gas, plus a broad plateau or double-peaked emission line arising in the stellar wind.

At 2″ to 4″ SE of the star, reflected narrow He I λ7067 emission from circumstellar gas is much stronger than at other positions, because the broad stellar wind 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 Fig. 1*a*). 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. Dense dust knots seen at thermal-IR wavelengths (Smith et al. 2002) are good candidates for blobs that are casting shadows.

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 Fig. 3) 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. The blue side of the broad He I line profiles is much stronger in the NW lobe, but roughly the same for the SE lobe and central star. In other words, low latitudes (below ~ 50°) seen from the NW lobe have asymmetric profiles with extra blueshifted emission, and high latitudes seen near the pole in the SE lobe have symmetric profiles and extra redshifted emission. The central star and reflected emission from the NW lobe (low latitudes) also show P Cygni absorption at $-400\,\mathrm{km\,s^{-1}}$ in He I lines, but the reflected spectra in the SE lobe show no detectable P Cygni features. Balmer lines show the opposite trend; namely, stronger absorption at high latitudes.

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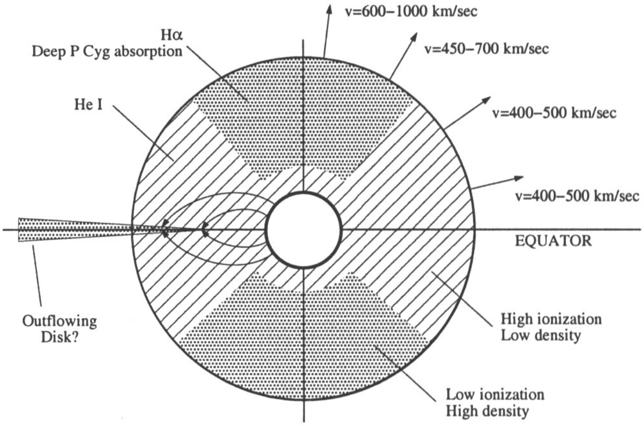

Figure 5. Cartoon model for latitudinal structure in η Car's stellar wind during the normal high-excitation state in March 2000.

4. Geometry of the Wind

Latitudinal variations of H and He I lines offer a powerful diagnostic of the 3-D 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.

Fig. 5 shows a hypothetical picture of latitudinal structure in η Car's stellar wind, deduced from observational clues. It essentially depicts two zones in η Car's outer wind: 1) a high-density, low-ionization zone where H recombines and produces Balmer absorption (shaded), and 2) a lower density, high-ionization zone (hatched) producing the He I emission, or at least relatively transparent so that the underlying He I zone is seen, and where H remains fully ionized. In reality, of course, demarcation between these zones is not so sharp.

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, Cranmer, & Gayley 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

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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 year spectroscopic cycle (Damineli 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 were also filled-in with 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 year cycle. However, the observations discussed here do not offer a clear alternative to the binary hypothesis for explaining η Car's X-ray variability.

Additionally, an extreme mass-loss rate of $10^{-3} M_{\odot}\,\mathrm{yr}^{-1}$ 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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