Line Identifications in the Spectrum of eta Carinae as Observed in 1990-1991 with CCD Detectors

Wallerstein, George; Gilroy, Kalpana Krishnaswany; Zethson, Torgil; Johansson, Sveneric; Hamann, Fred

Published in:
Publications of the Astronomical Society of the Pacific

DOI:
10.1086/323293

2001

Publications of the Astronomical Society of the Pacific, **113**:1210–1214, 2001 October

Line Identifications in the Spectrum of η Carinae as Observed in 1990–1991 with CCD Detectors

George Wallerstein[1] and Kalpana Krishnaswany Gilroy
University of Washington, Seattle, WA 98195; wall@astro.washington.edu, kalpanagilroy@hotmail.com
Torgil Zethson and Sveneric Johansson
Department of Physics, University of Lund; torgil.zethson@fysik.lu.se, sveneric.johansson@fysik.lu.se
and
Fred Hamann
Department of Astronomy, University of Florida, Gainsville; hamann@astro.ufl.edu
Received 2001 March 20; accepted 2001 June 12

ABSTRACT. We have used the Cerro Tololo Inter-American Observatory telescopes and spectrographs to record emission lines in η Carinae from 3093 to 8956 Å with a gap between 4432 and 5696 Å. A resolving power of about 20,000 was used throughout. Accurate wavelengths, peak intensities relative to the local continuum, and line identifications are presented. The data are briefly discussed with respect to the state of ionization present, the presence of oxygen lines, and the use of [S ii] lines to derive a lower limit on the local electron density. We also tabulate the wavelengths of interstellar absorption lines and diffuse interstellar bands.

1. INTRODUCTION

The peculiar supergiant η Carinae has a long and interesting history since it brightened to apparent visual magnitude -1 in 1843 (Davidson & Humphreys 1997). Since then it has settled down to an apparent visual magnitude of about 8 with minor flareups of a magnitude or 2 and a recent brightening to $V = 5.3$. It is clearly losing mass at a high rate and is surrounded by a nebula of complex structure (Davidson & Humphreys 1997).

In addition to being a fascinating object for study because of the rapidity of its evolution, η Car shows an emission-line spectrum that cannot be simulated by any single laboratory source. While a variety of ingenious laser techniques permit the selective excitation of specific levels in specific atoms and ions, no laboratory can simulate the conditions in the η Carinae Nebula, where a temperature of order 5–10 × 10^3 K and an electron density of 10^6–10^9 cm^3 prevail in a volume of perhaps 10^9–10^{10} AU^3! Vast numbers of permitted and forbidden lines of singly ionized iron-peak elements are present, as well as many lines of lighter elements whose ionization and excitation potentials are similar or somewhat higher (Thackeray 1962, 1967; Hillier & Allen 1992; Hamann et al. 1994; Damineli et al. 1998).

With the availability of CCD detectors on echelle spectrographs it is possible to record the spectrum of a star like η Car at moderate spectral resolution, 20,000, and high signal-to-noise ratio (S/N) with relatively short exposures. During 1990–1991 we obtained spectra at the Cerro Tololo Inter-American Observatory when opportunities presented themselves. The spectra are described in Table 1, in which we list the dates, wavelength coverage, continuum ADU pixel^{-1}, telescope, detector, and exposure times. Since the spectra were obtained at different times we have reduced the wavelengths to zero velocity. The observed radial velocities were -53.0, -38.7, and -40.2 km s^{-1}, respectively, on 1990 March 17, 1990 April 11, and 1991 April 27.

There are gaps in our wavelength coverage because it was necessary to use grating tilts determined by the needs of other programs and for other reasons as given below. Between 3640 and 3775 Å the higher Balmer lines show broad P Cygni structures of emission and absorption, making measurements of other lines difficult and the "continuum" impossible to locate. Between 4415 and 5700 Å and between 7100 and 7460 Å no spectra were obtained. Between 7560 and 7675 Å the atmospheric *A* band prevents effective extraction of useful spectra. The region between 8000 and 8300 Å contains many atmospheric H_2O lines that were divided out by hot stars. We endeavored to measure that region, but some emission lines may have been entirely blocked, so their nonpresence cannot be used as evidence to deny the presence of a specific multiplet. Finally, the relatively small chip used in the 7460–9000 Å region did not provide complete wavelength coverage; there

[1] Visiting observer, Cerro Tololo Inter-American Observatory, operated by Associated Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

TABLE 1
Observations of η Carinae

Date	Spectral Region (Å)	Exposure (minutes)	Telescope	Detector (CCD)	Size	Continuum Counts (ADU pixel^{-1})
1990 Mar 17	3800–4400	5	4 m	T.I.	800 × 800	7000–25000
1990 Mar 18	3100–3800	10	4 m	T.I.	800 × 800	500–4000
1990 Nov 4	7400–9000	2	1.5 m	G.E.G.	376 × 576	5000–8000
1991 Apr 27	5700–7000	0.5–5	4 m	G.E.C.	376 × 576	6000–15000

are small gaps between orders. The spectra were reduced with standard IRAF[2] routines that subtract bias, divide by flat field, extract a one-dimensional spectrum, and calibrate according to wavelength. Wavelengths were measured using the SPLOT routine in the ONED package. Intensities were estimated by recording the peak count number for each line. We hesitate to refer to any "continuum" because it is unclear as to the origin of the light that appears between the sharp emission lines. Since no stellar absorption lines can be recognized, it is not a stellar continuum in the usual sense but may be continuous emitted radiation (or scattered radiation) that originates in an optically thick wind, such as is present in hot luminous stars and at the early stages of some novae.

The seeing during our observing sessions was usually about 1''.5, so no effort has been made to extract the dependence of emission-line strength upon position along the east-west slit. Hence our data have far greater spectral resolution than that of Hillier & Allen (1992) but provide no information on the nebula's substructure. The recent spectra of Damineli et al. (1998) have a resolution of 20,000, as have ours. To improve the S/N the star was sometimes trailed along the slit for a few arcseconds.

2. LINE IDENTIFICATIONS

The main purpose of this paper is to report on new emission-line identifications in the interval of 3100–9000 Å. The vast majority of lines with wavelength longer than 3700 Å that we have measured have already been recorded by Thackeray (1962, 1967). Nevertheless, in Table 2 we provide a complete line list because our data are likely to be somewhat more accurate and on a better calibrated intensity scale than the older photographic work. We show only a portion of Table 2. The complete table is available in the electronic edition. As a summary we list in Table 3 all of the species that we have observed in emission, the number of multiplets of each species, and the hightest excitation of the upper level of emission lines of that species. A few qualitative remarks may be made on the basis of the information in Table 3. The only neutral species present are those with $\chi_{\rm ion} \geq 13.54$ eV. This indicates that much of the envelope is a H II region. The only ionized species with $\chi_{\rm ion} \leq 13.54$ eV are Ca II and possibly Sc II; Sr II is not present. For typical ions of metals such as Mg II, Si II, Cr II, Fe II, and Ni II, lines originating from levels with excitation as high as 8.7 eV are seen. It is likely that such high levels are populated by recombination rather than collisions. Collisions may well enhance the populations of many levels of lower energy. Mn II lines originating at 12.16 eV are present as a result of selective excitation (Johansson et al. 1995). The highest ionization states seen are Ne III, S III, and Ar III, all of which are represented by their forbidden lines. Their presence requires ionization energies of 40.9, 23.3, and 27.5 eV, respectively. They may be formed in the same region as the permitted lines of He I, which must be recombination lines following the ionization of He I by photons of energy greater that 24.5 eV. It appears that in addition to the H II region surrounding the central star, there is a region (or regions) of sufficiently high temperature and low density where the He I recombination lines and the forbidden lines of doubly ionized species originate. The high-temperature region may not be close to the central star because the density in the wind near the star may be too high for the production of the forbidden lines. Shock excitation of lower density gas may be responsible for the high levels of ionization. We have compared our list with that reported by Damineli et al. (1998). For the wavelength region covered by both investigations there is little difference, but our wider wavelength coverage revealed many multiplets below 3800 Å not present at longer wavelengths.

2.1. Unidentified Lines

Despite all of our efforts we still are unable to identify a substantial number of lines. Their wavelengths and ratio of peak flux to nearby continuum flux is given in Table 4. We also show their presence in stars with similar emission-line spectra: LkHα 101, MWC 300, and MWC 349 (Hamann & Simon 1988; Hamann & Persson 1989). To be sure that we have not missed the identification of C, N, and O permitted lines, we have used the newest compliation of their spectra (Moore 1993).

2.2. P Cygni Profiles

The profiles of a number of strong emission lines are quite broad and are sometimes accompanied by absorption on the

[2] The Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA) Inc., under cooperative agreement with the National Science Foundation.

TABLE 2
LINE LISTS

λ_{obs} (Å)	I_p/I_c	Identification	λ_{lab} (Å)
3094.02	2.11	Cr II (47) $b^4F_{3/2}$–$z^4G_{5/2}$	3093.97
3119.12	2.65		
3123.80	2.35	Fe II unclassified?	3123.72
3147.28	2.36	Cr II (5) $a^4D_{7/2}$–$z^4F_{7/2}$	3147.23
3154.26	1.70	Fe II (66) $b^2G_{9/2}$–$z^2G_{9/2}$	3145.20
3161.88	2.20	Fe II (7) $a^4P_{3/2}$–$z^4F_{3/2}$	3161.95
3163.00	2.85	Fe II (7) $a^4P_{5/2}$–$z^4F_{5/2}$	3163.09
3166.52	1.39	Fe II (6) $a^4P_{5/2}$–$z^4D_{3/2}$	3166.67
3167.73	2.14	Fe II (66) $b^2G_{7/2}$–$z^2G_{7/2}$	3167.85
3170.29	2.98	Fe II (6) $a^4P_{3/2}$–$z^4D_{1/2}$	3170.34
3175.34	1.40	[Fe II] (11F) $a^6D_{9/2}$–$b^4D_{7/2}$	3175.38
3183.30	1.37	Fe II (7) $a^4P_{3/2}$–$z^4F_{5/2}$	3183.12
3185.44	1.64	Fe II (7) $a^4P_{1/2}$–$z^4F_{3/2}$	3185.32
3191.91	1.19	Fe II (66) $b^2G_{7/2}$–$z^2G_{9/2}$	3192.06
3193.01	1.80	Fe II (6) $a^4P_{5/2}$–$z^4D_{5/2}$	3192.92
3193.80	1.95	Fe II (6) $a^4P_{1/2}$–$z^4D_{1/2}$	3193.81
3196.10	2.41	Fe II (7) $a^4P_{5/2}$–$z^4F_{7/2}$	3196.07
3208.50	1.53	V II (8) a^3F_3–z^3F_2	3208.35
3210.55	2.36	Fe II (6) $a^4P_{1/2}$–$z^4D_{3/2}$	3210.45
3213.47	2.78	Fe II (6) $a^4P_{3/2}$–$z^4D_{5/2}$	3213.31
3216.38	2.28		
3228.12	3.27	Cr II (4) $a^4D_{1/2}$–$z^6D_{3/2}$	3228.35
		Fe II (6) $a^4P_{5/2}$–$z^4D_{7/2}$	3227.73
3230.48	1.37	Fe II (95) $b^2F_{7/2}$–$x^4D_{7/2}$	3230.50
3232.81	1.32	Fe II (119) $c^2G_{7/2}$–$z^2F_{5/2}$	3232.79
3235.02	1.19	Fe II (1) $a^4D_{7/2}$–$z^6D_{5/2}$	3234.92
3236.63	1.13	Ti II (2) $a^4F_{7/2}$–$z^4F_{7/2}$	3236.57
3237.92	1.25	Fe II (81) $b^4D_{1/2}$–$y^4F_{3/2}$	3237.81
3239.73	1.30	Ti II (24) $a^2D_{5/2}$–$z^2P_{3/2}$	3239.66
3243.71	1.15	Fe II (119) $c^2G_{9/2}$–$z^2F_{7/2}$	3243.72
3246.40	1.45		
3247.23	1.53	Fe II (81) $b^4D_{3/2}$–$y^4F_{5/2}$	3247.17
3255.85	3.33	Fe II (1) $a^4D_{7/2}$–$z^6D_{7/2}$	3255.88
3258.76	1.98	Fe II (81) $b^4D_{5/2}$–$y^4F_{7/2}$	3258.77
		Fe II (81) $b^4D_{7/2}$–$y^4F_{9/2}$	3259.05
3264.68	1.51	Fe II (1) $a^4D_{5/2}$–$z^6D_{3/2}$	3264.76
3275.34	2.04	Ti II (23) $a^2D_{3/2}$–$y^2D_{3/2}$	3275.29
		Ni II (1) $b^2D_{5/2}$–$z^4D_{3/2}$	3274.90
3291.71	1.54	Cr II (68) $a^2P_{1/2}$–$z^2S_{1/2}$	3291.75
3295.73	?.??	Fe II (1) $a^4D_{3/2}$–$z^6D_{3/2}$	3295.81
3302.80	2.07	Fe II (1) $a^4D_{5/2}$–$z^6D_{7/2}$	3302.86
3303.36	2.62	Fe II (1) $a^4D_{1/2}$–$z^6D_{1/2}$	3303.47
3306.99	1.20	Cr II (51) $b^4G_{9/2}$–$z^4H_{11/2}$	3307.04
3313.88	1.45	Fe II (1) $a^4D_{1/2}$–$z^6D_{3/2}$	3314.00
3317.42	1.24		
3328.87	1.27	Cr II (4) $a^4D_{1/2}$–$z^6D_{3/2}$??	3328.35
3334.72	1.31	Ti II (7) $b^4F_{5/2}$–$z^4F_{5/2}$	3335.19
		Zr II (21)??	3334.62
3336.35	1.15	Cr II (4) $a^4D_{1/2}$–$z^6D_{1/2}$	3336.33
3338.74	1.32	Fe II (76) $b^4D_{5/2}$–$y^4P_{3/2}$?	3338.52
3339.85	1.62	Cr II (4) $a^4D_{3/2}$–$z^6D_{3/2}$	3339.80
3341.17	1.36		
3342.78	1.52	Cr II (4) $a^4D_{5/2}$–$z^6D_{5/2}$	3342.51
3344.70		Not remeasured	
3346.65		Ti II (7) $b^4F_{7/2}$–$z^4F_{5/2}$	3346.72

NOTE.—Table 2 is published in its entirety in the electronic edition of the *PASP*. A portion is shown here for guidance regarding its form and content.

violet side. These are typical P Cygni profiles indicating mass outflow from the stellar surface. Many of the emission-line profiles are asymmetric showing no wing on the red side while having a strong wing on the violet side. Lines with that type of profile must be formed within about 1 stellar radius, so the positively Doppler-shifted wing is obscured. We characterize the broad lines by the velocity range at their base and the velocity range of the P Cygni absorption line. Since the lines are not Gaussian nor do they appear to be the sum of Gaussians, the measurement of full width at half-maximum does not describe the lines in a useful way.

While it is not the purpose of this paper to derive a model on the basis of the emission-line profiles, we note a few of their characteristics. The main fact shown in Table 5 is that mass loss was currently occurring with a velocity of 500–600 km s^{-1}. Hα has been omitted from Table 5 because the apparent width of its emission is enhanced by the [N II] lines at 6548, 6584 Å. It is at least as wide as the separation of those lines, i.e., from -700 to $+950$ km s^{-1}.

2.3. Are Oxygen Lines Present?

η Car is known for its strong N lines and weak or absent O lines. We have made some tentative identifications of O lines but are uncertain as to their reliability. For [O I] the 6300 Å line appears to be present with a peak intensity 1.25 times the local continuum. The 6363 Å line may be present as a step in the strong [Ni II] line at 6365.39 Å. One permitted O I line appears to be present at 6158 Å, but its slightly weaker companion line is absent. The strong multiplet at 7773 Å is definitely absent in emission. Unfortunately, the 7773 Å multiplet of O I appears at the end of an order, so we can confirm that the line is not present in emission, but we cannot make a comparison with the spectrum discussed by Hamann et al. (1994) in which a violet displaced absorption line of 7773 Å is illustrated. Only the 8446.5 Å triplet is strongly present. It is known to be pumped by Lyβ, so its strength depends on the local intensity of Lyβ, which is likely to be large in the envelope of η Car. The strength of the 8446.5 Å feature cannot be used to predict the strength of any other line, nor may it be used to derive an oxygen abundance. For [O II] we have measured a sharp line at 3727.30 Å, but it is not a blend of 3726.03 and 3728.81 Å since they would be clearly separated at our resolution. The [S II] lines at 4068 and 4076 Å are very sharp, so we would expect the [O II] also to be sharp. According to Thackeray (1967) the line at 3727 Å in η Car is due to V II multiplet 21. Damineli et al. (1998) note the absence of [O I], [O II], and [O III].

2.4. The [S II] Lines

The forbidden lines of [S II] appear in pairs whose ratios are sensitive to density. Taking into account the blending line of [Fe II], the flux ratio of λ6731/λ6717 is 2.25, which is close to the high-density limit for which $\log n_e > 4$ at $T = 10^4$ K.

TABLE 3
Species Present

Species	Number of Multiplets	Highest Excitation (eV)	Species	Number of Multiplets	Highest Excitation (eV)	Species	Number of Multiplets	Highest Excitation (eV)
H I	10	13.53	[S II]	2	3.03	[Mn II]	2	3.70
He I	16	24.37	[S III]	1	3.35	Fe II	45	8.21
N I	5	13.61	[Ar III]	1	1.73	[Fe II]	1	3.95
[N I]	1	3.56	Ca II	1	3.14	[Fe III]	1	4.30
[N II]	2	4.04	Ti II	20	5.54	Co II	2	5.91
O I	2	12.70[a]	[Ti II]	2	3.11	Ni II	4	7.22
[O I]	1	1.96[a]	V II	9	6.02	[Ni II]	7	4.01
[Ne III]	1	3.19	Cr II	22	8.71	[Cu II]	2	3.24
Mg II	1	11.52	[Cr II]	2	3.84	Zr II	1	4.26
Si II	3	12.09	Mn II	3	12.16[b]			

[a] See discussion in § 2.3.
[b] Multiplet (13) is pumped by a Si II line (Johansson et al. 1995).

The flux ratio of λ4068/λ4076 is almost exactly 5, which is also at the high-density limit, indicating that $\log n_e \sim 7$ (A. Raga 2000, private communication).[3] Such a large electron density is to be expected for collisionally excited lines of permitted Fe II to be present.

[3] The line ratio as a function of Ne was calculated by solving a five-level atom problem with the atomic parameters tabulated by Mendoza (1983).

TABLE 4
Unidentified Lines

λ (Å)	λ (Å)	λ (Å)	λ (Å)
3119.12	3864.47	5987.46	6961.41
3123.80	4008.37	6069.50	6997.28
3246.40	5695.87	6182.27	6998.76
3317.42	5716.91	6193.63	7004.96
3476.51	5720.06	6215.87	7500.26[a]
3490.44	5729.71	6275.68	7539.06
3606.52	5787.66	6343.96	7808.51[b,d]
3618.30	5816.32	6414.40	7875.98[a,b,c,e]
3618.73	5838.91	6530.91	8121.10[a,b,c]
3651.37	5885.93	6722.55	8301.01
3653.42	5950.93	6745.42	8575.06[c,f]
3719.88	5951.96	6747.66	8695.33[a,c,g]
3727.30[h]	5955.95	6926.37	8936.05

[a] Present in LkHα 101 (Herbig 1971; Hamann & Persson 1989).
[b] Present in MWC 349 (Hamann & Simon 1988).
[c] Present in MWC 300 (Hamann & Persson 1989).
[d] Possibly due to 7808.96 Å, Fe II, c^4F–x^4D.
[e] 3 Fe II, transitions may contribute.
[f] Possibly Fe II, c^4D–w^4P.
[g] Possibly Fe II, z^6D–$c\ ^4F$.
[h] This sharp line is not a blend of the 3726, 3729 Å features of [O II].

2.5. Interstellar Absorption

Our spectra are sufficiently exposed that interstellar lines from a number of species are present. We list their identifications, radial velocities, and equivalent widths in Table 6. In addition to the usual atomic lines, several diffuse interstellar features are present, which we also list in Table 6. The correlation of color excess and strength of diffuse interstellar lines is fairly good, so we also show the derived color excess as derived from each diffuse line (Herbig 1975). The mean of E_{B-V} is 0.31 ± 0.04, in agreement with the reddening as derived from the K I line at 7699 Å (Hobbs 1974). This reddening probably refers to the interstellar medium and may not describe the gas close to η Car, where the radiation field may have profound effects on the physical conditions of the gas and dust. Damineli et al. (1998) also noted the presence of diffuse interstellar lines.

In fact, the large equivalent widths of the two interstellar Ti II lines indicates that somewhere along the line of sight the titanium that is usually attached to the grains has been released (Stokes 1978). If the region of evaporated grains is near the star itself, the presence of interstellar (or circumstellar) Ti II requires that the region be a H I region because the ionization potentials of Ti II and H I are virtually identical. The fact that the ratio of equivalent widths of the two Ti II lines is nearly proportional to the ratio of their *f*-values indicates a high velocity parameter, at least 15 km s^{-1}, in the region of formation. Such a large value is much greater than commonly seen in the interstellar medium, indicating that they are likely to be formed near the star.

TABLE 5
CHARACTERISTICS OF BROAD LINES IN η CARINAE

Element	λ(lab) (Å)	Emission (km s^{-1}) From	Emission (km s^{-1}) To	Absorption (km s^{-1}) From	Absorption (km s^{-1}) To	Note
H I	3797.90	Blended		−510	−237	
He I	3888.65	Blended		−657	−355	1
Ca II	3933.66	Blended		−543	−321	
Ca II	3968.47	Blended		−546		2
He I	4026.20	−313	−15	−611	−313	
H I	4101.74	−405	+326	−515		3
H I	4340.47	−455	+299	−515		3
He I	5875.65	−439	+225	−490		3
Na I	5889.95	Blended		−509	−382	
Na I	5895.15	Blended		−509	−382	
He I	6678.15	−395	+81			
He I	7065.19	−433	+150			

NOTES.—(1) Emission blended with H I emission. (2) Profile disturbed by [Ne III] and H I. (3) Absorption is relatively sharp, so its center is recorded.

TABLE 6
INTERSTELLAR ABSORPTION IN η CARINAE

λ(obs) (Å)	Identity	V_r (km s^{-1})	EW (mÅ)	Derived E_{B-V}
3241.99	Ti II	+0.9	155	
3383.74	Ti II	−1.8	226	
3933.59	Ca II	−5.3	402	
3934.79	Ca II	+86.2	88	
3968.37	Ca II	−7/6	...[a]	
5780.92	DIB	+26.5	318	0.40[b]
5797.25	DIB	+11.4	123	0.35[b]
5890.07	Na I	+6.1	651	
5896.09	Na I	+8.6	395	
6195.95	DIB	0.0	25	0.30[b]
6613.91	DIB	+12.7	76	0.20[b]
7699.03	K I	+1.9	96	0.30[c]

[a] Unreliable as a result of blending of emission lines.
[b] E_{B-V} derived from correlations of Herbig 1975.
[c] E_{B-V} derived from correlations of Hobbs 1974.

REFERENCES

Damineli, A., Stahl, O., Kaufer, A., Wolf, B. Quast, G., & Lopes, D. F. 1998, A&AS, 133, 299
Davidson, K., & Humphreys, R. M. 1997, ARA&A, 35, 1
Hamann, F., DePoy, D. L., Johansson, S., & Elias, J. 1994, ApJ, 422, 626
Hamann, F., & Persson, S. E. 1989, ApJS, 71, 931
Hamann, R., & Simon, M. 1988, ApJ, 327, 876
Herbig, G. H. 1971, ApJ, 169, 537
———. 1975, ApJ, 196, 129
Hillier, D. J., & Allen, D. A. 1992, A&A, 262, 153
Hobbs, L. M. 1974, ApJ, 191, 381
Johansson, S., Wallerstein, G., Gilroy, K. K., & Joueizadeh, A. 1995, A&A, 300, 521
Mendoza, C. 1983, in IAU Symp. 103, Planetary Nebulae, ed. D. R. Flower (Dordrecht: Reidel), 143
Moore, C. E. 1993, Table of Spectra of Hydrogen, Carbon, Nitrogen and Oxygen Atoms and Ions, ed. J. W. Gallagher (Boca Raton: CRC)
Stokes, G. M. 1978, ApJS, 36, 115
Thackeray, A. D. 1962, MNRAS, 124, 251
———. 1967, MNRAS, 135, 51