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Sr II AND [Sr II] EMISSION IN THE EJECTA OF η CARINAE¹

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ABSTRACT

We have discovered four extremely surprising emission lines of *strontium* in ejecta near η Carinae. *Hubble Space Telescope* (HST) Space Telescope Imaging Spectrograph (STIS) observations made in 1999 show two narrow features whose wavelengths correspond to the forbidden transitions of Sr II, and we have found no other plausible identification for these lines. The identifications are confirmed by new HST/STIS observations of the same stellar position, in which the Sr II resonance lines are observed. Moreover, [Ti II], [Ni II], [Mn II], and [Co II] lines are unusually strong relative to [Fe II] at the same position.

Key words: circumstellar matter — stars: individual (η Carinae) — stars: variables: other

1. INTRODUCTION

The mysterious superstar η Carinae has bewildered astronomers since its giant eruption in the 1840s. (For many recent studies in this topic, see Morse, Humphreys, & Damineli 1999; for general information, see Davidson & Humphreys 1997). One of η Car's most puzzling features is its emission-line spectrum, which has been the subject of intensive studies with the *Hubble Space Telescope* (HST) using the Faint Object Spectrograph (Davidson et al. 1995; Zethson et al. 1999), the Goddard High Resolution Spectrograph (Davidson et al. 1997; Zethson et al. 1999), and most recently the Space Telescope Imaging Spectrograph (STIS; Gull et al. 1999; Davidson et al. 1999). The star itself is surrounded by a bipolar circumstellar nebula, the Homunculus, mainly ejected during the Great Eruption 160 yr ago. A number of gaseous condensations have also been found close to the star, e.g., the “Weigelt components” (Weigelt & Ebersberger 1986; Davidson et al. 1995, 1997). The ejecta produce several distinct, position-dependent types of emission-line spectra. The star and Homunculus therefore constitute a very spectroscopically complex system, in which the observed spectrum changes drastically over distances as small as a few tenths of an arcsecond within an overall size greater than 10". High spatial resolution, such as that provided by the HST, is required for detailed spectroscopy of this object.

In 1999 February, a series of STIS observations of η Car was made, giving a full spectral coverage (1700–10500 Å) of the central star (or rather the stellar wind) and the Weigelt components. Other nearby locations were also observed in the wavelength range 6500–7050 Å as part of a project to map H α emission in the inner Homunculus. In one observation with the spectrograph slit offset from the star, a

region about 1".5 northwest of the star was found to have a spectrum substantially different from that seen elsewhere. Some of the emission lines are highly unusual in an astrophysical context. In this paper, we briefly describe this spectrum.

Throughout this paper, we quote vacuum wavelengths and heliocentric Doppler shift velocities, except where otherwise stated. Spectroscopic designations for most emission lines are omitted in the text but are listed in Table 1. Parity-forbidden lines are designated by placing the spectrum abbreviation inside square brackets, e.g., [Fe I].

2. OBSERVATIONS

Our data were obtained with the STIS. The first set of observations took place on 1999 February 21. For the observations discussed here, STIS grating G750M was used with only one grating tilt, which sampled wavelengths between 6490 and 7050 Å. The 52" \times 0".1 slit, oriented along a position angle of 332°.1, was placed successively at six locations spaced about 0".38 apart. (Strictly speaking, a telescope offset of 0".40 southwest was used to move from one slit position to the next.) Spectra with integration times of 10 and 175 s were recorded at each position. Additional 0.5 s exposures were obtained at the slit position that included the star and at the two adjoining positions.

We anticipated considerable velocity and spatial variations in the H α and [N II] $\lambda\lambda$ 6549, 6585 lines, and we were not disappointed. Many other emission lines are present and usually follow the velocity and spatial structure of H α and [N II]. In general, these nebular emission lines are slightly broadened at the spectral resolution of $R \sim 5000$ and are typically split.

In data recorded with the slit located about 0".4 west of the star, an unusual set of emission lines are seen at positions centered near $R \approx 1".55$, with a position angle of $\approx 318^\circ$ relative to the star, i.e., northwest of it; below we shall refer to this region as “location II” (Fig. 1). The anomalous lines discussed below are unresolved in width, extend for a distance of roughly 1" along the slit, and are either absent or much weaker at the adjoining slit locations.

A comparison with HST WFPC2 images (Morse et al. 1998) shows that this emission does not coincide with red features (mostly scattered starlight) nor with compact blue features (mostly nebular emission lines in the 3000–4000 Å bandpass). The emission-line patch does not correspond to

¹ Based on observations made with the NASA/ESA *Hubble Space Telescope* and supported by STIS IDT GTO 8036 and grant GO 8327 from the Space Telescope Science Institute. The STIS is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

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TABLE 1
EMISSION LINES AT LOCATION II^a

λ_{obs} (Å)	Identification	E_{exc} (cm ⁻¹)	λ_{rest} (vac., Å)	Velocity (km s ⁻¹)
6508.99.....	[Mn II] (8F)	29,951	6511.43	-112
6508.99.....	[Mn II] (8F)	29,951	6511.43	-112
6519.17.....	[Co II]	25,147	6521.28	-97
6535.53.....	[Mn II] (8F)	29,890	6537.79	-104
6549.79.....	[N II] (1F)	15,316	6549.86	-3
6553.48.....	[N II] (1F)	15,316	6549.86	+166
6564.3.....	H α	97,492	6564.61	-14
6585.15.....	[N II] (1F)	15,316	6585.21	-3
6588.76.....	[N II] (1F)	15,316	6585.21	+162
6603.95.....	[Mn II] (8F)	29,919	6605.79	-83
6616.46.....	[Mn II] (8F)	29,890	6618.87	-109
6642.17.....	[Mn II] (8F)	29,951	6644.41	-101
6646.82.....	[Ti II] (8F)	15,266	6648.98	-98
6650.41.....	[Ti II] (8F)	15,257	6652.61	-99
6656.23.....	[Mn II] (8F)	29,919	6658.57	-105
6666.40.....	[Ni II] (2F)	14,996	6668.67	-102
6679.71.....	He I (46)	186,105	6680.00	-13
6717.33.....	[S II]	14,885	6718.29	-43
6721.83.....	[Ti II] (8F)	15,266	6723.96	-95
6725.38.....	[Ti II] (8F)	15,266	6727.67	-102
6731.29.....	[S II]	14,853	6732.67	-61
6738.04.....	[Sr II] (1F)	14,836	6740.25	-98
6748.08.....	[Fe II]	37,227	6748.79	-32
6760.35.....	[Fe I] (15F)	21,716	6762.48	-94
6791.69.....	[Ni II] (8F)	24,836	6793.35	-73
6794.26.....	[Ni II] (8F)	23,108	6796.07	-80
6810.59.....	[Fe II] (31F)	22,637	6811.10	-22
6813.94.....	[Ni II] (8F)	24,788	6815.45	-66
6827.78.....	[Co II]	27,902	6829.85	-91
6836.65.....	[Fe I] (15F)	21,999	6838.84	-96
6849.57.....	[Mn II] (2F)	14,594	6852.21	-115
6867.85.....	[Sr II] (1F)	14,556	6870.07	-97
6874.2.....	[Fe II] (31F)	22,939	6874.07	...
	[Fe II] (43F)	30,389	6875.74	...
6896.95.....	[Fe II] (14F)	16,369	6898.08	-49
6923.53.....	[Co II]	25,147	6925.74	-96
6932.00.....	[Co II] (3F)	17,772	6934.27	-98
6945.55.....	[Fe II] (43F)	30,764	6946.80	-54
6966.70.....	[Fe II] (31F)	23,031	6968.23	-66
6971.83.....	[Fe I] (15F)	21,716	6974.00	-93
6977.79.....	[Mn II] (2F)	14,594	6980.38	-111
6998.61.....	Unidentified
7004.46.....	[Fe I] (15F)	21,716	7007.18	-116

^a See Figs. 1 and 2.

any obvious localized red, blue, or dark feature, although it is in the same general region as the diffuse “blue glow” noted by Morse et al. (1998).

To examine further the nature of this emission feature, we revisited location II with STIS on 2000 March 13. The second visit for location II was performed using a different instrument configuration. A wider long slit of $52'' \times 0''.2$ was placed across the star at a position angle of 317.5° . The bright star and nebular blobs (i.e., location I, described in the next section) were occulted by a $0''.2$ “fiducial bar” across the slit in order to avoid saturation of the CCD detector. Wavelength intervals used here were sampled with STIS gratings G230MB, G430M, and G750M, at grating tilts centered on 2557, 2697, 2836, 3936, 4194, 4961, 6768, 7283, 9396, and 9851 Å, using exposure times of 100–250 s. This paper focuses only on the data sets taken at central wavelengths 3936, 4196, 6768, and 9851 Å. More detailed

analyses will be given to the other data sets in future publications.

3. RESULTS

3.1. 1999 STIS Spectrum

Figure 2 shows a $4''$ extraction of the STIS spectrum. The wavelength scale goes from 6490 Å at the left edge to 7050 Å at the right edge. The intensity scale is logarithmic. Two emission-line regions separated by $1''.5$ are marked I and II in the figure. The spectrum at location I resembles that of the Weigelt components B and D obtained at the same time (Zethson et al. 2001). The strongest lines there are H α and [N II] $\lambda\lambda 6549, 6585$, [Ni II] $\lambda 6668$ and He I $\lambda 6680$ are also strong. Other emission lines seen in this region are almost exclusively Fe II, [Fe II], and [Ni II]. The [S II] doublet $\lambda\lambda 6718, 6732$ is present but weak.

The spectrum at location II, however, is significantly different, especially in its faintest velocity component. H α and [N II] still dominate. As mentioned in § 2, we see velocity structures in these lines. The [N II] lines are double peaked, with the peaks corresponding to velocities of ~ 0 and $+160$ km s⁻¹. H α is not as well resolved but has a peak at ~ -15 km s⁻¹ and additional emission on the red side. [Ni II] $\lambda 6668$ is strong and seems also to show some velocity structure. He I $\lambda 6680$ is weak and rather diffuse (it may be scattered light from the star). No permitted Fe II emission is present, and [Fe II] lines are surprisingly weak.

More importantly, a number of lines not present at location I or in the Weigelt blobs appear in the spectrum at II. These features are narrower than the [Fe II] and [Ni II] lines; the strongest of the narrow lines, observed at 6725.38 Å, has a FWHM of ~ 50 km s⁻¹, whereas [Fe II] $\lambda 6946$ has a FWHM of ~ 120 km s⁻¹. Since no corrections for instrumental broadening have been attempted here, the anomalous features must be intrinsically very narrow indeed.

Figure 3 shows tracings of a part of the spectrum at location II compared with the corresponding spectrum of the Weigelt blobs B and D obtained at the same date. Table 1 presents line identifications for location II. All but four of the identified lines (not counting H α and [N II]) are parity-forbidden transitions between metastable states ($E_{\text{exc}} < 30,000$ cm⁻¹) of Ti II, Mn II, Fe I, Fe II, Co II, and Ni II. These identifications are based on agreements between observed wavelengths, corrected for the Doppler shift (~ -100 km s⁻¹), and corresponding energy level differences in the respective ions. Most of the identifications are supported by the presence of more than one line from the same multiplet; for example, six of the lines are identified as a^5D-a^5P of [Mn II] (noted as multiplet 8F in Moore’s multiplet table) and four lines are identified as a^4D-b^2G of [Ti II] (8F).

Table 1 indicates that the narrow lines are Doppler shifted by -100 ± 15 km s⁻¹, whereas [Fe II], [Ni II], and [S II] have smaller velocities. [Ni II] $\lambda 6668$ has a peak at -102 km s⁻¹ but also a “bump” in its red wing, indicating a component of lower velocity. This suggests that the narrow and the broad lines are formed in different regions, although they appear at the same place along the STIS slit.

3.2. Strontium

Three of the narrow lines at location II, observed at 6738.04, 6867.85, and 6998.61 Å, cannot be explained as forbidden transitions of any iron group element. They are all narrow, which suggests that they should be Doppler

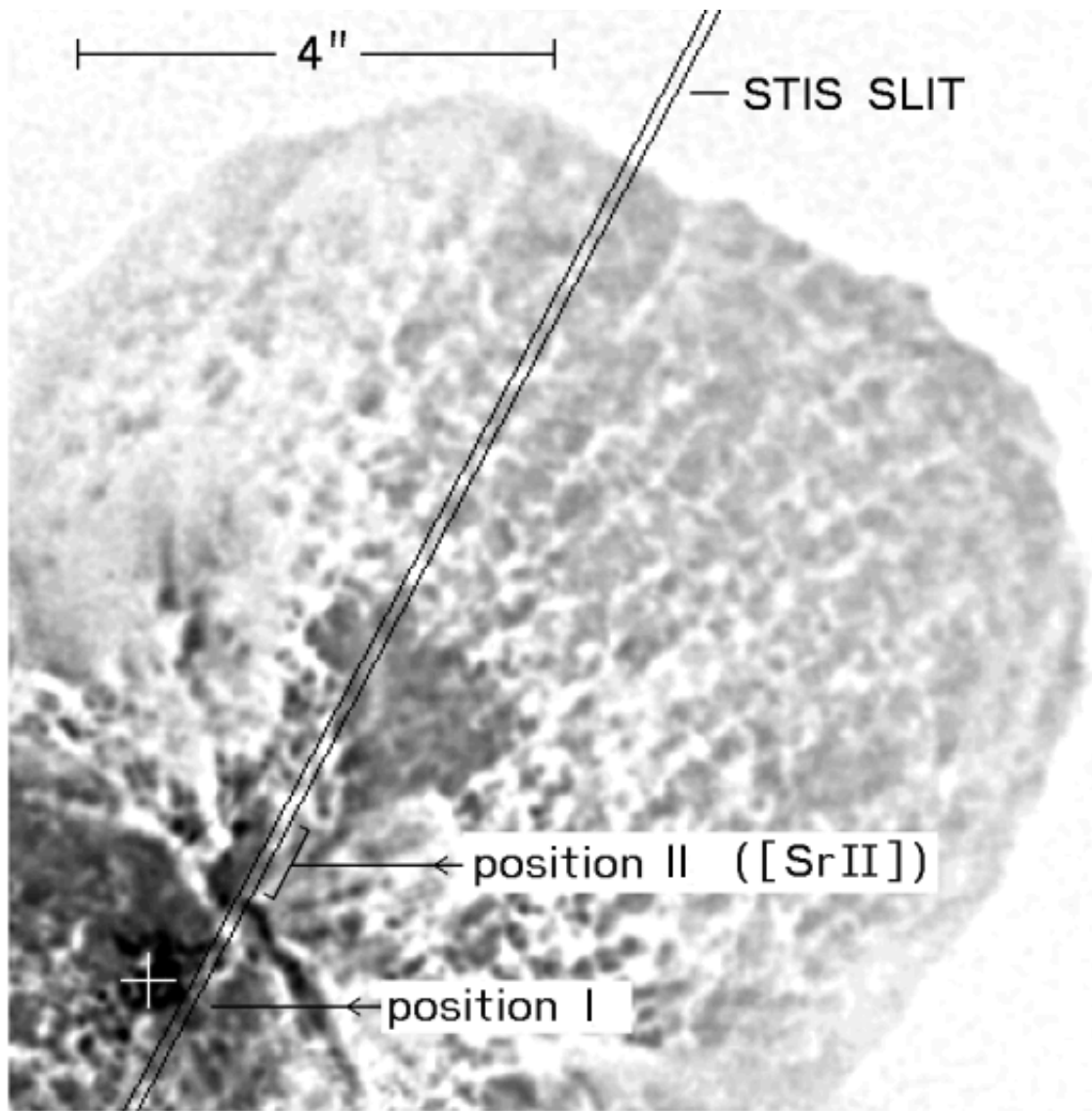


FIG. 1.—Location of the STIS slit in the 1999 observation and positions I and II along the slit. The northwest Homunculus lobe is shown, and the star's position is marked with a plus sign. Compare with figures in Morse et al. (1998).

shifted by $\sim -100 \text{ km s}^{-1}$, implying rest wavelengths of 6740.3, 6870.1 and 7000.9 Å. Two of them coincide with the forbidden lines of the [Sr II] multiplet 1F.

Table 2 presents the transitions connecting the three

lowest LS terms in Sr II. The ground configuration of Sr II is $4p^6 5s$. The $5s-5p$ resonance lines, $\lambda 4078$ and $\lambda 4216$, fall outside the wavelength range covered by the 1999 STIS data. They are expected to be faint, since strontium is nor-

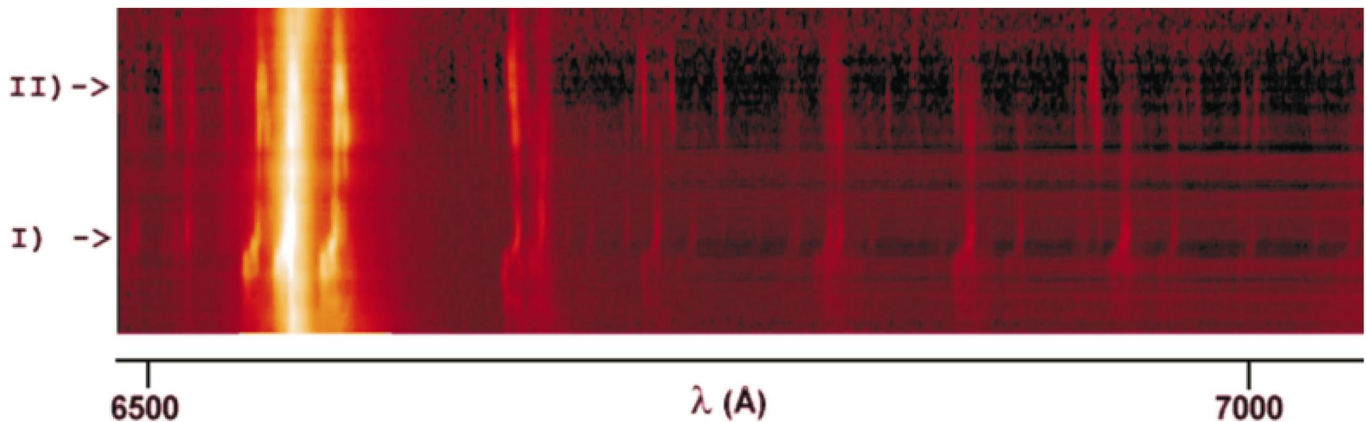


FIG. 2.—Part of the STIS observation covering 6490–7050 Å

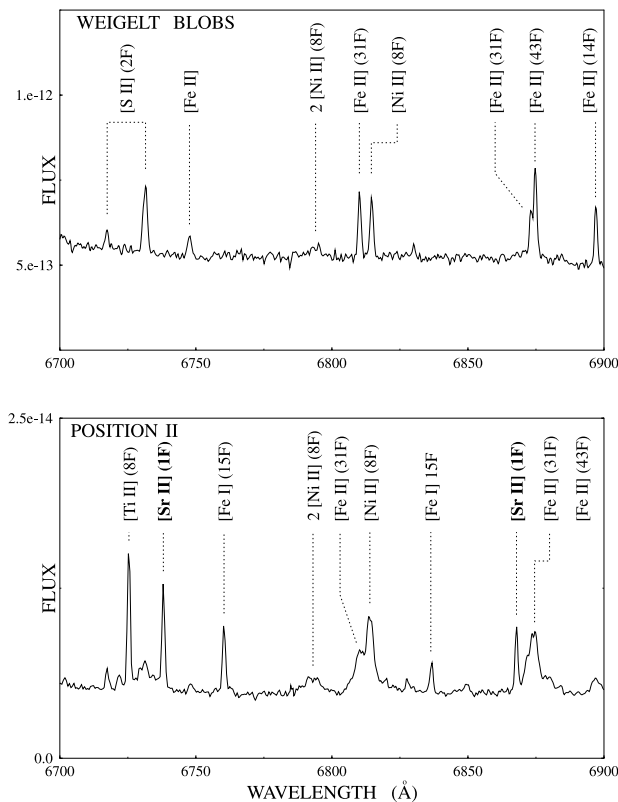


FIG. 3.—Plots showing parts of the spectrum of location II in Fig. 2, including the two [Sr II] lines at 6738 and 6868 Å, and the spectrum of the Weigelt blobs B and D.

mally very scarce, and indeed there is no sign of them in the Weigelt gas blobs near η Car. However, the lowest excited term in Sr II is 2D of the $4p^64d$ configuration, not $4p^65p$, and it has the same parity as the ground state. The two parity-forbidden transitions from this term down to the ground state have rest wavelengths of 6740.25 and 6870.07 Å, which coincide perfectly with two of the observed lines mentioned above if their Doppler velocities are -98 and -97 km s $^{-1}$, respectively. The narrow line at 6998 Å (rest wavelength 7000.9 Å) remains unidentified.

3.3. 2000 STIS Spectrum

In order to further investigate the nature of the spectrum of location II and to confirm the identification of the [Sr II] lines, new STIS observations of location II were carried out in 2000 February. The new observations covered the wave-

TABLE 2

TRANSITIONS CONNECTING THE THREE LOWEST LS TERMS IN Sr II

Lower level	Upper level	E_{upper} (cm $^{-1}$)	Wavelength (vac., Å)
$5s^2S_{1/2}$	$5p^2P_{3/2}$	24,517	4078.86
$5s^2S_{1/2}$	$5p^2P_{1/2}$	23,715	4216.71
$5s^2S_{1/2}$	$4d^2D_{5/2}$	14,836	6740.25 ^a
$5s^2S_{1/2}$	$4d^2D_{3/2}$	14,556	6870.07 ^a
$4d^2D_{3/2}$	$5p^2P_{3/2}$	24,517	10039.40
$4d^2D_{5/2}$	$5p^2P_{3/2}$	24,517	10330.14
$4d^2D_{3/2}$	$5p^2P_{1/2}$	23,715	10917.88

^a Forbidden transition.

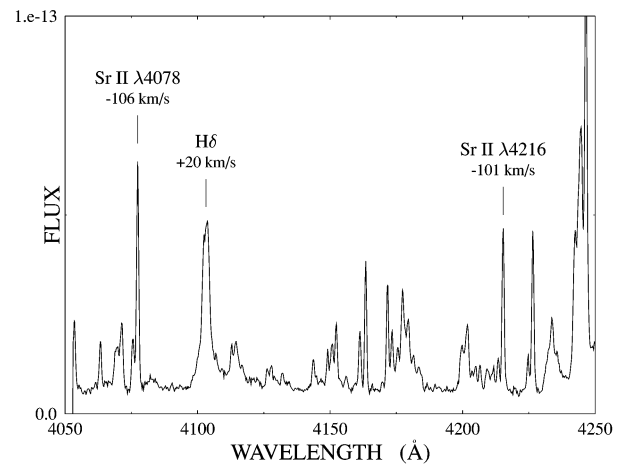


FIG. 4.—The 4050–4250 Å spectrum of location II as observed by the STIS in 2000 February, showing the presence of the Sr II resonance lines. For line identifications, see Hartman et al. (2001).

length regions 2477–2637, 2617–2777, 2756–2916, 3789–4083, 4047–4341, 4814–5107, 6473–7063 (the region observed in 1999), 6988–7578, 9042–9630, and 9558–10144 Å. A list of line identifications of these observations is presented by Hartman et al. (2001). Here we will only note that the appearance of the newly observed spectra is very similar to the spectrum observed in 1999; we see strong lines of, e.g., Ti II, Fe I, and Sc II, whereas H I and Fe II are weak or absent.

Furthermore, as shown in Figure 4, the Sr II $5s$ – $5p$ resonance lines $\lambda\lambda 4078, 4216$ are observed, which confirms the identification of [Sr II] in the 1999 data. (The spectral resolution of the data is high enough to exclude a possible blend of Sr II $\lambda 4078$ with [S II] $\lambda 4077$; [S II] are observed to be very weak at location II, as seen in Fig. 3.)

The $5p$ levels of Sr II can also decay to $4d$, giving rise to lines at 10039.4, 10330.1, and 10917.9 Å. The 10039 Å line is covered by the 9558–10144 Å observation in 2000 February, but there is no sign of it in the data. However, the efficiency of the detector at that wavelength is rather poor, and the quality of the observed data is therefore low. In addition, the 10039 Å line is expected to be more than an order of magnitude weaker than the 4078 Å line coming from the same upper level.

4. DISCUSSION

Strontium is cosmically less abundant than iron and nickel by factors on the order of 30,000 and 3000, respectively, and normally we cannot detect this element in a nebular spectrum (although Sr II lines observed in *absorption* are not unusual in stars), even if it is overabundant by a factor of 10. Merrill & Lowen (1954) report the presence of the Sr II resonance lines in emission in peculiar emission-line stars, notably T Tauri variables and long-period variables after maximum light. The fact that we detect Sr II and [Sr II] and their relative strengths compared with [Fe II] and [Ni II] suggest that strontium is locally overabundant in the η Car ejecta by a large factor.

In principle, resonance fluorescence or some other peculiar excitation mechanism (Johansson & Hamann 1993) might conceivably enhance the Sr II and [Sr II] intensities. This seems unlikely, however, for the following reasons: Selective radiative excitation by accidental wavelength

coincidences often occur for Fe II and other line-rich spectra, largely because they have a high density of energy levels and a high cosmic abundance with a large probability for selective excitation processes. Sr II, by contrast, is essentially a simpler one-electron system in the same sense as Na I or Ca II; beyond the filled $n = 1, 2$, and 3 shells, its ground configuration is $4s^2 4p^6 5s$. Only a small number of low-lying excited levels exist, with the outer electron in $4d$, $5p$, etc., states rather than $5s$. We have been unable to identify any levels of Sr II suitable for resonance excitation by hydrogen Ly α or other bright emission lines or any other special excitation process that may be efficient for this ion in particular. Therefore, one must tentatively assume that the observed [Sr II] lines result from collisional excitation by thermal electrons, like most emission lines in a typical nebular spectrum. The [Sr II] $\lambda 6740/\lambda 6870$ intensity ratio is consistent with collisional excitation in the low- n_e limit.

A severe overabundance of strontium in any gas ejected from η Car would be surprising. In the lore of nuclear astrophysics, ^{88}Sr , having a magic number of neutrons ($N = 50$), is produced by s -process neutron capture. It can become overabundant only in a neutron-rich situation, during helium burning or later stages of stellar core evolution. However, the large-scale ejecta of η Car are known to have H/He/C/N/O abundance ratios characteristic of CNO cycle hydrogen burning (Davidson, Walborn, & Gull 1982; Davidson et al. 1986; Dufour et al. 1999); while N III] emission suggests that this is probably also true of the stellar wind. CNO cycle processed ejecta seem inconsistent with a major strontium overabundance in the fainter gas that we described above.

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