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# NOTES

## ON THE INFRARED EXCESS OF W CEPHEI AND SIMILAR STARS*

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### ABSTRACT

Emission lines in W Cep are analyzed to yield an electron temperature of 5000°–6000° K and an electron density of 2–4 × $10^9$ electrons $\mathrm{cm}^{-3}$. Much of the infrared excess can be explained by free-free emission from an envelope of radius 15 a.u. and the parameters listed above. The upturn in the emission from 8.4 to 11.0 $\mu$ cannot be due to free-free emission but must be due either to dust at a temperature less than 300° K or to emission lines.

It is suggested that objects with infrared excesses can be placed into a sequence running from almost pure-dust envelopes as in NML Cygnus to pure-gas envelopes as in the Be stars.

### I. INTRODUCTION

Many late-type supergiants and symbiotic stars of various sorts show a large excess of radiation at wavelengths larger than 3 $\mu$ (Geisel 1970; Gehrz and Woolf 1970; Gehrz, Ney, and Strecker 1970). At the suggestion of Dr. Woolf we have observed W Cep at high dispersion because it shows one of the largest infrared excesses as judged from the $L - O$ (3.5 $\mu$ − 11.0 $\mu$) index. References to earlier work, all at low dispersion, on W Cep are listed by Bidelman (1954), who has classified the spectrum as K0pe Ia.

### II. RADIAL VELOCITIES

Spectrograms in the blue and visual-red at a scale of 9 and 13.5 Å $\mathrm{mm}^{-1}$, respectively, were obtained at the coudé spectrograph of the 200-inch Hale telescope on the night of 1970 December 10–11. The absorption lines are strong and broad as in a late-type extreme supergiant, and no TiO is present—in agreement with Bidelman's spectral type. Emission lines of H$\alpha$, H$\beta$, Fe II, and [Fe II] are present. The hot continuum that has occasionally been reported is not visible.

Radial velocities with respect to the Sun are listed in Table 1. The only lines which deviate significantly from the mean of the absorption lines, −43 km $\mathrm{sec}^{-1}$, are the violet-displaced absorption cores of H$\alpha$ and H$\beta$ and the sodium D-lines. It is important to note that the zero-volt lines (mostly of Fe I, multiplet 2) do not appear to be coming from an expanding envelope. The cores of the hydrogen emission lines are difficult to interpret since they can only be described by the solution of a complicated transfer problem.

The sodium D-lines are resolved into two components which were blended in D2, but separately measurable in the weaker line, D1. The component at −22 km $\mathrm{sec}^{-1}$ is probably due to the local interstellar gas while the component at −52 km $\mathrm{sec}^{-1}$ is probably a blend of a stellar feature near −43 km $\mathrm{sec}^{-1}$ and an interstellar line with a velocity in the range of −50 to −60 km $\mathrm{sec}^{-1}$. Münch's (1957) data for stars near W Cep show only

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* Based upon spectrograms obtained at the Hale Observatories.

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TABLE 1

RADIAL VELOCITIES IN W CEPHEI

| Type | $n$ | Velocity (km sec$^{-1}$) | Type | $n$ | Velocity (km sec$^{-1}$) |
|---|---|---|---|---|---|
| Absorption Lines | | | Emission Lines | | |
| From excited levels...... | 17 | −44 | Hα......... | 1 | −42 |
| From ground levels...... | 6 | −41 | Fe II........ | 3 | −46 |
| H cores................ | 2 | −59 | [Fe II]...... | 7 | −43 |
| Na I.................. | 1 | −52 | | | |
| | 1 | −22 | | | |

the local component for stars with $m - M$ about 10 mag and the additional negative component for stars with $m - M$ in the range of 11.8–13.3. Using an absolute visual magnitude of −7 and a $V - L$ color of 2.3 mag for a K0 Ia supergiant, we find from the measured $L$-magnitude of +1.8 (which is affected minimally by interstellar absorption and circumstellar emission) a true modulus of 11.1 mag. As a reasonable compromise with the interstellar data we adopt a modulus of 12 mag for W Cep. If the D-line component at −52 km sec$^{-1}$ is entirely stellar and circumstellar, a modulus near 10 mag may be more appropriate.

## III. THE PHYSICAL CONDITIONS IN THE ENVELOPE

The presence of both Fe II and [Fe II] permits us to compute the electron density under the assumption that both lines are formed in the same region, which seems reasonable since they have the same velocity. The general expression for the emission coefficient per atom in an emission line is

$$j = \frac{g_B/g_A h\nu A_{BA} \exp\left(-\chi/kT\right)}{1 + A_{BA}/n_e\langle\sigma_{BA}v\rangle} \tag{1}$$

following Spitzer (1949) and noting that $\sigma_{BA}$ is the de-excitation cross-section. Using the assumption that $n_e\langle\sigma_{BA}v\rangle \gg A_{BA}$ for a forbidden line while $A_{BA} \gg n_e\langle\sigma_{BA}v\rangle$ for a permitted line, we derive the following expression for the electron density:

$$n_e = \frac{I[g_B/g_A][\nu]/\nu[A_{BA}]e^{-([\chi]-\chi)/kT}}{[I]g_B/g_A\langle\sigma_{BA}v\rangle}\,, \tag{2}$$

where we have placed in brackets all quantities that refer to the forbidden transition·

To compare forbidden and permitted Fe II lines we need the measured intensities as well as the transition probabilities of the forbidden lines and the excitation rate, $\langle\sigma_{AB}v\rangle$, which is a function of temperature.

The emission lines were measured relative to the continuum and reduced to absolute intensities by using the spectrophotometric gradient of α Ori (M2 Ia) which is a fair representation for a reddened K0 Ia star. They are reduced to flux per unit wavelength interval and normalized to unity for the strongest line, λ4287.40. The wavelengths, multiplets, upper excitation potential, transition probability, and intensities are listed in Table 2. The transition probabilities for the forbidden lines are taken from Garstang (1962). A plot of the fluxes against $Ag_B/g_A$ yields a fairly good correlation.

For the purpose of calculating the density we will compare λ4243 with λ4233 for two reasons. Their wavelengths are almost the same, so any error in our continuum will have almost no effect. Second, both are excited from the $a^4F$ level of Fe II. The $a^4F$

TABLE 2

INTENSITIES OF EMISSION LINES OF IRON

| $\lambda$ (Å) | Mult. | $\chi$ upper (eV) | Å (sec$^{-1}$) | $F_\lambda/F_\lambda(4287)$ |
|---|---|---|---|---|
| 4452.11........... | 7*F* | 2.88 | 0.18 | 0.38 |
| 4416.27........... | 7*F* | 2.88 | 0.37 | 0.415 |
| 4413.78........... | 7*F* | 2.88 | 0.58 | 0.445 |
| 4359.34........... | 7*F* | 2.88 | 0.82 | 0.425 |
| 4319.62........... | 21*F* | 3.21 | 0.53 | 0.52 |
| 4287.40........... | 7*F* | 2.88 | 1.12 | 1.00 |
| 4276.83........... | 21*F* | 3.19 | 0.65 | 0.23 |
| 4243.98........... | 21*F* | 3.14 | 0.90 | 0.60 |
| 4233.28........... | 27 | 5.50 | ... | 0.275 |
| 4178.86........... | 28 | 5.55 | ... | 0.14 |
| 4173.45........... | 27 | 5.55 | ... | 0.075 |

level is not the ground state, but is metastable and lies 0.23–0.35 eV above the ground state.

To calculate $\langle\sigma_{BA}v\rangle$ we use the general formula given by Allen (1963)

$$\langle\sigma_{BA}v\rangle = \frac{17.0 \times 10^{-4}}{T^{1/2}\chi_{\mathrm{eV}}} f 10^{-5040\chi_{\mathrm{eV}}/T} P(\chi/kT) \tag{3}$$

for the excitation rate and then convert to the de-excitation rate, where $\chi_{\mathrm{eV}}$ and $\chi$ are excitation energy in eV and ergs, respectively. The function $P(\chi/kT)$ is tabulated by Allen (who uses $W$ in place of $\chi$). The $f$-value for the excitation of λ4233 is the sum of the $f$-values of three transitions that lead to the ${}^4D^{o}{}_{J=7/2}$ state for which we use the values of Corliss and Bozman (1962), reduced by Warner (1967) by a factor of 10 and further reduced by Smith, Whaling, and Lawrence (1969) by a factor of 1.7. The total $f$-value is then 0.0243. From equation (2) we have calculated $n_e$ for various electron temperatures from $2.5 \times 10^3$ ° to $20 \times 10^3$ ° K. Some results are listed in Table 3. The lowest two temperatures are impossible because iron is almost entirely neutral. Similarly, the highest temperature yields double ionization of iron. Furthermore, hydrogen is mostly ionized above 6000° K, so we could expect the hydrogen emission lines to be due to recombination. The extreme steepness of the Balmer decrement, however (H$\alpha$ is badly overexposed and H$\beta$ is quite weak), indicates collisional excitation at a fairly low temperature. A temperature of 4000° K leads to such a low ionization of hydrogen that the total gas pressure becomes 100 dyn cm$^{-3}$, which is much too high for an envelope. Hence we will proceed in the discussion using $T = 5000$° K and $n_e = 4 \times 10^9$. Hydrogen is only 1 percent ionized, so $n_{\mathrm{H}} = 4 \times 10^{11}$.

We now use these parameters to calculate the volume necessary to produce the observed infrared excess near 10 microns by free-free emission. In the $N'$ and $O$ bands of Gehrz and Woolf (1970) the apparent magnitude of W Cep is about −1.0. With the

TABLE 3

ELECTRON DENSITY AS A FUNCTION OF TEMPERATURE

| $T$ (° K) | $n_e$ (cm$^{-3}$) | $T$ (° K) | $n_e$ (cm$^{-3}$) | $T$ (° K) | $n_e$ (cm$^{-3}$) |
|---|---|---|---|---|---|
| 2880.......... | $1.65 \times 10^{11}$ | 4000.......... | $1.5 \times 10^{10}$ | 6700........... | $1.15 \times 10^{9}$ |
| 3300.......... | $5.4 \times 10^{10}$ | 5000.......... | $4.1 \times 10^{9}$ | 10000........... | $3.7 \times 10^{8}$ |

calibration of Johnson (1966) and a distance of 2.5 kpc the luminosity near 10 $\mu$ is $6 \times 10^{23}$ ergs sec$^{-1}$ Hz$^{-1}$. From the expression for free-free emission

$$j_\nu = 6.85 \times 10^{-38} z^2 g e^{-C_2/\lambda T} T^{-1/2} n_e n_i \qquad (4)$$

with $g = 1$ (Gayet 1970) and $z = 1$, we find $j_\nu = 1.2 \times 10^{-20}$ ergs sec$^{-1}$ Hz$^{-1}$ cm$^{-3}$. We then find that a sphere of radius $2.3 \times 10^{14}$ cm = 15 a.u. can provide the bulk of the emission near 10 $\mu$.

We should point out, however, that free-free emission cannot explain the rise in intensity as seen by Gehrz and Woolf from 8.4 to 11.0 $\mu$. Such a rise could be due either to dust at a temperature less than 300° K or to emission lines which are more plentiful in the $O'$ band than in the $N$ band (Spitzer 1949, Table 2).

Our parameters must pass one further test; the flux in H$\beta$ should not be greater than the flux in 1 Å of the continuum at λ4860. Assuming collisional excitation only, hence equation (1), without cascades from higher levels, and using the branching ratio given by the ratio of $f$-values for H$\beta$/P$\alpha$, we find a flux in H$\beta$ from the volume calculated above to be $4.4 \times 10^{31}$ ergs sec$^{-1}$. Using the absolute visual magnitude of $-7$ and the solar continuum flux at λ4860 of $6 \times 10^{29}$ ergs sec$^{-1}$ Å$^{-1}$, we find a continuum flux in W Cep of $3 \times 10^{34}$ ergs sec$^{-1}$ Å$^{-1}$ which is larger than the H$\beta$ flux by a factor of 700. However, the H$\beta$ flux is so sensitive to temperature that a temperature of 6000° rather than 5000° K raises the H$\beta$ flux by a factor of 100. The small remaining difference can be accounted for by reducing the absolute visual magnitude from $-7$ to $-5$, which reduces the modulus to 10.5 mag. At a temperature of 6000° K of electron density from the Fe II and [Fe II] is $2 \times 10^9$ cm$^{-3}$.

## IV. DISCUSSION

We suggest that the envelope emission from stars with an infrared excess probably comes both from dust and from free-free emission in varying degrees, depending upon the ratio of dust to gas and the level of excitation of the gas. The most extreme dusty object is NML Cyg, which does not show any emission lines at all (Herbig and Zappala 1970). An object which has an envelope that is mostly dust but which shows a very low-temperature emission spectrum is VY CMa (Hyland *et al.* 1969; Herbig 1970). Perhaps RW Cep is an example of a somewhat hotter object in the sequence, since its emission spectrum is mostly from neutral atoms, but of higher excitation than the emission features in VY CMa (Merrill and Wilson 1956). The object RW Cep shows the same upturn in flux from 8.4 to 11.0 $\mu$ as does W Cep. Next we have W Cep with an excitation (5000°–6000° K) emission spectrum of Fe II. Hotter objects such as RY Sct (Merrill 1928) and BF Cyg (Merrill 1950) show lines of [Fe III]. Probably the Be stars represent the extreme situation of free-free emission only (Woolf, Stein, and Strittmatter 1970).

It is very difficult to understand how the gas and dust can be intermingled in the hotter objects (including W Cep). If there is any intreaction between them, we should see simultaneous changes of several observable parameters. If the dust content were increased, then the visual light should become fainter, the infrared should become brighter, and the polarization should increase. At the same time the emission lines should show a lower excitation and ionization as the increased radiation from the dust cools the gas. Perhaps the systems which show both Fe II and Fe III in emission would be the strategic ones for simultaneous observations.

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