Preliminary Analysis of STIS-HST Spectra of Compact Ejecta from Eta Carinae

Fred Hamann  
Center for Astrophysics & Space Science, University of California – San Diego, La Jolla, CA 92093-0424

K. Davidson and K. Ishibashi  
Department of Astronomy, University of Minnesota, 116 Church St., SE, Minneapolis, MN 55455

T. Gull  
Goddard Space Flight Center, Code 680, Greenbelt, MD 20771

Abstract. We describe some preliminary results from spatially-resolved spectroscopy of the compact ejection knots B and D in the $\eta$ Carinae wind. We emphasize various line diagnostics of the abundances, kinematics and physical conditions. The data are from new STIS-HST observations described by Gull et al. elsewhere in this volume.

1. Introduction

Spectroscopic studies of the central star(s?) and complex ejecta of $\eta$ Car have been severely limited by the low spatial resolution of ground-based observations. Recent studies using the Hubble Space Telescope (HST) have thus led to an explosion of information. For example, we now know that the many strong and narrow emission lines that dominate $\eta$ Car’s spectrum come from several brights knots of nebulosity within $\sim 0.3''$ of the central star (Davidson et al. 1995, 1997). These knots are almost certainly slow ejecta in a dense equatorial wind that bisects the much larger high-velocity lobes (the Homonculus, see also Weigelt et al. 1995, Falcke et al. 1997). The most prominent emission lines are due to singly-ionized metals, notably Fe$^+$, with typical velocity widths of 30–50 km s$^{-1}$ (Damineli et al. 1998, Hamann et al. 1994).

We obtained spatially-resolved (<0.1'') long-slit spectra of the star, the brightest knots and the extended Homonculus using the Space Telescope Imaging Spectrograph (STIS) – please see T. Gull’s description of the data elsewhere in this volume. The combination of high spectral resolution (20–30 km s$^{-1}$) and wide wavelength coverage ($\sim 1650$ Å to $\sim 1.0$ µm) allow us to employ for the first time crucial line diagnostics of the abundances, kinematics and physical conditions in spatially distinct regions. Below we describe some preliminary results derived for the bright knots B and D, with a few notes on applications.
to the direct stellar spectrum. A more complete analysis will appear in future papers.

2. Reddening

Estimates of the reddening due to dust are essential for interpretation of the emission line ratios and the overall spectral energy distribution. The simplest approach is to examine flux ratios of forbidden lines that arise from the same upper energy level of a given ion. As long as the transitions are optically thin, the intrinsic line ratios are then simply equal to $A_1 \lambda_2 / A_2 \lambda_1$, where $\lambda_1$ and $A_1$ are respectively the wavelength and spontaneous decay rate for line 1, etc. Comparisons to measured ratios then provide estimates of the reddening (Osterbrock 1989). Among the line pairs that appear not to be blended with other features, we found that [FeII] $\lambda3175/\lambda5551$, [FeII] $\lambda3533/\lambda6355$ and [NiII] $\lambda4326/\lambda7256$ yield consistent results for both knots B and D – corresponding to $A_v \approx 2$ for a standard interstellar reddening curve (Osterbrock 1989). It is not clear that the reddening towards $\eta$ Car is “standard,” but we will use this result to make first-order corrections to other diagnostic line ratios below.

In the next section, we will show that the gas densities are probably above the critical densities of the various low-lying metastable levels of Fe$^+$ and Ni$^+$ that produce the forbidden lines. The levels should therefore be in collisional equilibrium, with populations determined by the (uncertain) gas temperature. In a forthcoming paper, we will use this result to simultaneously employ many [FeII] and [NiII] lines and derive both the reddening and temperature.

The direct stellar spectrum in our STIS-HST data set shows some broad forbidden lines that apparently form in the inner stellar wind and not the extended ejecta. Since the star and knots have similar observed brightness, the extinction toward the star must be much larger than toward the knots. We would like to measure their extinctions and reddenings separately. Unfortunately, the only useful pair of broad forbidden lines that appears to be free of blends, [NII] $\lambda3063/\lambda5755$, yields an unphysical result and so must be corrupted by blends after all.

3. Density

The STIS-HST spectra of knots B and D provide many forbidden line diagnostics of the density. All of them indicate densities at or near their critical limits for collisional deexcitation. For example, the ratios [SII] $\lambda6716/\lambda6731$ and [SII] $\lambda4069/\lambda6731$ imply densities of $n_e \geq 10^4$ and $\geq 10^6$ cm$^{-3}$, respectively, based on theoretical results in Osterbrock (1989) and Hamann (1994). The highest densities come from lines of [FeII] and [NiII], with reference to calculations by Bautista & Pradhan (1996). For example, the measured ratio [FeII] $\lambda7155/\lambda8617$ implies $n_e \geq 10^7$ cm$^{-2}$, while [NiII] $\lambda7412/\lambda7387$ and [NiII] $\lambda3439/\lambda3993$ indicate electron densities $n_e \geq 10^8$ cm$^{-2}$. There is, perhaps, a range of densities within the knots such that each of these lines forms near its critical density.
Not surprisingly, the measured ratio of broad [FeII] $\lambda$7155/$\lambda$8617 lines in the direct stellar spectrum also indicates $n_e \gtrsim 10^7$ cm$^{-2}$ in the stellar wind.

4. Temperature

The usual nebular diagnostics of temperature (Osterbrock 1989) are either too weak (for example [OIII]) or too sensitive to the density in this high-density environment (eg. [NII]).

5. Ionization

The STIS-HST spectra were obtained near the time of the periodic 5.5 yr “event,” which is known to correspond to a low ionization state in the nebular emission-lines (Damineli 1996 and this volume). Thus, as expected, the doubly ionized lines such as [OIII], [ArIII], and [SIII] are very weak or absent. Also weak or absent are narrow recombination lines of HI, HeI and HeII. The weakness of these lines, plus the great strength of singly ionized lines like FeII and other discussed above, suggests that knots are just partially ionized – that is, there is a significant amount of H$^0$ relative to H$^+$. Substantial partially ionized zones do not occur in normal low-density nebular environments that are photoionized by early type B stars. We will return to the significance of this point in §7 below. Here we note that the preponderance of H$^0$ is consistent with the detection of narrow absorption features in the HI Balmer lines (see Gull et al. this volume, also below). The location of the absorber with respect to the knots is unknown, but its small velocity shift and low velocity dispersion suggest an association with the dense equatorial ejecta.

6. HI Balmer Line Absorption

Balmer line absorption in the extended ejecta is interesting because it requires significant populations in the $n = 2$ level of HI, 10.2 eV above the ground state. If the local velocities are thermal and the gas temperature is $\sim$10,000 K, it is easy to show that optical depth $\tau \sim 1$ in H$\beta$ requires a column density of $N(n = 2) \gtrsim 10^{13}$ cm$^{-2}$ in the $n = 2$ level. If the local velocities are larger due to turbulence, the column density needed for $\tau \sim 1$ is also larger.

Significant populations in $n = 2$ might occur by collisions from $n = 1$ in an environment where Ly$\alpha$ is very optically thick. The $n = 2$ level can be “thermalized” if the following condition is met,

$$\frac{n_e q}{A \beta} \approx \frac{n_e \tau_o}{n_{cr}} \gtrsim 1$$

where $q$ is the downward collision rate coefficient, $\tau_o$ is the line center optical depth in Ly$\alpha$, $\beta \approx 1/\tau_o$ is the escape probability of Ly$\alpha$ photons, and $n_{cr} \approx A/q \approx 3 \times 10^{17}$ cm$^{-3}$ is the critical density for collisional deexcitation of the $n = 2$ level. If the product $n_e \tau_o$ is too small to satisfy this relation, collisions will be too infrequent to build up a significant $n = 2$ population. For densities
\[ n_e \lesssim 10^9 \text{ cm}^{-3} \], Equation 1 implies that the required optical depth is \[ \tau_o \gtrsim 3 \times 10^8 \] and the total HI column density must be \[ N(HI) \approx N(n = 1) \gtrsim 5 \times 10^{21} \text{ cm}^{-2} \] (again assuming thermal line widths).

The situation is actually more complicated because recombination into, and photoionization out of, \( n = 2 \) will also affect the level population. Furthermore, the 2s level of HI is metastable – depopulated by 2-photon decay but not by Lyα line radiation. The transition probability for 2-photon decay from 2s is just \( \sim 8 \text{ s}^{-1} \) compared to \( \sim 5 \times 10^8 \text{ s}^{-1} \) for Lyα out of 2p. Thus substantial 2s populations might occur without large optical depths in Lyα. On the other hand, collisional mixing among the \( I \) states at high densities will work to decrease the 2s population. We will present a more thorough study of this problem in a forthcoming paper.

7. FeII, Resonant Line Pumping and Partially-Ionized Gas

Several metal ions are known to be photo-excited in \( \eta \) Car by the absorption of HI Lyman line radiation. This resonant photoexcitation occurs via accidental wavelength coincidences. One of the most important cases involves Fe\(^+\), where Lyα photons are absorbed and electrons are “pumped” from lower metastable levels into highly excited states (see also contributions by Johansson, Zethson and Davidson in this volume). The subsequent cascades produce a unique and sometimes dramatic spectral signatures. This process might actually dominate the overall production of FeII flux from \( \eta \) Car and other astrophysical sources (Penston 1987). Measurements of primary FeII cascade lines show clearly that substantial Lyα pumping occurs in both the star and knots of \( \eta \) Car (also Johansson & Hamann 1993, Hamann et al. 1994). One of us (FH) has begun a collaboration with G. Ferland, K. Verner and D. Verner to numerically simulate the FeII emission from various environments. Resonant line pumping is important only in special circumstances, and we hope to use the pumped FeII lines as diagnostics of the local conditions.

We can already draw several conclusions without detailed simulations. First, the metastable Fe\(^+\) levels must be significantly populated and, therefore, the gas densities are probably above the critical densities of those levels, ie. \( n_e \gtrsim 10^6 \text{ cm}^{-3} \). This result is consistent with our density estimates above. Second, the local Lyα line width must be large because the transitions feeding some of the clearly pumped Fe\(^+\) levels do not have good wavelength coincidences with Lyα. In particular, the upper level of FeII \( \lambda 2508 \) is fed by a transition shifted \( \sim 640 \text{ km s}^{-1} \) from the Lyα central wavelength. This level is clearly pumped by Lyα, so we conclude that the Lyα line is at least \( 2 \times 640 = 1280 \text{ km s}^{-1} \) wide. Similarly, the fluorescent line FeII \( \lambda 9123 \) requires a Lyα line width of \( 2 \times 670 = 1340 \text{ km s}^{-1} \). Since the region is optically thick to Lyα radiation, the Lyα photons must be produced locally and the line width (in this otherwise low-velocity region) must be caused by the large optical depths. A simple scaling relation between the width and optical depth in Lyα (Elitzur & Ferland 1986) suggests that \( \tau_0 \gtrsim 2 \times 10^8 \) is needed to achieve the widths noted above (if the local Doppler velocities are roughly thermal and \( T \approx 10,000 \text{ K} \)). This optical depth corresponds to a column density of \( N(HI) \gtrsim 4 \times 10^{21} \text{ cm}^{-2} \), which is
surprisingly similar to our estimate from the Balmer line absorption (§6). This similarity is surely a coincidence, but it strengthens the case for large amounts of neutral hydrogen (§5). Given that the knots have diameters $<4 \times 10^{15}$ cm (based on angular diameters $<0.1''$ and a distance of 2300 pc to $\eta$ Car), we conclude that the space density in HI is $>10^6$ cm$^{-3}$.

Another interesting conclusion follows from the extensive work on FeII emission from quasars and active galactic nuclei (AGNs, eg. Kwan & Krolick 1981, Wills et al. 1985, Verner et al. 1998). The FeII lines do form in ionized (HII) regions, but rather in partially-ionized zones behind the nominal HII–HI recombination front. Such zones are relatively small (thin) around normal stellar HII regions because they are very optically thick to the ionizing Lyman continuum radiation. But AGNs can have extensive partially-ionized zones because 1) penetrating X-rays from the non-thermal continuum source heat the gas and maintain significant ionization levels, and 2) high gas densities can maintain substantial populations in the $n = 2$ level of hydrogen (see also §6) and thus allow photoionization by Balmer continuum radiation. The latter situation is also known to occur in the dense envelopes around luminous young stellar objects (Hamann & Persson 1989 and refs. therein).

The strong FeII emission, its pumping by Ly$\alpha$, and the Balmer line absorption (§6) all indicate that there are extensive partially-ionized zones associated with the knots and inner ejecta of $\eta$ Car. Further evidence for such a region comes from measured Ly$\beta$-pumped lines of OI and probably MgII in the $\eta$ Car knots (see also Hamann et al. 1994 and refs. therein), which requires optical depths in H$\alpha$ of at least 1000 (to keep Ly$\beta$ photons from “leaking” out via H$\alpha$, Grandi 1980). We are planning photoionization simulations, with J. Hillier and the collaborators mentioned above, that will use the overall emission-line spectra of the knots to constrain both the local physical conditions and the spectral energy distribution (SED) of the central source. This indirect study of the unobservable SED could be valuable for testing models of the stellar wind (Hillier this volume) and of the single versus binary nature of the central object (Damineli, Davidson this volume). In particular, the proposed companion star should be much hotter than the luminous primary, dominating the overall SED at short wavelengths. We will try to determine if such a hot component is needed to understand the nebular line spectrum.

8. Abundances

The many collisionally-excited forbidden and semi-forbidden (intercombination) emission lines from the $\eta$ Car knots provide numerous opportunities for abundance estimates. The theoretical flux ratio for any two collisionally-excited lines emitted from the same volume by idealized two-level atoms is,

\[
\frac{F_1}{F_2} = Q \frac{n_{\lambda_1}}{n_{\lambda_2}} \frac{\Omega_{\lambda_1} \lambda_2 g_{\lambda_2}}{\Omega_{\lambda_2} \lambda_1 g_{\lambda_1}} e^{-\frac{\Delta E_{12}}{kT}}
\]

(2)

where $Q$ is defined by,

\[
Q = \frac{1 + \frac{n_e}{n_{c\lambda_2} \beta_2}}{1 + \frac{n_e}{n_{c\lambda_1} \beta_1}}
\]

(3)
For each line 1 and 2, $F$ is the flux, $\lambda$ is the wavelength, $\Omega$ is the collision strength, $n_l$ and $g_l$ are the number density and statistical weight of the lower energy state, $\beta$ is the line escape probability ($0 \leq \beta \leq 1$) and $n_{cr}$ is the critical density. $T_e$ is the electron temperature and $\Delta E_{12} \equiv E_1 - E_2$ is the energy difference between the two upper states.

The factor $Q$ in Equation 2 corrects for possible photon trapping and collisional deexcitation. If the densities are low such that $n_e \ll n_{cr}\beta$ for both lines, then collisional deexcitation is not important and $Q \approx 1$. If, on the other hand, the densities are high or the line photons are significantly trapped such that $n_e \gg n_{cr}\beta$, then collisional deexcitation is important and $Q \approx n_{cr}\beta_1/n_{cr}\beta_2$. If the line photons escape freely ($\beta_1 \approx \beta_2 \approx 1$) in the high density, the correction factor limit is simply $Q \approx n_{cr}\beta_1/n_{cr}\beta_2$. The collision strengths ultimately cancel out of Equation 2 in this limit because the levels are populated according to Boltzman statistics. In that case we have,

$$\frac{F_1}{F_2} = \frac{A_1 \lambda_2 n_1 g_{u1}}{A_2 \lambda_1 n_2 g_{u2}} \frac{G_1}{G_2} e^{-\Delta E_{12}/kT_e} \quad (4)$$

where $g_{u1}$ and $g_{u2}$ are the statistical weights of the upper states, and $G_1$ and $G_2$ are the partition functions and $n_1$ and $n_2$ are the space densities of the ions 1 and 2. This expression can be applied to excited-state lines and multi-level atoms without correction (as long as the densities are high and $\beta_1 \approx \beta_2 \approx 1$).

We can derive abundances from Equations 2 or 4 by noting that,

$$\frac{n_{11}}{n_{12}} \approx \frac{n_1}{n_2} = \frac{f(X^1_1)}{f(X^2_2)} \left(\frac{X_1}{X_2}\right) \quad (5)$$

where $f(X^i_j)$ is the fraction of element $X_1$ in ion stage $X^i_1$, etc., and $X_1/X_2$ is the abundance ratio by number. We must choose line pairs that 1) are emitted from the same or nearly the same region, 2) require small ionization corrections, and 3) have similar excitation energies so that the temperature-sensitive exponential factors are small. One strategy is to consider summed combinations of lines of the same element to average over these uncertainties.

Abundance studies of $\eta$ Car will help quantify the enrichment of the interstellar medium, test models of the stellar evolution and nucleosynthesis, and probe the existence of dust within various ejecta via depletion signatures. For example, we are interested in the relative CNO abundances to gauge the amount of CNO processing of the gas. (The nuclear reaction rates are such that, in equilibrium, CNO burning of H into He converts most of the C and O into N.) Several UV intercombination lines are particularly valuable for this purpose, e.g. CIII] $\lambda$1909, SiIII] $\lambda$1892, NIII] $\lambda$1749 and OIII] $\lambda$1664. Unfortunately, these and other lines from doubly-ionized species were weak in our on-event data (§5). However, they are present in our spectra of the knots obtained in 1996 using the HST Faint Object Spectrograph (FOS, Davidson et al. 1997). We find that N/C is roughly 25–140 times solar and N/Si is 12–63 times solar, depending on the density. N/O is at least 60 times solar for any density. From the new STIS-HST data, we similarly estimate Fe/O of 90–180 times solar based on [FeII] $\lambda$8617/[OII] $\lambda$6300 and [FeII] $\lambda$7155/[OII] $\lambda$6300. These results
imply that the knot gas has been extensively CNO processed, consistent with previous findings for the outer lobes (Davidson et al. 1986, and Dufour et al. this volume). We will examine the abundances in more detail in our forthcoming paper.

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