Spectral imaging of \( \eta \) Carinae

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Abstract: We have secured spectra at high signal/noise ratio in a grid of points across the entire Homunculus Nebula surrounding the peculiar, massive star \( \eta \) Carinae. The data cover the wavelength range 420–1000 nm. Included are parts of the outer nebulosity dating from a prehistoric ejection episode. At a spatial resolution of about 1 arcsec we find dramatic differences in emission line ratios and profiles, sometimes in adjacent resolution elements.

1. What is \( \eta \) Carinae?
It appears to be the most massive and luminous star known, at least in our Galaxy. In the absence of a recent review of the star, the ultraviolet spectra presented by Viotti et al. (1989) provide an entry into the literature. Mass estimates range around \( 160 M_\odot \), and the luminosity is about \( 5 \times 10^6 L_\odot \). Now invisible to the naked eye, it became in 1843 the second brightest star in the sky, despite its distance of some 2500 parsecs. At that time it appears to have shed about \( 4 M_\odot \) into a nebula that is expanding at about 800 km s\(^{-1}\). The nebula is known as the Homunculus (Gaviola 1950). It has a roughly bipolar form, though the symmetrical nature of the outflow is seen only at infrared wavelengths, being hidden in the optical by patchy obscuration.
\( \eta \) Car lies in association with many young, luminous OB stars in the Carina Nebula. It is therefore young in years. However, outlying gas almost certainly ejected in a prehistoric eruption shows enhanced nitrogen and suggests a high degree of processing (Davidson et al. 1984). The star is thus clinically old. Its fate will surely be to erupt as a supernova, though it may be an unusual one, muffled by the extensive mass loss.

2. What did we do with it?
The spectrum of the central star has long been known (e.g., Thackeray 1953, 1962). It varies, but over the last few decades has shown intense emission of hydrogen, helium and iron. Oxygen is absent. The spectrum of the Homunculus Nebula is known to be quite similar, but with line broadening and redshifts due to reflection of the spectrum of the central star by outflowing dust. The details of the spectrum of the Homunculus have not been explored.

So we mapped the spectrum at high S/N over the entire Homunculus, using 0.7 arcsec angular resolution. By suitably adjusting the exposure time we have achieved good data over the entire nebula. The data are still being analysed, and are turning up novel features everywhere we look. It’s exciting stuff.

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Figure 1 - Spectra of \( \text{H}_\alpha \) and [N II] at nine positions in the receding NW lobe of the Homunculus. Each is averaged over adjacent 2.1 x 2.1 arcsec boxes, and offsets from the central object along and across the major axis are given at top left of each box. The velocities refer to the \( \text{H}_\alpha \) line; [N II] lies at \(-670 \) and \(+950 \) km s\(^{-1}\). The narrow component is attributed to stray light, and when this is removed a broad, shallow P-Cygni profile is seen. Note the rapid acceleration between 4.3 and 6.4 arcsec.

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This presentation can do no more than select a few facets of this remarkable object to give an indication of what will eventually emerge.

We covered the wavelength range 420–1000 nm at a resolution of about 0.3 nm. We also examined a few selected regions at higher spectral resolution so as to separate interesting diagnostic lines and examine profiles of Balmer, helium, Fe II and [Fe II] lines. Some representative spectra are shown in Figure 1.

3. What did we find?

(a) Near the centre there are two dominant components to the lines, one narrow and the other > 500 km s\(^{-1}\) FWHM. The latter surely arises in a wind from the star, but the narrow component must originate in a static region, probably a disk of gas. Surprisingly, the ratio of [Fe II] to Fe II lines is similar in both, suggesting comparable densities. The narrow component persists over a substantial area, probably because of stray light in the non-Gaussian outer parts of the central star’s seeing disk. The spectra appear sensible if we subtract a scaled fraction of the central source from the outer parts, and the scaling function appears appropriate for stray light.

(b) There are many strong lines in the red that appear to be Fe II fluoresced by Lyman \(\alpha\). Some of these are new identifications.

(c) The velocity of the reflected emission shows two components along the major axis to the NW. One is fixed at about 900 km s\(^{-1}\) while the other shows remarkable acceleration, from 250 to about 800 km s\(^{-1}\) in a space of under 3 arcsec.

(d) There is intrinsic emission from the Homunculus. We see lines of Ca II, [Ca II], Na I, [Cr II], [Fe II] and [Ni II], but hydrogen is weak or absent. The velocities of these lines are not always compatible with those shown by the reflection spectra, so they may arise in different regions. It is therefore not straightforward to use the velocities of reflected and intrinsic emission to estimate the expansion velocity and orientation of the flow, as has been done in the past (e.g., Thackeray 1961). However, we see some places where consistent values arise, and confirm that the NW lobe is receding, at an angle around 30° to the plane of the sky.

Nor are all these intrinsic emission lines showing the same velocities. For example, to the NW of the central star, where all other lines show red shifts, strong blue-shifted [Ca II] components appear. We cannot yet say whether the excitation mechanism for such regions is photoionisation by the central star or shocks.

(e) P-Cygni absorption is seen at some positions, suggesting an outflow of about 350 km s\(^{-1}\). When we correct for the stray light, we find that the P-Cygni absorption is present everywhere the spectrum of the central object is seen in reflection. We therefore believe it arises in the wind close to the central star. Such wind velocities are typical of the few other luminous blue variables. This confirms that mass loss continues, but at a lower velocity than in the 1843 outburst. The Homunculus thus should comprise two kinematic components: a homologous outer region due to the 1843 outburst, and an inner zone of continuous outflow, with acceleration (point (c) above). We probably see these two regions in our data, but have yet to deconvolve orientation effects.

(f) Surrounding the Homunculus is an older, patchy shell which shows a range of excitation, including He II \(\lambda468.7\), which is absent in the central star and indicates shock excitation. Parts of the outer shell overlie the Homunculus and may account for some of the local emission patches. In at least one region, to the extreme SE, the outer shell has the velocity structure of a hollow cone, reminding one of the structure seen in the Homunculus at infrared wavelengths (Hackwell, Gehrz and Grasdalen 1986; Allen 1989).