

The origin of Fe II and [Fe II] emission lines in the BD Blobs of Eta Carinae

E. M. Verner

Catholic University of America and NASA/Goddard Space Flight Center, Greenbelt MD 20771

T. R. Gull

Laboratory of Astronomy and Space Science, NASA/Goddard Space Flight Center, Greenbelt MD 20771

F. Bruhweiler

Catholic University of America NASA/Goddard Space Flight Center, Greenbelt MD 20771

S. Johansson

Dept. of Physics, Lund University, PO Box 118, 22100 Lund, Sweden

K. Ishibashi

Massachusetts Institute of Technology, Center for Space Research, 77 Massachusetts Ave. NE80-6011 Cambridge, MA 02139

K. Davidson

Department of Astronomy, University of Minnesota, Minneapolis, MN 55455

Abstract. We present numerical simulations that reproduce the salient features of the amazingly strong [Fe II] and Fe II emission spectra in the B&D Weigelt Blobs of Eta Carinae. For our studies we have used spectra obtained during the 1998 epoch observations with the Hubble Space Telescope (HST). The spectrum of the B&D Weigelt Blobs dominates in [Fe II] and Fe II emission lines. We have compared our measurements of the strongest (≥ 200) [Fe II] and Fe II lines and blends in the spectrum with theoretical predictions. Our predictions are based on non-LTE modeling of the Fe II atom. We have investigated the dependence of the spectrum on electron density, pumping by the blackbody-like stellar continuum, and intense Ly α -emission. Comparison between the model and observations reveals details of the radiation field. Pumping by the blackbody-like stellar radiation field from Eta Carinae explains the numerous strong [Fe II] and Fe II lines in the range of 4000 - 6500Å. The strongest Fe II lines in a range of 8000 – 10000Å are pumped by intense Ly α radiation.

1. INTRODUCTION

In 1986, the object known as Eta Carinae was resolved by speckle interferometry into four components (Weigelt & Ebersberger, 1986). Today we name them the Weigelt components A, B, C, and D. The bright component A is due to the central star, while B through D are bright gaseous condensations. The size of the Weigelt Blobs B & D (thereafter BD) are about that of our Solar System (Davidson and Humphreys 1997).

More detailed spectra of the central source, Eta Carinae and the BD Blobs have been obtained with the Space Telescope Imaging Spectrograph (STIS/HST) (e.g. Gull et al. 1999). The angular distance from the BD Blobs to the central stellar source is $\sim 0.1''$. Thus, it is large enough to be spatially resolved in STIS/HST long-slit spectra.

These STIS data sets span 1640-10400 Å spectrum range with most of the strong [Fe II] and Fe II lines found from 4000 to 10000 Å. Moreover, since there is no Fe I or Fe III emission in the spectrum, the iron must be almost entirely in the form Fe⁺.

Using the unique spatial and wavelength resolution capabilities of HST/STIS, we have performed a detailed study of the Fe II spectrum of the BD knots. We present the first

sophisticated numerical model of Fe II emission as a part of fully self-consistent photoionization plasma calculations.

2. THE OBSERVED FE II SPECTRUM

We have analyzed the highest quality HST/STIS spectra of the compact BD ejecta of the Eta Carinae recorded March 19, 1998 during the 1998 broad spectroscopic minimum (Gull et al. 1999). The spectra were taken with the STIS 52" \times 0.1" aperture oriented at a position angle, $P.A. = -27.9^\circ$. Spectral coverage is complete from 1640 Å to 10600 Å using ~ 30 grating settings with the CCD and G230MB, G430M, and G750M gratings. The spectral resolving power of the CCD is $R = \lambda/\Delta\lambda \sim 5,000$ to 10,000. The spatial sampling is 0.0507" for the STIS/CCD, which corresponds to $\sim 0.10''$ at 6500 Å and broadens to $\sim 0.14''$ at 10000 Å. While the data resolve the B and D Blobs up to 5000 Å, we cannot easily separate the individual spectrum of B from D at longer wavelength as they are $\sim 0.1''$ apart. Therefore, we have extracted a single spectrum for 0.095" to 0.40" offset from Eta Carinae A.

Data reduction and analysis were performed using the IDL CALSTIS software package (Lindler 1999). It was necessary to disentangle spectra of objects with small angular separation. Thus, the standard STScI pipeline software products were inadequate. The CALSTIS tools available at GSFC/NASA were used to correct for the temporal variations of the optical elements and to linearize the spectral dispersion.

At wavelengths below 3500 Å, both the first order and echelle spectral modes of the STIS (Walborn 2002) demonstrate the presence of complex circumstellar and interstellar absorption along the line-of-sight to the Weigelt BD Blobs.

3. FE II LINE IDENTIFICATIONS AND MEASUREMENTS

Preliminary spectroscopic line identification suggested that most of lines/blends in BD Blobs are due to singly ionized iron (Zethson 2001). The strongest [Fe II] and Fe II lines are the most prominent candidates to reveal the physical conditions in the gas. Consequently, we have limited the measurements to lines with high signal-to-noise ratio. Our final line identifications are heavily influenced by the results of the model calculations.

Using the energy level data from Johansson (2002, private communication) we have identified the relevant Fe II and [Fe II] transitions in the 1998 HST spectra. We have adopted atomic data (Quinet et al. 1996; Zhang & Pradhan 1995; Bautista et al. 1996; Kurucz 1981; Nahar 1995; and Fuhr 1988) in our modeling. We have compiled a list of strongest Fe II and [Fe II] lines that are expected to appear in the spectrum of the BD Blobs. Based upon this list, we identified more than 200 strong Fe II and [Fe II] lines. For non-blended Fe II lines the heliocentric velocity range is $v_{\odot} = -44 \pm 4 \text{ km s}^{-1}$. A number of the observed emission features have several possible identifications due to uncertainties in atomic data.

Since we found no appropriate Fe II transitions to derive an extinction correction, we used the flux ratios of [S II] $\lambda\lambda 4069, 4079, \text{ and } 10288$. These lines all arise from the same upper level and can provide reasonable extinction estimates. The observed flux ratio of these lines indicates that they have low extinction. From the measured [S II] intensities, we derived the corrected intrinsic intensities (I_{λ}) for other lines $I_{\lambda} = k_{\lambda} \times I_{\text{obs}}$, where $k_{\lambda} = 8.3e10^{-5} \times \lambda + 0.63$.

The measured FWHM of the observed [Fe II] and Fe II lines are in a range from 30 to 158 km s^{-1} . For most of the single lines the FWHM is $50 \pm 10 \text{ km s}^{-1}$. Lines with larger FWHM

are typically blends. Blends are common due to the richness of the Fe II ionic spectrum as well as that of other ions.

4. BASIC PARAMETERS FOR THE MODELING

We need to define the initial parameters for the modeling. As a first step we have searched for the traditional nebular line diagnostics in the spectrum. The FWHM of [SII] λ 6731 is twice large of that [S II] λ 6716. That means the [S II] λ 6731 line must be a blend. The [N II] $\lambda\lambda$ 3063/5755 line ratio is not reliable due to large UV continuum uncertainties. There is no [O II] emission, and the [O I] line at λ 6300 is very weak, while the [O I] λ 6363 is not detected. Also, no carbon lines are identified. We find none of the normal emission line diagnostics are reliable indicator. Since Fe II and [FeII] lines dominate the spectrum of the BD Blobs, we cannot avoid them in our modeling. Moreover, failure to use them will certainly lead to the wrong conclusions. Intensities of the strongest and weakest Fe II and [Fe II] lines provide initial clues to the dominant excitation mechanisms and to the range of the electron densities in the Fe⁺-emitting plasma. Specifically, the simultaneous presence of strong permitted and forbidden Fe II lines suggests that the electron density range is between $10^4 - 10^7 \text{ cm}^{-3}$ (Verner et al. 2000).

The range of physical parameters for numerical modeling is defined using the analysis of Davidson & Humphreys (1997), Davidson (1999), and Hillier et al. (2001). Based upon these works, we assume the total luminosity of central star is $\sim 10^{40} \text{ ergs s}^{-1}$ and its effective blackbody temperature is in the range $T_{\text{bb}} = (1 - 3) \times 10^4 \text{ K}$. The distance from the central star (ionizing source) to the BD Blobs is taken to be $R_{\text{BD}} = 10^{16} \text{ cm}$. The BD Blobs have estimated particle densities from 10^5 cm^{-3} to 10^{10} cm^{-3} .

5. WHAT DO WE KNOW FROM FE II EMISSION ANALYSIS?

The BD Blobs spectrum of Eta Carinae is uniquely rich in Fe II and [Fe II] lines. The Fe II studies reveal details of physical conditions in the emitting region, and indicate shortcomings in the atomic data for Fe⁺ ion.

We conclude that Fe II and [Fe II] lines in BD Blobs spectrum are due to the dominant excitation mechanisms (see also Figure 1):

- 1) Pumping by the blackbody-like stellar radiation field from the central source of Eta Carinae produces the strong and rich spectrum in 4000 – 6500 Å range. Most of observable [Fe II] and Fe II lines have accurate A-values (Quenet 1996). These lines are in a good agreement with model predictions.
- 2) Primary cascades after Ly α fluorescence is responsible for 24 strong Fe II lines in 8000 – 10000 Å range and in particular Fe II $\lambda\lambda$ 2507, 2509 in the BD Blobs. Secondary cascades have much weaker effects. However, they contribute to the strengths of many other Fe II emission lines. We have postulated a large Ly α flux along with a broad emission profile to explain the observed Fe II primary cascades. In our future work we will study Ly α pumping in greater details. The Fe II level mixing, the number Fe II channels involved in excitation, the Ly α intensity as well as profile width and shape are the most important unknown factors.

- 3) Collisional excitation dominates in the formation of strong [Fe II] lines in the 7000 – 9000 Å range. For $n_e = 10^5$ to 10^7 cm⁻³, the lowest levels of Fe⁺ can be populated by collisions. The strength of the [Fe II] λ 7156 is systematically underpredicted for a constant density model. It is not clear if its intensity is due to lower density component (B or D), uncertainties in atomic data, or geometric effects. Small collisional strengths or an overlooked excitation route might also affect the predicted intensity.

Figure 1 shows Fe II and [Fe II] spectra predicted at different excitation conditions. Collisional excitation and continuum pumping are responsible for the origin lines below 2eV (e.g. 7156Å and 8619 Å). Lines below 6eV are pumped by continuum (e.g. 5020 Å and 6458 Å). Ly α -pumping results the Fe II primary cascades observed in UV (e.g. 2507 Å and 2509 Å) and near IR (e.g. 9178 Å and 9199 Å).

We have used the Fe II spectrum to derive physical conditions in BD Blobs. The best fit to the observed spectrum is achieved in the 4000 – 6000 Å range at constant density $n_e \sim 10^6$ cm⁻³, and $T_{BB} \sim 15,000$ K. The dominant Fe⁺ ionization fraction and rich Fe II spectrum suggest the electron temperature range $T_e = 5,000 - 7,500$ K. Our model predicts that the Fe⁺/Fe²⁺ has very sharp transition due to collisional ionization at $\sim 10^6$ cm⁻³ and the size of blob $\approx 10^{15}$ cm⁻³. The Fe ionization structure, low electron temperature in plasma, the shape of blackbody radiation and intense Ly α radiation provide conditions favorable for a rich Fe II spectrum. Blackbody radiation and Ly α -pumping are the main excitation mechanisms for the Fe II ion in the BD Blobs.

As our first step, we have focused on Fe II emission analysis of the spectrum of the BD Blobs from 1998 observations. Extensive STIS/HST Eta Carinae observations at different positions and during other epochs are available. The morphology of the Homunculus Nebula, surrounding Eta Carinae is very complex. Line profile analysis by Viotti et al. (1989) and Davidson et al. (1995) suggest a wider range of velocities than expected from spherical geometry. In addition, an inhomogeneous dust distribution may selectively obscure the radiation field. As a result any of considered above combinations (e.g. collisions, blackbody radiation) may be responsible for Fe II and [Fe II] emission spectrum at other than BD positions.

For the first time we have used detailed non-LTE Fe II models to bracket physical parameters of Fe⁺-rich plasma in the BD Blobs of Eta Carinae. Most of [Fe II] and Fe II lines that predicted by our model are in a good agreement with observations (Verner et al. 2002).

EV research in Eta Carinae at GSFC/NASA and the CUA is supported by STIS resources. EV is grateful to J. Hillier for the discussion of different aspects on photoionization modeling on the central star. We thank G. Ferland for adding a high-resolution option into CLOUDY code to treat more accurately line-pumping processes. We give special thanks Keith Feggans, Don Lindler, and Terry Beck for their computational and data reduction support.

6. REFERENCE

- Bautista, M. A., Peng, J., & Pradhan, A. K., 1996, ApJ, 460, 372
 Davidson, K. 1999, in ASP Conf. Proc. 179, Eta Carinae At The Millennium, ed. J. A. Morse, R. M. Humphreys, and A. Damineli (San Francisco: ASP), p.6
 Davidson, K., Ebbets, D., Weigelt, G., Humphreys, R.M., Hajian, A.R., Walborn, N.R., Rosa, M. 1995, ApJ, 109, 1784

Davidson, K. & Humphreys, R. M. 1997, *ARA&A*, 35, 1
Gull, T., Ishibashi, K., Davidson, K., 1999, in *ASP Conf. Proc. 179, Eta Carinae At The Millennium*, ed. J. A. Morse, R. M. Humphreys, and A. Damineli (San Francisco: ASP), 144
Hillier, D. J., Davidson, K., Ishibashi, K., Gull, T., 2001, *ApJ*, 553, 837
Johansson, S., et al. 2002 *Physica Scripta* in press
Kurucz, R.L. 1981, *SAO Special Report 390*
Lindler, D. 1999, *CALSTIS Reference Guide*
Nahar, S.N., 1995, *A&A*, 293, 967
Osterbrock, D. E. 1989, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, University Science Books: Mill Valley, California
Quinet, P., Le Dourneuf, M., & Zeippen, C. J. 1996, *A&AS*, 120, 361
Verner, E., Verner, D., Baldwin, J., Ferland, G., Martin P., 2000, *ApJ*, 543, 831
Verner, E. et al., 2002 *ApJ* submitted
Viotti, R., Rossi, L., Cassatella, A., Altamore, A., Baratta, G., 1989, *ApJS*, 71, 9832
Walborn, N. R., Danks, A.C., Vieira, G., Landsman, W., 2002, *ApJS*, 140, 407
Weigelt, G., Ebersberger, J. 1986, *A&A*, 163, L5
Zethson, T. 2001, Ph.D. thesis, Univ. of Lund
Zhang, H.L., Pradhan, A.K. 1995, *A&A*, 293, 953

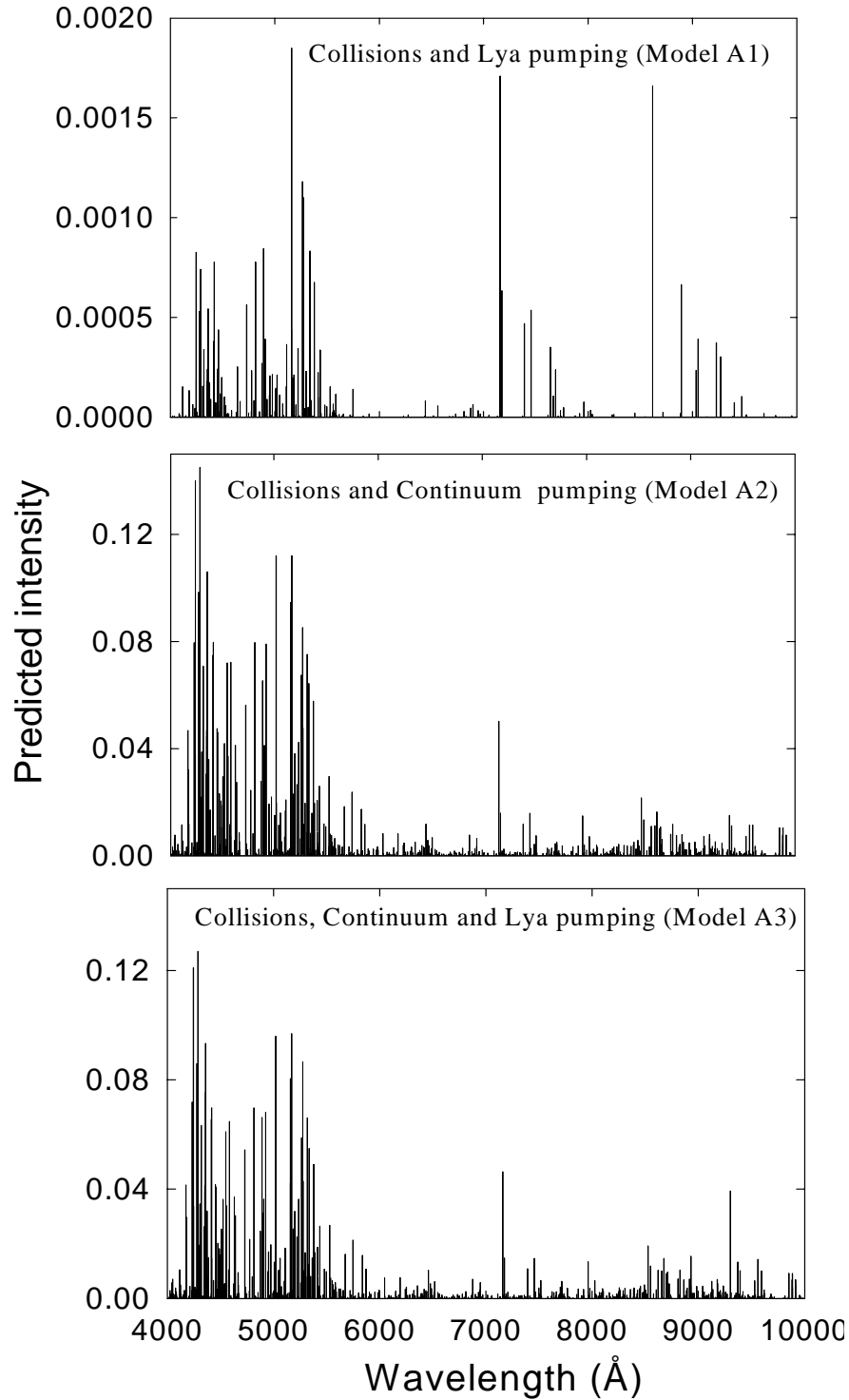


Figure 14: Fe II intensities predicted at various excitation conditions $n_e=10^6 \text{ cm}^{-3}$ and $T_{\text{BB}} = 15,000\text{K}$. The total luminosity is $10^{40} \text{ erg s}^{-1}$ and the distance to BD Blobs from central star is 10^{16} cm .