Unique Spectroscopic Problems Related to Eta Carinae

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Abstract. The wind and ejecta of η Car contain a number of spectroscopic puzzles, differing in their nature but all located within a region several arcsec across. Moreover, the HST/STIS instrument has acquired a very large amount of data related to these questions. Therefore this is an almost uniquely promising object, or field, for theoretical spectroscopic investigation. In this respect, it has not yet received the attention it deserves.

1. Extraordinary Data for Extraordinary Problems

Eta Carinae plays a special role at this meeting for two reasons. First, its wind and ejecta present a variety of unfamiliar, relatively unexplored spectroscopic puzzles. These are interesting with regard to excitation processes and radiative transfer, but they also matter for other branches of astrophysics. (As I’ve often remarked, the tag “η Car” now connotes a substantial broad topic, not merely a particular object.) Secondly, impelled by a combination of circumstances, we have used the Space Telescope Imaging Spectrograph (HST/STIS) to obtain a huge data set, extensive in wavelength and spatial coverage and the most intensive HST spectroscopy yet attained on any object. This data set is a unique astrophysical resource.

For general information on η Carinae, and references where none is cited here, see Davidson and Humphreys (1997). Developments in 1996–98 were reported by many authors in Morse et al. (1999), and a more recent overview is summarized in Davidson (2000). Eta Car proper is the most luminous evolved star, and site of the biggest non-terminal stellar eruption, that we know much about. Its unique opaque wind has a spectrum of broad emission lines, some of them with P Cyg absorption components. A fraction of an arcsec (several hundred AU) away, the dense “Weigelt blobs” of ejecta produce many hundreds of intense, narrow emission lines unlike the spectrum of any other known object. Many of these are radiatively excited. Farther out, equatorial ejecta produce very different emission spectra, spatially dependent and again unlike anything else we know. At scales of a few arcsec we see the notorious dusty bipolar “Homunculus nebula” ejected about 160 years ago, with its combination of reflected and intrinsically emitted lines, differing from the spectra mentioned above. Fainter emission can be seen outside the Homunculus. Altogether, these distinct classes of spectra, all located close together, provide test cases for the excitation physics discussed at this meeting. No one has yet explained them
quantitatively. Meanwhile the same emission lines provide essential clues to the nature of the star and the dynamics of its massive outflows.

Moreover, the situation is almost perfectly suited to the HST/STIS. We need spatial resolution of about 0.1 arcsec in order to study intricately position-dependent spectra, a much more complex task than merely separating two objects 0.1" apart. Good spectral resolution is also required, since most of the emission lines are narrow and closely spaced. Equally relevant, the central star and inner ejecta are brighter than most other current “frontier” astrophysical objects, so we can attain the HST’s best feasible resolution with small amounts of spacecraft time. If one were to design an instrument expressly devoted to Eta’s most urgent problems, the result would be much like the STIS. A slightly different assertion is that η Car has been the best example for demonstrating the capabilities of the STIS, which in my opinion is the most effective astronomical instrument ever built. In any case it acquires data on η Car at a prodigious rate. A modest number of HST orbits have produced more information than we can soon deal with; frankly, this long-term program needs help from more analysts.

— And the story has another dimension: spectra of the stellar wind and ejecta vary in a systematic but puzzling way! “Spectroscopic events,” with temporary fading of doubly-ionized species in the ejecta, recur every 5.5 years. This periodicity may represent the eccentric orbit of an unseen companion star, or it may be a thermal/rotational/magnetic cycle in a single star. Almost all authors have favored binary scenarios, but – contrary to some assertions – the evidence is weak, the most definite predictions have failed, and no successful quantitative model has yet been adduced. Therefore single-star scenarios are still in the running even though they haven’t gotten much attention. (See many papers in Morse et al. 1999, and Davidson 2000.) This review does not directly concern the physical origin of the 5.5-year period and the binary versus single-star question; variability is pertinent here because it gives additional clues to the excitation physics problems. I should also acknowledge that the 5.5-year cycle has strongly justified continuing observations with HST/STIS. Without repeated observations our coverage of the Homunculus would have been less.

In the following I shall briefly recount a few extraordinary puzzles of ionic excitation and radiative transfer in Eta’s wind and ejecta; this emphasis differs from most recent discussions of the Homunculus which have concentrated, instead, on doppler velocities and gas-dynamic problems. Others at this meeting (e.g. Johansson, Hillier, Zethson) will give more specific details, but I’ll attempt a broad (albeit superficial?) overview including aspects that they may omit. Positions in the Homunculus will be specified with reference to Figure 1; e.g., the “northwest fan” structure in this HST/WFPC2 image is located around 2′′N, 2′′W, measured from the central star.

2. The Stellar Wind

The star itself is hidden in its dense, opaque wind. This fact was recognized earlier (Davidson et al. 1995), but the old HST/FOS observations had poor spectral resolution and didn’t include wavelengths longer than 5500 Å. We have obtained excellent STIS data on five occasions so far: 1998.0, 1998.2, 1998.9,
1999.1, and 2000.2. The first and third of them sampled only narrow wavelength intervals, but the others included the entire STIS/CCD range 1700–10000 Å. The 1998.0 observations occurred a few weeks after the onset of the “spectroscopic event” that Damineli (1996) had predicted. The wind spectrum contains, of course, extremely bright hydrogen lines and hundreds of emission features of Fe II and other species. During the event the normally weak He I and other high-excitation emission almost disappeared, ultraviolet Fe II absorption made the object practically dark in many wavelength intervals between 2200 and 2800 Å, and the hydrogen Balmer lines developed P Cygni absorption that they don’t normally have. However the net equivalent widths of hydrogen and Fe II emission at visual and far-red wavelengths scarcely changed. By March 1998 the spectrum had begun to return to its normal state. We think that the 1999.1 observations represent more or less the “normal” spectrum, although various small changes occurred between then and 2000.2. This is not a suitable place to review possible interpretations of the event; let me say merely that (1) the general ionization or excitation level decreased appreciably for a few weeks; (2) we suppose that this was triggered either by a periodic internal thermal/rotational/magnetic upheaval or else by a close passage of an undetected companion star; (3) no quantitative model for the event has been proposed yet; and (4) the STIS data provide a large fraction of the best available clues.

Hillier (this volume) has developed a wind model that reproduces many of the features in the 1998.2 data. The mass-loss rate is about $10^{-3} \ M_\odot \ yr^{-1}$ as expected earlier, and inhomogeneities in the wind are important. The model parameters are refreshingly extreme compared to other stellar winds, and observable Fe II and even [Fe II] emission originate far out as 200 AU ($3 \times 10^{15}$

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Figure 2. $\text{H}\alpha$ and He I $\lambda 6680$ profiles in the stellar wind, observed with STIS on three occasions. Each half of this figure shows fluxes relative to the varying continuum. In the left half, the $\text{H}\alpha$ flux is so strong that the underlying continuum is barely above each zero-level line. Helium emission, on the other hand, is weak and the zero flux level at 6680 Å is not shown here.

cm). In a case like this on the ragged edge of modeling experience, some of the most valuable clues are found in those aspects where a model fails rather than succeeds. Thus it is important to note that Hillier’s model spectrum resembles that of $\eta$ Car in an unusual state following the 1997–98 event. For example, the Balmer lines still had strong P Cyg absorption features then, which are not seen in the “normal” state observed at later times 1998.9, 1999.1, and 2000.2. Moreover, P Cyg absorption deepened in the Paschen lines as the Balmer absorption faded! My impression is that the “normal” spectrum (seen at least 80 percent of the time) is harder to model than the post-event spectrum which persists for only a few months in the 5.5-year cycle. Also note that the model’s ultraviolet spectrum, $\lambda < 3000$ Å, does not match the observed spectrum. Most aficionados of $\eta$ Car will not be surprised if spherical symmetry is a poor approximation for this object; rotation very likely causes low wind speeds near the equator, and if a hot companion star is present then even axial symmetry is questionable. Unfortunately (as Hillier has often remarked), too many adjustable parameters arise when we abandon spherical symmetry. On the other hand, some non-routine observables may help a little as hinted below.

Surely the line profiles contain clues, especially since they vary with time. Figure 2 shows the very bright $\text{H}\alpha$ and rather weak He I $\lambda 6680$ emission on three occasions observed with STIS. Several details in the $\text{H}\alpha$ profiles are worth noting. First, the conspicuous – and variable! – absorption near $-140$ km s$^{-1}$ does not occur in the stellar wind, and I’ll mention it again later. The $\text{H}\alpha$ profiles may appear smoothed in the figure, but they haven’t been; the data are quite good even in the far wings of the line. Indeed, although not clearly visible
here, Eta's Balmer line wings beyond ± 600 km s⁻¹ are beautiful examples of scattering by free electrons. P Cyg absorption around -500 km s⁻¹ became quite strong during the spectroscopic event (the 1998.0 and 1998.2 curves) but nearly disappeared later – though a weak depression remains visible near -400, not -500 km s⁻¹. The long-wavelength side of Hα has wriggled continuously, and in 1998.9 (not shown here) it had a pronounced bulge around +100 or +200 km s⁻¹. Need I say that we don’t yet understand all these effects?

The He I profile in Fig. 2 is equally suggestive. High-excitation features weakened during the spectroscopic event, and I suspect that helium emission would have been undetectable if the first STIS observations had been done a few weeks earlier. He I presents us with an interpretational dilemma, related to the question of whether the changes are induced by a companion star. In a conventional model for a wind with this density and luminosity, helium lines originate relatively deep within the wind; and the 1998.2 profile seemed consistent with this idea since its P Cyg absorption occurred around -300 km s⁻¹ rather than -500 km s⁻¹ as seen in the Balmer lines. (Presumably the wind was being further accelerated outside the helium emission region.) However, the emission profile seen in 1999, with its sloping flat top, may suggest that a hot companion star ionized some helium in the outer parts of the wind, mostly on one side. But this possibility has at least one serious quantitative difficulty, namely that the hypothetical second star must produce an unusual flux of helium-ionizing photons; while the lower-velocity P Cyg absorption also needs explanation. The profile had changed again by 2000.2. In summary, we should devote more thought to the evolving, somewhat tantalizing helium lines.

Aspects of the stellar wind that I’ve just mentioned are relevant to this meeting because they concern radiative transfer and, perhaps, excitation processes. One more detail deserves mention because it is so unusual. The stellar wind spectrum is reflected by dust in the Homunculus at locations such as, e.g., 5°N, 5°W and 4°S, 4°E in Figure 1. The P Cyg absorption in Hα there differs from that seen when we observe the star directly. Light travel time delays (two weeks for the southeast lobe, a few months for the northwest lobe) do not alter this statement. Most likely the spectrum of the wind depends on viewing direction. This idea is not surprising for η Car, but if true it means that we can “see” this extra-solar object, in a spectroscopic sense, from several different directions.

3. The Weigelt Blobs

About 15 years ago Gerd Weigelt’s speckle-interferometry group resolved η Car as several objects. Today the brightest of them is known to be the star while the others, within 0.3° to the northwest, are dense slow-moving knots of ejecta, near the equatorial plane. (They’re too close together to discern in Fig. 1.) If one of these blobs were somehow isolated in space without changing its excitation, it would be famous – more luminous than a bright planetary nebula, less than 300 AU in size (< 5×15 cm), and having a spectrum unique among known astronomical objects. Each blob emits many hundreds of narrow, intense lines of Fe II, [Fe II], and similar species, many of them excited by the fluorescent processes described by Johansson and Hamann (1993). Gas densities there greatly exceed
Figure 3. Ultraviolet spectra of AE Andromedae in M31, and a region 0.5" across centered on η Car. These are the only two objects where the Fe II lines near λ2507 are known to be extremely intense. The data shown here were obtained about 8 years ago with the HST’s Faint Object Spectrograph (FOS), whose resolution was greatly inferior to that of the STIS.

10^7 atoms per cm^3 and may be of the order of 10^{10} cm^{-3}, almost comparable to the broad-line regions of AGN’s. Considerable fractions of H^0 exist in the Fe II emission zones. Hamann et al (1999) briefly discussed physical conditions in this gas based on various emission-line diagnostics. Johansson, Letokhov, and Zethson will comment on excitation processes in the Weigelt blobs (this volume), but let me offer a few pertinent remarks.

First, consider the amazingly intense Fe II lines near 2507 Å. These are a pair of bright lines with a satellite pair that are faint, in fact mysteriously faint compared to straightforward predictions. The line ratios induced Johansson et al (1996, 1998) to propose stimulated emission (a natural dichromatic UV laser!) as the only evident explanation. That idea is quantitatively implausible, as Sveeneric agrees – the expected photon occupancy ratios are too small by about seven orders of magnitude – but was a desperate recourse that indicates how strange the line intensities and ratios seem to be. Letokhov (this volume) has lately been developing alternative explanations. I think this problem is fascinating as a novel warning that unexpected phenomena may still be found in nebular spectra, and also because it has never arisen in other nebulae. We know only one other object with very intense Fe II λ2507 emission, the very luminous star AE Andromedae in the galaxy M31 (Fig. 3). The violet-to-red spectrum of this object, observed with ground-based telescopes, is strikingly like that of η Car seen at low spatial resolution.

According to Johansson et al. (1998), the λ2507 emission is probably pumped by Lyman α photons, either from the stellar wind or generated locally. However, the resonant wavelength is several hundred km s^{-1} from the Lo
center, so this line must be quite wide which requires large optical depths if it’s produced in the blobs themselves. (See Hamann et al. 1999.) Is there something special about Eta’s $\text{L}\alpha$ radiation field, or does this type of pumping occur merely because some relevant gas column densities are large? The peculiar $-140 \text{ km s}^{-1}$ Balmer absorption shown in Fig. 2 occurs in diffuse gas well separated from the star and from the Weigelt blobs; it, too, presumably requires $\text{L}\alpha$ photons to keep enough hydrogen atoms in the $n = 2$ level. Why, specifically, do $\eta$ Carinae and AE Andromedae excite Fe II $\lambda 2507$ so much brighter than seen anywhere else? Indeed the same question may apply to other Fe II lines as well. Does the explanation involve some peculiarity in the dense stellar winds of these stars, or in ejected blobs farther out? Another clue: $\lambda 2507$ and some other radiatively excited Fe II transitions weakened considerably during the 1997-98 spectroscopic event, while normal collisionally excited [Fe II] scarcely changed. Therefore Fe II fluorescence is correlated, somehow, with the doubly ionized species mentioned below. HST/STIS data on AE Andromedae would be valuable regarding the Fe II line ratios and other details, but unfortunately we have not yet succeeded in getting approval for such observations.

One sign of a spectroscopic event of $\eta$ Car is the disappearance of [Ne III], [Fe III], N III], and He I emission, the highest stages of ionization seen near this object. My own tentative guess is that these species result from photoionization (including He$^+$ whose recombination accounts for the He I lines); excitation in shocks seems less likely because it would require either terrific local mass flows at low speeds or else some indirect process converting energy from fast X-ray shocks, in order to produce the observed intensities. But a dense spherical wind like that calculated by Hillier cannot produce enough photons above 25 eV; we need the services of either a hot companion star, or peculiar hot spots in the polar regions of $\eta$ Car proper, or some other unconventional source hotter than 30000 K. Anyway, the Weigelt blobs normally produce these doubly-ionized emission lines. This should be yet another clue to what is going on, but no one has attempted a proper analysis yet. Only a few people – Johansson, Hamann, myself, perhaps one or two others – have even considered the problem of spectral excitation in the Weigelt knots as yet; but it is a good multi-faceted puzzle that deserves much more attention. The same is also true of the less dense regions mentioned below.

### 4. The Homunculus lobes, and equatorial ejecta

The UV-to-near-IR spectrum of each lobe (e.g., around 5′′N, 5′′W and 5′′S, 5′′E in Fig. 1) is primarily the broad-line spectrum of the stellar wind, reflected by dust grains. Locally emitted narrow emission lines do occur, [Fe II] and the other usual suspects. I don’t have much to say about them except that no proper model for the spectrum has been attempted.

The equatorial debris seem more interesting in a variety of respects. Velocity trends allow us to clearly distinguish narrow emission lines produced near the equatorial midplane of the Homunculus from those originating in the northwest lobe. In some recent data we’ve noticed that [Ni II] $\lambda 7380$, for instance, is relatively more prominent in the equatorial gas. Also, the equatorial region
Figure 4. Spectrum observed with the HST/FOS (not STIS) in equatorial debris located near 0.9°N, 0.9°W in Fig. 1. Farther out the spectrum is similar though less extreme.

is notably bright in the near ultraviolet. Fig. 4 shows the spectrum about 1.3″ northwest of the star (see Fig. 1). The underlying continuum there is weak and we see a dense forest of narrow lines; see Zethson et al. (1999). I'm impressed by the wonderfully bright bunch of Fe II lines massed together near 2750 Å. In general, radiative excitation seems to be working more effectively in the equatorial debris than it does in the lobes. But shouldn't this surprise us a little? Since this stuff is all close to a plane, while most of Eta's ejecta contain abundant dust, we might naively have expected the UV radiation field from the star to be inhibited by dust more in the equatorial ejecta than in the lobes. Mass flow isn't a promising energy source with the observed velocities and rates. Therefore I sense an interesting theoretical problem here, with some scope for paradox.

Torgil Zethson identified two [Sr II] lines about 1.5″ northwest of the star, close to but not the same as the location mentioned above; later we verified that the more familiar permitted Sr II lines near 4100 Å are also present. Figure 5 seems to indicate a novel situation. First, so far as we know these [Sr II] lines have never been seen in any other nebular object, but here they are unmistakable. Second, they are accompanied by [Fe I] emission — un-ionized atoms, not Fe⁺ — along with the less surprising [Ti II], etc. Third, we cannot detect associated Hα emission at the same velocity. Fourth, despite considerable effort Torgil has not been able to identify a sharp feature near 7000 Å. The region with this peculiar spectrum is almost 1″ across, diffuse and not a compact knot.

The ratio between blue permitted Sr II emission and red forbidden [Sr II] suggests that these are radiatively, not collisionally excited. The gas in question may be rather cool and only mildly ionized. But Sr⁺ does not seem a very promising candidate for fluorescence, since it's basically a one-electron ion; it doesn't have huge numbers of levels as Fe⁺ does. It should be analogous to Ca II, etc. I'm surprised if the star provides enough radiation within the two narrow permitted Sr II lines to explain the observed [Sr II] directly by alternative decay. Meanwhile (caution: the following statement may be a red herring!) strontium occasionally appears in the lore of astrophysics as a neutron-capture
isotope, $^{88}\text{Sr}$. Processing of that sort has no place in conventional views of $\eta$ Car, whose ejecta, remember, are famously CNO-processed, indicating only hydrogen burning. Fig. 5 shows an unidentified line at 7000 Å; but so do certain peculiar luminous red supergiant stars whose spectra contain emission of other elements as bizarre as strontium (R.M. Humphreys, private comm.). I'm almost tempted to speculate about nuclear processing by high energy particles, produced by magnetic/convective "activity" on a stellar surface! But that would take us far afield, and the underlying point here is that equatorial ejecta of $\eta$ Car provide us with several different examples of unfamiliar, almost unique spectroscopic excitation. Some other interesting questions haven't even been mentioned here. This topic needs far more work!

A parting comment: the HST/STIS, though the most effective instrument for studying $\eta$ Car, does not supplant ground-based observations of this object. We obviously cannot obtain enough HST orbits to monitor Eta's behavior with adequate sampling in either time or space. Some of the new instruments using adaptive optics may have spatial resolutions of, say, 0.2", adequate for most studies of the Homunculus. Such equipment can obtain broad spatial and spectral coverage (i.e., spectroscopic mapping) much more cheaply than the HST can do -- except, of course, in the UV. Moreover, smaller telescopes can still play a very productive role in following the object's behavior on time scales of months, weeks, or days -- provided that such modest instruments continue to be available!

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Discussion

Viotti: Concerning the 2750A feature observed in DISK1, DISK2 spectra, simple computations (e.g. Viotti, MNRAS, 1976) show that this is one of the strongest features of the FeII spectrum for an optically thin source. In fact, it can be used to identify FeII emitting stars in distant galaxies, as well as in AGNs. In Eta Car and its surroundings, self-absorption effects play a crucial role. In some regions the line opacity is so large that the high-excitation, optically thin lines become prominent in addition to the fluorescence lines.
Davidson: Good. Spectra in the equatorial gas are interestingly different from emission in the Homunculus lobes. By the way, we should clarify that the 2750 Å feature is a set of emission lines, not just one.

Najarro: If I understand correctly your argument, the mass of the companion was based on its \(v(\text{escape velocity})\) as inferred from x-rays, not requiring much UV flux and does not need much evolution to break it down. However, if you had used the derived \(M\) for the companion as a constraint, you may very well have ended up with a much higher mass. I guess that \(v(\text{wind}) \approx 2000\) and \(M \approx 10^{-5}\) are in a sense incompatible with an unevolved object (except maybe an O3f star, but this would violate the UV argument.)

Davidson: To some extent, you are right. I forgot to mention the hypothetical secondary mass-loss rate. In some proposed models for the x-rays, the primary rate is said to be \(\dot{M} \approx 10^{-4}\) (suspiciously low) while the secondary is said to be losing mass at a rate of \(\dot{M} \approx 10^{-5}\) (suspiciously high for a normal star). My own view is that a good model for the x-rays is not as obvious as enthusiasts often imply.

Walborn: There is an observed class of massive binaries with invisible companions that have masses comparable to those of the primaries, e.g. Plaskett’s star, UW CMa, and HD163181. Some of them are nitrogen-rich and display colliding- wind phenomena. They are interpreted as heavy mass-transfer systems in which the companions have become enshrouded in dense shells or disks. (Examples at the somewhat lower masses are Beta Lyrae and Epsilon Aurigae). Such a situation in Eta Car should suppress the optical light and ionizing radiation from a massive companion.

Davidson: I think we should begin by trying to invent the simplest possible scenario. This would invoke a hot, less massive secondary star. To help excite the outer layers of the primary wind and the Weigelt blobs, we try to get UV light from that companion – but an opaque shroud would seem to defeat that intent. And the primary stellar wind is obviously not hidden!

Remember too that we need a remarkably fast wind, well above 2000 km/s, somewhere in the system. This presumably requires either a high escape velocity or else an unfamiliar acceleration mechanism. A noticeably evolved secondary star isn’t expected to have a fast enough wind, unless it’s a highly evolved Wolf-Rayet-like object, which, however, would probably show itself by making special broad emission lines while also complicating the combined evolution story. Therefore, the easiest idea to begin with, the most obvious arrangement, invokes a companion star whose mass is perhaps 30 or 40 solar masses but not much more (since it’s relatively unevolved). Admittedly a mass ratio of 4:1 is larger than usual for a binary system, but it does seem the simplest working hypothesis in other respects. If something more rococo is needed, we’ll learn that in due course.
Is Eta Carinae This Way or That?