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# INFRARED SPECTRA OF $\gamma^2$ VELORUM AND $\zeta$ PUPPIS

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## ABSTRACT

Observations of $\gamma^2$ Vel and $\zeta$ Pup are presented for the spectral region 5800–11,000 cm$^{-1}$ (1.7–0.9 $\mu$), at resolutions of 2 and 4 cm$^{-1}$, respectively. This constitutes the first reported spectroscopy of a Wolf-Rayet star beyond 1.1 $\mu$. The new spectral region contained numerous emission features for the WC8 component of $\gamma^2$ Vel, but only the P$\beta$ line in absorption for the O4f star $\zeta$ Pup. Line identifications are given for $\gamma^2$ Vel and are shown to be consistent with visual spectroscopy. The species identified are H, He I–II, and C II–IV.

In the spectral region 0.8–1.1 $\mu$ our identifications are in excellent accord with previous spectroscopy. However, after correcting the emission-line intensities for dilution by the O9 I component of $\gamma^2$ Vel, we find the lines to be 2–5 times stronger than the same lines in the WC7 star HD 192103, as given by Kuhi. This is attributed in part to a 1-$\mu$ excess in HD 192103 and in part to a lower excitation in $\gamma^2$ Vel.

From the absence of He I $\lambda$10830 in $\zeta$ Pup we are able to exclude the presence of an oft-conjectured WN companion.

The blueshifted absorption component to He I $\lambda$10830 in $\gamma^2$ Vel and the line profile of the He II $\lambda$10,124 emission feature in $\zeta$ Pup are also discussed.

*Subject headings:* line identifications — spectra, infrared — stars, individual — Wolf-Rayet stars

## I. INTRODUCTION

Kuhi (1966*a*, *b*) has provided the most thorough study of the near-infrared spectra of Wolf-Rayet stars. A summary of this and earlier work is given by Kuhi (1968). His observations were made with a photoelectric spectrum scanner in the 0.8–1.1 $\mu$ region at resolutions as high as 10 Å. For representative stars of both the carbon and nitrogen sequences, he identified essentially all of the emission lines and determined continuous energy distributions. In brief, the WC stars were found to exhibit emission lines arising from H, He I–II, and C II–IV, with C III $\lambda$9710 dominating the spectrum. On the other hand, the WN stars show only emission lines of He I–II, with He II $\lambda$10,124 prominent. The continuous energy distributions are roughly similar for the two sequences, but peculiar in the sense that the color temperature decreases to the red. Temperatures from $10^5$ ° to $10^4$ ° K were indicated in the region 0.35–0.95 $\mu$.

Recent instrumental advances enable extension of Kuhi's work to longer wavelengths. Michelson-type interferometers are now available for moderately high resolution studies beyond 1 $\mu$. As an exploratory application of this method to Wolf-Rayet stars, we have obtained 0.9–1.7 $\mu$ spectra of $\gamma^2$ Vel and $\zeta$ Pup.

As the brightest Wolf-Rayet star in the sky, $\gamma^2$ Vel is an ideal choice for investigation. It is a triple system, containing a B1 IV visual companion $\gamma^1$ Vel (Baschek 1970) as well as an unresolved O star, O8 according to Baschek and Scholz (1971*a*) or O9 I according to Conti and Smith (1972). The Wolf-Rayet component is classified WC8. Ganesh and Bappu (1967) have analyzed the spectroscopic orbit and have found a period of 78.5 days and values of $\mathfrak{M} \sin^3 i$ of 46.3 $\mathfrak{M}_\odot$ for the O star and 13.0 $\mathfrak{M}_\odot$ for the WC8 component. Observations with the stellar intensity interferometer (Hanbury Brown *et al.* 1970) demonstrated that the emission line region appears to fill the Roche lobe of the WC8 star, given the above spectroscopic mass ratio. Baschek and Scholz (1971*a*) showed that the O star dominates the visual spectrum and Conti and Smith (1972) derived $M_v$(WC8) − $M_v$(O) = 1.4 mag. Spectroscopy of $\gamma^2$ Vel extends from the rocket-ultraviolet (Carruthers 1968; Stecher 1970) through the visual (Aller and Faulkner 1964) to the near-infrared (Code and Bless 1964).

We have included $\zeta$ Pup here since not only is it the brightest early O star but also it has several spectral features in common with Wolf-Rayet stars. The visual spectrum has been listed as WN7+O5 by Underhill (1966), but more recently as O5f by Baschek and Scholz (1971*b*) and O4f by Conti and Alschuler (1971) and Heap (1972). Baschek and Scholz (1971*c*) and Heap (1972) have studied the visual spectrum and the former remark that an unresolved Wolf-Rayet component

TABLE 1

OBSERVATIONAL PARAMETERS

| Star | JD (2,441,000+) | $\tau$ (sec) | Resolution ($cm^{-1}$) | Unsmoothed S/N (8050 $cm^{-1}$) | $X$ |
|---|---|---|---|---|---|
| $\gamma^2$ Vel ... | 385.675 | 4526 | 2 | 26 | 4.792 |
| $\zeta$ Pup.... | 384.664 | 5397 | 4 | 24 | 3.030 |
| Sirius.... | 385.568 | 288 | 4 | 72 | 1.531 |

cannot be excluded. Rocket-ultraviolet spectra by Carruthers (1968), Morton, Jenkins, and Brooks (1969), Stecher (1970), and Smith (1970) show similarities to Wolf-Rayet spectra. The only spectral observations beyond 0.86 $\mu$ are those of the He II $\lambda$10,124 emission by Mihalas and Lockwood (1972). Davis *et al.* (1970) obtained an angular diameter from observations with the stellar intensity interferometer.

## II. OBSERVATIONS

Our observations were made with a Michelson-type, rapid-scan interferometer at the coudé focus of the McDonald Observatory's 272-cm telescope. A germanium detector at liquid-nitrogen temperature provided a spectral bandpass of 5800–11,000 $cm^{-1}$ (1.7–0.9 $\mu$). Nominal resolutions of 2 $cm^{-1}$ ($\gamma^2$ Vel) and 4 $cm^{-1}$ ($\zeta$ Pup) were used. The observations of $\gamma^2$ Vel were made with $\gamma^1$ Vel excluded from the aperture. A 4 $cm^{-1}$ resolution spectrum of Sirius was obtained for comparison purposes. Table 1 gives the observational parameters. The quantity $\tau$ is the integration time (summed over all scans), S/N is the unsmoothed signal-to-noise ratio at 8050 $cm^{-1}$, and $X$ is the mean air mass.

The spectra are shown in figures 1–3. No corrections for atmospheric extinction or instrumental sensitivity have been applied. However, the spectrum of $\gamma^2$ Vel has been smoothed to a resolution of 10 $cm^{-1}$ by means of a running average. The regions 6600–7600 $cm^{-1}$ and 8650–9000 $cm^{-1}$ have been omitted since they are greatly obscured by telluric bands. The telluric $CO_2$ features near 6200 and 6350 $cm^{-1}$ are evident in all the spectra (fig. 1). The 7890 $cm^{-1}$ $O_2$ band is also seen (fig. 2).

## III. LINE IDENTIFICATIONS

Inspection of figures 1–3 shows a few absorption lines in the spectrum of Sirius, a nearly continuous spectrum for $\zeta$ Pup, and numerous emission features in the spectrum of $\gamma^2$ Vel. The absorption lines in the spectrum of Sirius are readily seen to be the Brackett lines B12 6093 and B14 6296 and the Paschen lines P$\beta$ 7800, P$\gamma$ 9140, P$\delta$ 9948, and possibly P9 10,833. B13 6206 and B15 6367 are interfered with by telluric $CO_2$, but are clearly present. P$\epsilon$ 10,473 is masked by telluric $H_2O$. (All lines are identified in terms of $cm^{-1}$, *in vacuo*, unless preceded by the symbol $\lambda$, in which case the wavelength is given in angstrom units in air.) Only two stellar features are positively identifiable in the spectrum of $\zeta$ Pup: P$\beta$ 7800 and He II 9875. The former is in absorption; the latter, in emission. Line identifications for $\gamma^2$ Vel were made from predictions using the best available energy-level tabulations for the ions H I, He I–II, C I–V, N II–V, O II–V, and Si II–IV. Only identifications with H I, He I–II, and C II–IV were established (table 2). Discussions of individual ions in $\gamma^2$ Vel follow.

### *a*) *Hydrogen* (*energy levels: Moore 1949*)

The Paschen lines P$\beta$–P9 are within the observed spectral region. P$\beta$ 7800, P$\gamma$ 9140, and P$\delta$ 9948 are definitely present, although P$\gamma$ is severely mutilated by the nearby $\phi$-band of $H_2O$. P$\epsilon$ 10,473 is masked by the $\rho$-band of $H_2O$. P9 10,833 is possibly present in a blend with C II.

### *b*) He I (*energy levels: Moore 1949*)

Singlet transitions involving lower levels with principal quantum number $n = 3$ are located in the 1-$\mu$ region. None are apparent in our spectrum, although all are affected by telluric $H_2O$ absorption or by Paschen line emission, so that weak lines may be obscured. The singlet transitions observed in the visual spectrum of $\gamma^2$ Vel are weak, indicating that the infrared singlets are unlikely to be present.

The metastability of the $2s\,^3S$ level ensures the presence of $\lambda$10,830 $2s\,^3S$–$2p\,^3P^o$ (9231 $cm^{-1}$), as well as the well-observed $\lambda$3889 $2s\,^3S$–$3p\,^3P^o$. The former is observed both in emission and in absorption. As in the singlet case, the triplet series 3–$n$ lies within the spectral region of interest. Only $3p\,^3P^o$–$5d\,^3D$ at 8353 $cm^{-1}$ is clearly present. All lines predicted to be of comparable strength to this one are blended or obscured: $3s\,^3S$–$4p\,^3P^o$ (7980, blended C III), $3p\,^3P^o$–$5s\,^3S$ (7782, blended P$\beta$), $3d\,^3D$–$5f\,^3F^o$ (7820, blended P$\beta$), and $3s\,^3S$–$5p\,^3P^o$ (10,564, obscured by $H_2O$). The low intensity of the infrared triplets is consistent with the visual observations.

### *c*) He II (*energy levels: Moore 1949*)

In view of the numerous lines of the 4–$n$ series in the visual spectrum of $\gamma^2$ Vel, we would expect its leading member $4f\,^2F^o$–$5g\,^2G$ (9875 $cm^{-1}$) to be present in the infrared spectrum, and it is. The only members of the 5–$n$ series within our spectral region are $5f\,^2F^o$–$7g\,^2G$,

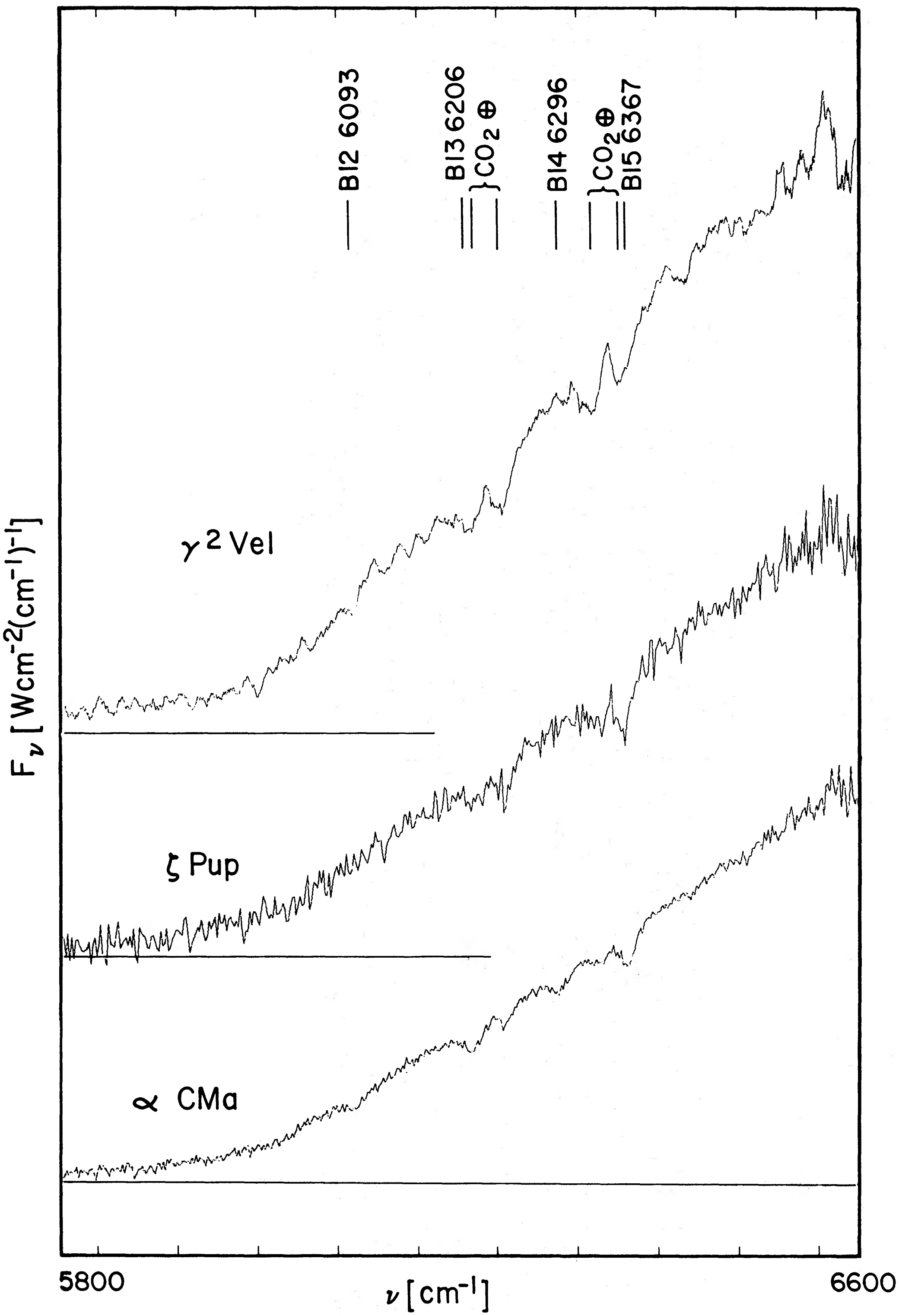


FIG. 1.—The spectra of $\gamma^2$ Vel, $\zeta$ Pup, and Sirius in the region 5800–6600 $cm^{-1}$. No corrections for atmospheric absorption or system sensitivity have been applied. The flux zero point is indicated by the line below each spectrum, and the flux coordinate is linear. Intervals of 80 $cm^{-1}$ are marked along the abscissa. Line identifications are marked.

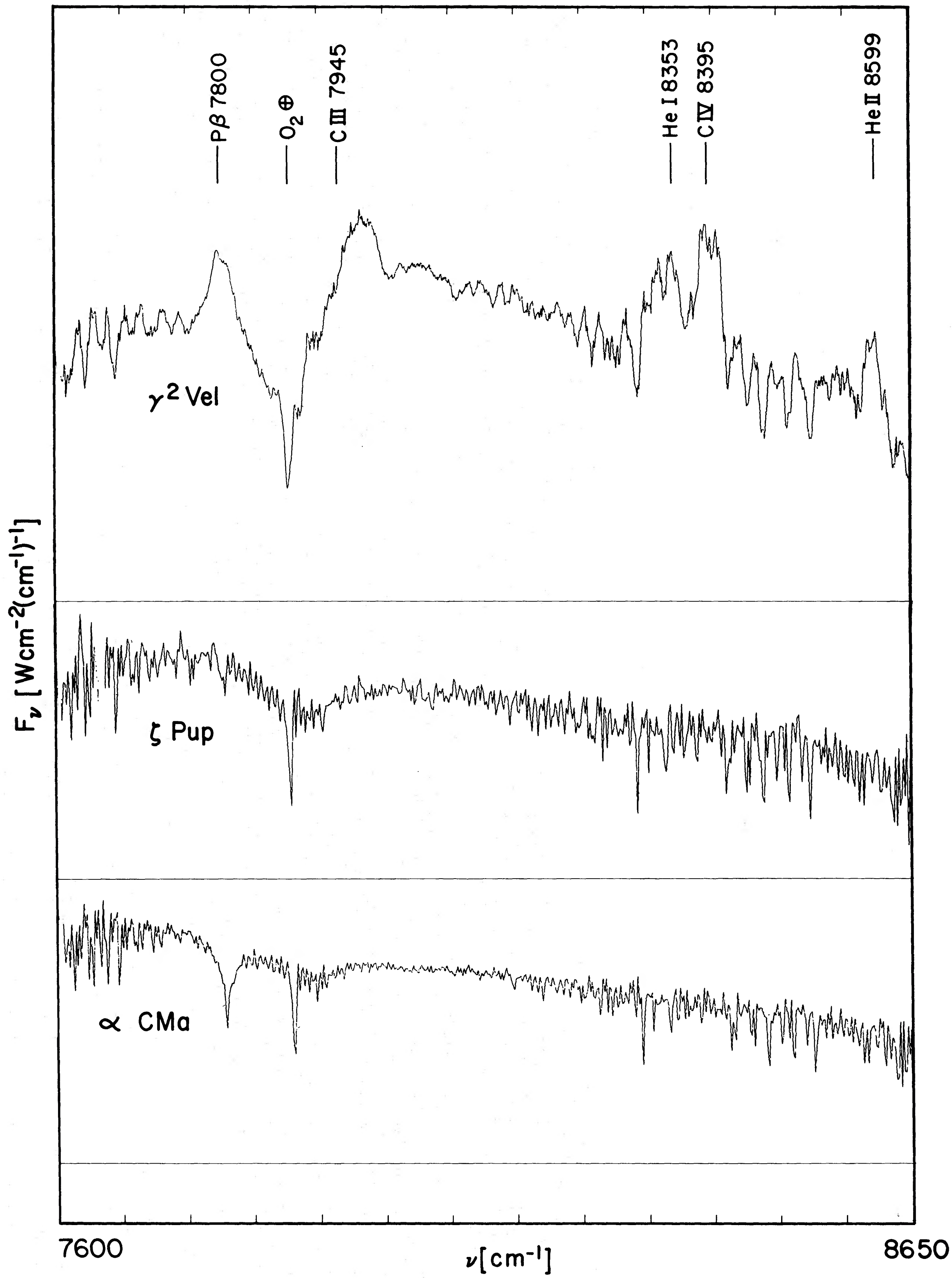


FIG. 2.—The spectral region 7600–8650 $cm^{-1}$. The comments to fig. 1 apply here as well.

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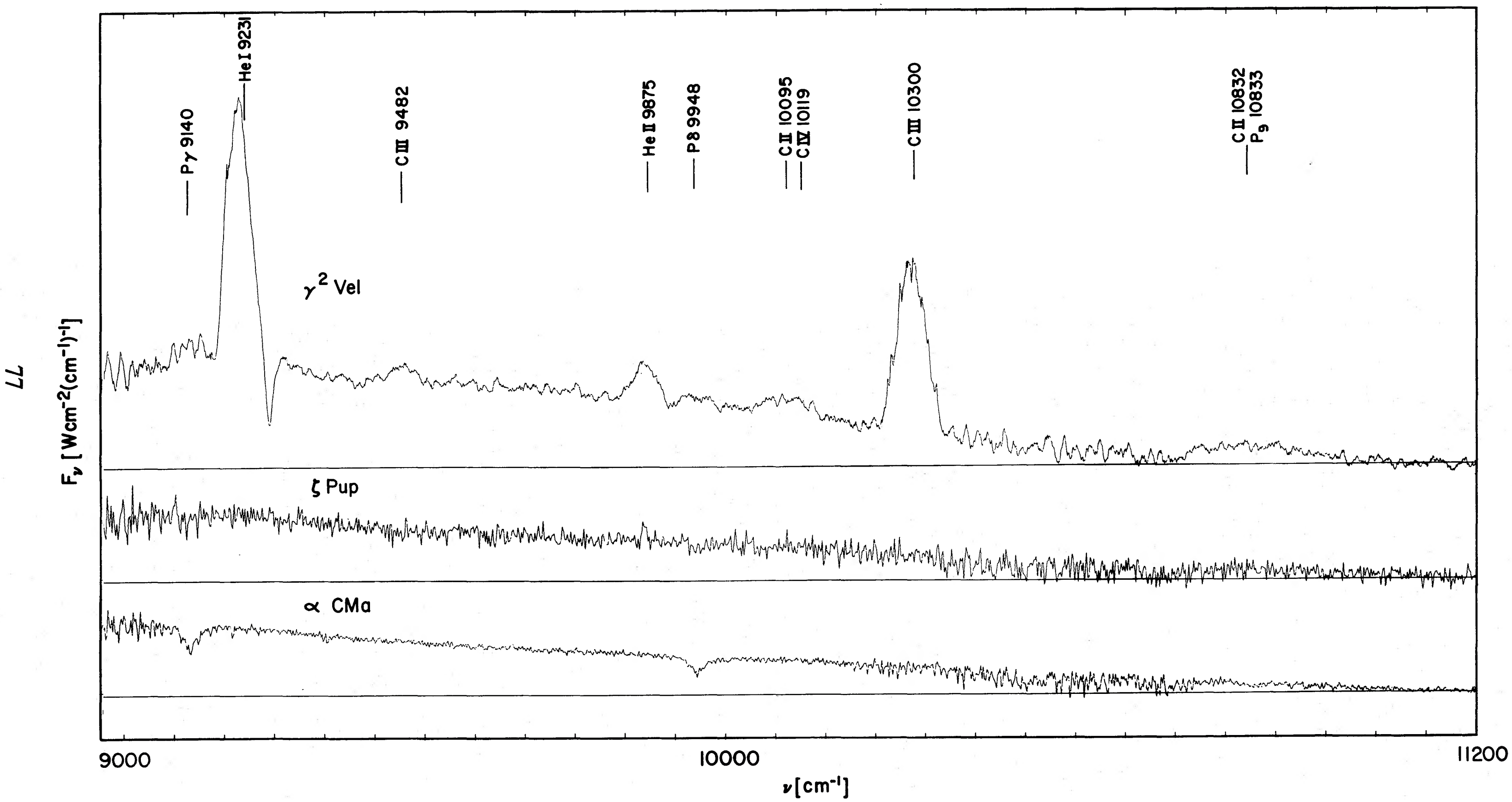


FIG. 3.—The spectral region 9000–11,200 cm$^{-1}$. The comments to fig. 1 apply here as well.

TABLE 2

LINE IDENTIFICATIONS FOR $\gamma^2$ VELORUM

| $\nu$ (cm$^{-1}$) | Identification | Central Intensity | FWHM (km s$^{-1}$) | Remarks |
|---|---|---|---|---|
| 7800..... | P$\beta$ 7800 ($3\,{}^2D$–$6\,{}^2F^o$) | 121 | 1100 | in $H_2O$ |
| | He I 7782 ($3p\,{}^3P^o$–$5s\,{}^3S$) | | | |
| | He I 7820 ($3d\,{}^3D$–$5f\,{}^3F^o$) | | | |
| 7975..... | C III 7945 ($3p'\,{}^3P$–$3d'\,{}^3D^o$) | 120 | 1500 | in $O_2$ |
| | C III 7981 ($4s'\,{}^3P^o$–$4p'\,{}^3P$) | | | |
| 8340..... | He I 8353 ($3p\,{}^3P^o$–$5d\,{}^3D$) | 133: | 1450: | in $H_2O$ |
| | C III 8340 ($4s\,{}^3S$–$4p\,{}^3P^o$) | | | |
| 8395..... | C IV 8400 (7...–8...) | 142: | 1300: | in $H_2O$ |
| 8595..... | He II 8599 ($5f\,{}^2F^o$–$7g\,{}^2G$) | ... | ... | in $H_2O$, weak |
| | C III 8588 ($6p\,{}^3P^o$–$7d\,{}^3D$) | | | |
| 9145..... | P$\gamma$ 9140 ($3\,{}^2D$–$6\,{}^2F^o$) | ... | ... | in $H_2O$, v. weak |
| 9230..... | He I 9231 ($2s\,{}^3S$–$2p\,{}^3P^o$) | 356 | >1400 | Abs. at −1255 km s$^{-1}$ affects width |
| 9485..... | C III 9482 ($4p\,{}^3P^o$–$3p'\,{}^3S$) | 118 | 1500 | |
| 9870..... | He II 9875 ($4f\,{}^2F^o$–$5g\,{}^2G$) | 157 | 1200 | |
| | C III 9873 ($5f\,{}^1F^o$–$6d\,{}^1D$) | | | |
| | C III 9832 ($5f\,{}^1F^o$–$6g\,{}^1G$) | | | |
| 9950..... | P$\delta$ 9948 ($3\,{}^2D$–$7\,{}^2F^o$) | ... | ... | Weak |
| 10,095..... | C II 10,095 ($4f\,{}^2F^o$–$5g\,{}^2G$) | 136 | 2900 | Width due to blend |
| | C II 10,097 ($3p\,{}^4P^o$–$3d\,{}^4D$) | | | |
| | C IV 10,119 ($8p\,{}^2P^o$–$10\,d\,{}^2D$) | | | |
| 10,300..... | C III 10,300 ($3p\,{}^3P^o$–$3d\,{}^3D$) | 503 | 1550 | in $H_2O$ |
| | C III 10,309 ($3p'\,{}^3D$–$3d'\,{}^3F^o$) | | | |
| 10,825..... | P9 10,833 ($3\,{}^2D$–$9\,{}^2F^o$) | ... | ... | Uncertain feature |
| | C II 10,832 ($4d\,{}^2D$–$5f\,{}^2F^o$) | | | |
| | C II 10,827 ($4p\,{}^2P^o$–$5s\,{}^2S$) | | | |

which is present at 8599 cm$^{-1}$, and $5f\,{}^2F^o$–$8g\,{}^2G$, which is obscured by $H_2O$ at 10,698 cm$^{-1}$. No definite statement can be made concerning the 6–$n$ series: 6–9 (6773, masked by $H_2O$), 6–10 (7803, blended with H$\beta$), 6–11 (8564, possibly present but blended with He II 8599), and 6–12 (9144, blended with H$\gamma$). Transitions above 6–12 and in higher series are definitely absent.

*d*) C II (*energy levels: Moore 1970*)

C II is represented in the visual region by the weak line at $\lambda$4267 $3d\,{}^2D$–$4f\,{}^2F^o$. The broad emission feature at 10,095 cm$^{-1}$ is thus likely to be attributable to $4f\,{}^2F^o$–$5g\,{}^2G$ (10,095 cm$^{-1}$) rather than to $3p\,{}^4P^o$–$3d\,{}^4D$ (10,097 cm$^{-1}$). The breadth of the feature is probably a result of blending with C IV $8p\,{}^2P^o$–$10d\,{}^2D$ (10,119 cm$^{-1}$).

The marginally identifiable feature at 10,825 cm$^{-1}$ may be C II $4d\,{}^2D$–$5f\,{}^2F^o$ (10,832 cm$^{-1}$) plus $4p\,{}^2P^o$–$5s\,{}^2S$ (10,827 cm$^{-1}$), blended with P9 10,833.

*e*) C III (*energy levels: Moore 1970*)

These emission lines are prominent in the visual spectrum. The strongest lines are $\lambda$5695 $3p\,{}^1P^o$–$3d\,{}^1D$ and $\lambda$4650 $3s\,{}^3S$–$3p\,{}^3P^o$, which is blended with a C IV line. In the infrared spectrum, C III is responsible for several emission features.

The strong feature near 10,300 cm$^{-1}$ is a blend of $3p\,{}^3P^o$–$3d\,{}^3D$ (10,300 cm$^{-1}$) and some components of $3p'\,{}^3D$–$3d'\,{}^3F^o$ (10,309 cm$^{-1}$). The intrinsic line width prevents a detailed separation of the contributions of the two multiplets. Nonetheless, the facts that the line is approximately symmetric about 10,300 cm$^{-1}$, that there is no significant contribution near 10,245 cm$^{-1}$ ($3p'\,{}^3D_3$–$3d'\,{}^3F^o{}_2$), and that $3p'\,{}^3D$–$3d'\,{}^3F^o$ is predicted to have a lower intensity are all consistent with the assumption that the $3p\,{}^3P^o$–$3d\,{}^3D$ multiplet is dominant.

The weaker emission feature near 7975 cm$^{-1}$ is a blend of the multiplets $3p'\,{}^3P$–$3d'\,{}^3D^o$ (7945 cm$^{-1}$) and $4s'\,{}^3P^o$–$4p'\,{}^3P$ (7981 cm$^{-1}$). The former probably dominates. (The latter cannot be fully predicted because the $4p'\,{}^3P$ and ${}^3P^o$ terms have not been located.) The multiplet $3p'\,{}^3P$–$3d'\,{}^3D^o$ has components spread over 60 cm$^{-1}$ and is affected on the red side by strong telluric $O_2$ absorption. This undoubtedly accounts for the difference between the central wavenumber of the multiplet and that of the observed emission. The $6d\,{}^3D$–$7f\,{}^3F^o$ multiplet, predicted to occur at 7971 cm$^{-1}$ may also contribute to the 7975 cm$^{-1}$ feature.

Another weak feature, at 9485 cm$^{-1}$, is attributable to the interparental transition $4p\,{}^3P^o$–$3p'\,{}^3S$, centered at 9482 cm$^{-1}$.

There are several possible blends of C III lines. The singlets $5f\,{}^1F^o$–$6d\,{}^1D$ at 9873 cm$^{-1}$ and $5f\,{}^1F^o$–$6g\,{}^1G$ at 9832 cm$^{-1}$ may contribute to the He II 9875 line. The multiplet $6p\,{}^3P^o$–$7d\,{}^3D$ may be blended with the weak He II 8599 line. Finally, the $4s\,{}^3S$–$4p\,{}^3P^o$ multiplet with components at 8344, 8339, and 8337 cm$^{-1}$ probably contributes to the weak line attributed to He I 8353.

*f*) C IV (*energy levels: Moore 1970*)

With the exception of the $4s\ ^2S$–$4p\ ^2P^o$ transition at 6976 cm$^{-1}$, the predicted infrared lines arise from transitions involving lower levels with $n = 7$ or 8. Unfortunately, the $4s$–$4p$ doublet is obscured by the $\psi$-band of $H_2O$. The other transitions are expected to be weak on the basis of the C IV lines in the visual spectrum. There is, however, a complex of emission lines corresponding to the 7–8 series at about 8395 cm$^{-1}$.

As previously mentioned, the feature at 10,095 cm$^{-1}$ attributed to C II is probably blended with C IV $8p\ ^2P^o$–$10d\ ^2D$ (10,119 cm$^{-1}$).

*g*) *Other Ions*

Lines of the ions C I, C V, N II–V, O II–V, and Si II–IV could not be identified on the tracings. Energy levels were taken from the following: (1) C I, C V, and O II from Moore (1970); (2) N II–III and O III from Moore (1949); (3) O IV from Bromander (1969); (4) O V from Bockasten and Johansson (1968); (5) N IV–V from Moore (1971), and (6) Si II–IV from Moore (1965).

The absence of these ions was predictable. For example, the oxygen ions are represented in the visual region by weak lines. Since the infrared transitions are between higher levels, their intensities are expected to be below those of the visual region lines. Hence they correspond to undetectable features in the present spectrum.

## IV. DISCUSSION

*a*) *Emission lines in $\gamma^2$ Velorum*

Emission line identifications for $\gamma^2$ Vel are presented in table 2. Central intensities are given in terms of the local continuum set to 100. Total line widths at half intensity (FWHM) are also given.

The only other study of $\gamma^2$ Vel which overlaps the spectral interval 0.9–1.7 $\mu$ has been done by Code and Bless (1964). They identified nine spectral features in the interval 0.85–1.09 $\mu$ from a I-Z plate at a dispersion of 640 Å mm$^{-1}$, corresponding to a resolution of about 10 Å. A comparison of our identifications with theirs shows very good agreement. In common we identify He I 9231, C III 9482, He II 9875, C II 10,095, and C III 10,300. C II 10,829, which they identify, is possibly present in our spectrum. Their identification C III 10,630 lies within the $\rho$-band of $H_2O$, which is particularly strong in our spectrum. Their remaining identifications, C III 10,937 and C III 11,055, not only are weak but also lie at one extreme of our bandpass.

Longward of 9100 cm$^{-1}$ (1.1 $\mu$) our identifications are new for $\gamma^2$ Vel as well as for W-R stars in general. The identified features are consistent with those at shorter wavelengths, being attributable to H I, He I–II, and C II–IV. In view of the severe mutilation of the new features by telluric absorption, we have made no attempt to interpret the intensities and profiles of these lines.[1]

TABLE 3

CENTRAL INTENSITY VARIATIONS WITH EXCITATION CLASS

| Line | HD 192641* WC6 | HD 192103* WC8 | $\gamma^2$ Vel† WC8 |
|---|---|---|---|
| He I 9231 . . . . . | 220 | 330 | 1285 |
| He II 9875 . . . . . | 165 | 215 | 364 |
| C II 10095 . . . . . | 130 | 133 | 267 |
| C III 10300 . . . . | 625 | 990 | 1966 |

* Central intensities from Kuhi (1966*b*).

† Observed values corrected for the presence of the companion.

On the other hand, to the blue of 9100 cm$^{-1}$ the line intensities in $\gamma^2$ Vel may be compared with those found by Kuhi (1966*b*) for similar stars. In this region the telluric absorption is much less severe. However, in making such a comparison, account must be taken of the presence of the O-star component in the $\gamma^2$ Vel system.

As mentioned previously, the O star has been shown to dominate the visual and ultraviolet spectra. Baschek and Scholz (1971*a*, *b*) considered the *absorption*-line intensities in $\gamma^2$ Vel compared to those in single O stars. They concluded that the WC8 component must be 1.5 mag fainter than the O star in the visual region. On the other hand, Conti and Smith (1972) examined the *emission*-line intensities in $\gamma^2$ Vel compared with HD 192103, a single WC8 star. They found the O star to be brighter in the visual by 1.4 mag. That both absorption- and emission-line intensities agree in indicating the O star to be about 1.4 mag brighter, strongly implies the correctness of this value.

Following Conti and Smith (1972), we have considered the central intensities of the infrared emission lines in $\gamma^2$ Vel relative to the intensities in HD 192103, the same comparison star as used by them. Table 3 gives the central intensities as a percentage of the local continuum for the strongest lines in the 0.9–1.1 $\mu$ region. Values for HD 192103 and HD 192641 are taken from Kuhi (1966*b*). The observed values for $\gamma^2$ Vel have been corrected to eliminate the effect of the O-star companion, assuming a luminosity ratio of 3.63 (1.4 mag) between the O star and the WC8 star. The observed line intensities are then clearly much stronger than expected.

It should be pointed out that Kuhi's observations of HD 192103 were done at 10 Å resolution, whereas our observations of $\gamma^2$ Vel were done at 2 cm$^{-1}$ (2 Å at

[1] We wish to point out, however, that the He II 8599 emission line shares its upper level with the He II $\lambda$5411 emission line. Because of this the ratio of fluxes emitted in the lines is well defined, and the ratio of equivalent widths becomes a sensitive measure of the relative continuum levels at 0.54 and 1.16 $\mu$. This introduces a possible approach to determining interstellar reddening corrections.

1 $\mu$). However, the emission lines in this spectral region are nearly 100 Å wide, enabling both studies to resolve the lines fully. In consequence the central intensities should be little affected by the different resolutions. This was confirmed by smoothing our spectrum to an effective resolution of 10 $cm^{-1}$ and remeasuring the central intensities.

The large discrepancy between the predicted and observed line strengths may be attributable to one or more of the following effects: (1) eclipse of the O star by the WC8 component, (2) rapid decrease in the relative continuum contribution of the O star between the visual and near-infrared, (3) intrinsic variation in the emission-line strengths, and (4) different excitation conditions or continuum distribution in HD 192103 from that in the WC8 component of $\gamma^2$ Vel.

The possibility of eclipse can be discounted on several grounds. To produce the observed effect the eclipse would have to be nearly total, implying an eclipse depth of 1.6 mag. Although small-scale variations have been reported for $\gamma^2$ Vel (Gaposchkin 1959), nothing of this size has been noted. Furthermore, the visual appearance of $\gamma^2$ Vel at the telescope was inconsistent with such a large change in magnitude. The difference in magnitude between $\gamma^2$ Vel and $\gamma^1$ Vel was observed to be quite consistent with the expected difference of 2.4 mag. Finally the spectroscopic orbit of Ganesh and Bappu (1967) implies a phase of 0.77 for the epoch of our observation, whereas eclipse of the O star, if it occurs, would occur at about phase 0.45.

Kuhi (1966*a*) has published continuum observations of a variety of W-R stars and compared them with the O9 V star 10 Lacertae. Inspection of his results shows that the O9 I component of $\gamma^2$ Vel may be as much as a few tenths of a magnitude fainter, relative to the WC8 component, at 1 $\mu$ than in the visual region. This change is too small to affect the values in table 3 significantly, and thus excludes the second possibility.

We cannot completely rule out the third possibility, that the emission-line strengths of the WC8 star are intrinsically variable and were particularly intense during our observation. There are no reports in the literature of emission-line strengths increasing by a factor of 5, which is required to eliminate the discrepancy in table 3; yet variations in the line strengths of W-R stars are well known. However, we have a very poor spectrum of $\gamma^2$ Vel, obtained by the same techniques discussed above, for an epoch about 100 days earlier than the observation discussed here. The intensities for He I 9231 and C III 10,300, the strongest features in the 1-$\mu$ region, are essentially the same in that spectrum as are reported for the present spectrum in table 3. This would seem to exclude short-term variability in the line strengths as the reason for the discrepancy.

By default we tentatively adopt the fourth alternative, that the excitation conditions or continuum distribution in HD 192103 and $\gamma^2$ Vel are sufficiently different to introduce the observed difference in line strengths. Some support is given to this interpretation by the remark by Conti and Smith (1972) that $\gamma^2$ Vel seems to be of somewhat lower excitation than HD 192103 on the basis of the emission lines in the visual region. Furthermore, the values in table 3 shows that for the species He I and C II the emission-line fluxes above the continuum are *five* times stronger than expected, but the lines of the next ionization stages He II and C III are only *two* times stronger. However, the increase in strength from HD 192103 to $\gamma^2$ Vel is perhaps more than expected solely on the basis of a lower excitation for $\gamma^2$ Vel, as shown in table 3. We are therefore led to attribute some of the discrepancy to a difference in continua between the two stars.

It is clear that a 1-$\mu$ excess, presumably due to circumstellar emission, in HD 192103 without a corresponding excess in $\gamma^2$ Vel could explain the apparently strong emission lines in $\gamma^2$ Vel by means of *dilution* of the emission-line strengths in HD 192103. The central intensities for the $\gamma^2$ Vel emission lines in table 3 would then not be too large, but rather the central intensities for HD 192103 would be too small by virtue of the failure to correct for the 1-$\mu$ excess.

Evidence that this interpretation is viable comes from the infrared photometry of Allen, Swings, and Harvey (1972). They show that HD 192103 does indeed have excess emission at 1.6 $\mu$ and at 2.2 $\mu$, relative to other WC stars. On the other hand, Allen and Porter (1972) find $\gamma^2$ Vel to be anomalously weak at 2.2 $\mu$, which implies the absence of a circumstellar shell, and hence no 1-$\mu$ excess. Without more detailed observations we cannot surmise the size of the correction required to the central intensities of the HD 192103 emission lines, but we are convinced that this effect must contribute to the apparent discrepancy in relative line strengths.

### *b*) He I 9231 *Absorption in* $\gamma^2$ *Velorum*

The only positive identification of stellar absorption in $\gamma^2$ Vel is the blueshifted absorption component of He I 9231 ($\lambda$10,830). (The absorption structure in the C III 10,300 emission is entirely attributable to telluric $H_2O$.) The radial velocity and intensity of the line are consistent with the available observations of the weaker line He I $\lambda$3889, which shares the same lower level as $\lambda$10,830. From a tracing provided by M. Scholz, the $\lambda$3889 radial velocity is estimated as $-1200$ km $s^{-1}$ and the central intensity implies an optical depth $\tau_{3889} \simeq 0.06$. For $\lambda$10,830 the measured radial velocity is $-1255 \pm 30$ km $s^{-1}$. This value is also in agreement with the velocities estimated for the components of ultraviolet resonance lines; Carruthers (1968) gives the velocities $-1370$ km $s^{-1}$ for Si III $\lambda$1207 and $-1275$ km $s^{-1}$ for C III $\lambda$1175.

From the above optical depth for $\lambda$3889 the central depth of $\lambda$10,830 can be readily predicted. Using the known oscillator strengths for the two transitions, we have $\tau_{10,830}/\tau_{3889} \simeq 23$ and hence $\tau_{10,830} \simeq 1.3$. The central intensity is then $I/I_0 = e^{-1.3} = 0.27$, in excellent agreement with the observed value of $0.27 \pm 0.08$.

TABLE 4

IDENTIFICATIONS FOR $\zeta$ PUPPIS

| Line | $V_r$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | $I/I_0$ | Remarks |
|---|---|---|---|---|
| P$\beta$ 7800...... | $-85 \pm 30$ | $385 \pm 30$ | $0.10 \pm 0.01$ | Absorption |
| He II 9875.... | $+205 \pm 30$ | $273 \pm 30$ | $1.32 \pm 0.02$ | Emission |

### c) *The Spectrum of $\zeta$ Puppis*

We are able to identify only two stellar features in the spectrum of $\zeta$ Pup: P$\beta$ 7800 in absorption and He II 9875 in emission. Table 4 gives the heliocentric radial velocity ($V_r$), the full line width at half-intensity (FWHM), and the residual intensity ($I/I_0$).

The radial velocities are in agreement with the expected velocities for absorption and emission lines in $\zeta$ Pup. Morton *et al.* (1969) report $+160$ km s$^{-1}$ for the He II $\lambda$1640 emission, and Baschek and Scholz (1971*c*) give velocities $-70$ and $+180$ km s$^{-1}$ for the absorption and emission components, respectively, in He II $\lambda$4686. A tentative identification of an absorption component at $-70$ km s$^{-1}$ in He II 9875 by Mihalas and Lockwood (1972) is not confirmed here. However, the signal-to-noise ratio in our spectrum is not as good as in theirs, and furthermore the overall structure of He II 9875 appears to have changed between their observation and ours (see below).

Buscombe (1969) investigated the rotational broadening in $\zeta$ Pup, determining $v_e \sin i = 340$ km s$^{-1}$ from several absorption lines. Our value of $385 \pm 30$ km s$^{-1}$ for P$\beta$ is in accord with this.

The width of the He II 9875 line is considerably narrower than expected. In the visual spectrum the typical emission-line width is 500 km s$^{-1}$ (Heap 1972). From the line profile published by Mihalas and Lockwood, we estimate a line width of nearly 500 km s$^{-1}$ for their observation of He II 9875. Our value of $273 \pm 30$ km s$^{-1}$ is about half as large.

The residual intensity observed by us is, however, much greater than that found by Mihalas and Lockwood. At the time of our observation, He II 9875 extended 32 percent above the local continuum, compared with 13 percent at their epoch. Since the line width decreased by about the same factor that the central intensity increased, the total flux in He II 9875 at the two epochs was about the same.

It has been pointed out by Baschek and Scholz (1971*c*) that the similarities between $\zeta$ Pup and the WN stars may be attributable to a faint WN companion to the O4f star. Davis *et al.* (1970) showed that $\zeta$ Pup appears single when observed with the stellar intensity interferometer, thus providing an upper limit to the brightness of any secondary of 3.1 mag fainter than the primary. From our spectrum we can set a much more stringent condition on the secondary's brightness.

Kuhi (1966*b*) has shown that the two strongest lines in the 1-$\mu$ region for WN stars are He II 9875 and He I 9231. For the low-excitation WN stars, as the hypothetical companion to $\zeta$ Pup is generally assumed to be, He II 9875 dominates. For the WN6 star HD 192163 the central intensities given by Kuhi are 300 for He II 9875, and 220 for He I 9231.

Our observation of He II 9875 in $\zeta$ Pup cannot be used to set a useful limit on the brightness of the secondary because it clearly arises from the O4f star. The line width of about 273 km s$^{-1}$ is far too narrow for this line to be attributable to a WN star. For example, from the published spectrum of HD 192163 (Kuhi 1966*b*) we estimate a full width of half-maximum of greater than 2000 km s$^{-1}$ for He II 9875.

However, from the absence of He I 9231 we can set a very effective limit on the secondary's brightness. An upper limit to the central intensity of He I 9231 in the $\zeta$ Pup spectrum is 5 percent above the continuum. Comparing this with the value of 220 for HD 192163, we derive a magnitude difference at 1 $\mu$ between the O4f and the hypothetical companion of $\geqslant 4.0$ mag. From Kuhi's (1966*a*) energy distributions of WN stars, we estimate that a WN6 star will have $\sim 0.3$ mag excess flux at 1 $\mu$ relative to an O star if the visual magnitudes are equal. Thus in the visual our limit on the secondary becomes 4.3 mag.

Adopting Conti and Alschuler's (1972) absolute magnitude for $\zeta$ Pup, $M_v = -6.6$, we estimate $M_v \geqslant -2.3$ for the companion. This is much fainter than the absolute magnitudes of WN stars according to Smith (1968), $M_v = -3.9$ to $-6.8$. We conclude that the W-R characteristics exhibited by $\zeta$ Pup in the visual spectrum are intrinsic to the O4f star and not the result of an unresolved WN companion.

## V. SUMMARY

We have extended the observed spectroscopic limits for WC and Of stars to 1.7 $\mu$ by means of a rapid-scan, Michelson-type interferometer. The new region (1.1–1.7 $\mu$) contained numerous emission features for the WC8 component of $\gamma^2$ Vel, but only the P$\beta$ line in absorption for the O4f star $\zeta$ Pup. Line identifications for $\gamma^2$ Vel were made from predictions based upon the best available energy level tabulations of the ions H I, He I–II, C I–V, N II–V, O II–V, and Si II–IV. Identifications with H I, He I–II, and C II–IV were established.

In the spectral region 0.8–1.1 $\mu$ our identifications of the emission features in $\gamma^2$ Vel are in excellent accord with the previous investigation by Code and Bless (1964). However, after correcting the line intensities for dilution by the O9 I component of $\gamma^2$ Vel, we find the lines to be 2–5 times stronger than the same lines in

HD 192103, as given by Kuhi (1966*b*). This is attributed in part to a 1-$\mu$ continuum excess in HD 192103 and in part to a lower excitation in $\gamma^2$ Vel.

The absorption component to He I $\lambda$10,830 in $\gamma^2$ Vel is shown to have a radial velocity and central depth in agreement with the absorption component to He I $\lambda$3889.

For $\zeta$ Pup we identify the only line in the 0.8–1.1-$\mu$ interval with He II $\lambda$10,124 in emission. This confirms the observation by Mihalas and Lockwood (1972), although we do not observe the blueshifted absorption component tentatively claimed by them. The line profile for the He II $\lambda$10,124 emission differs from that given by Mihalas and Lockwood in the sense of being stronger and narrower. The equivalent width is essentially unchanged from their value.

From the absence of He I 9231 in emission in $\zeta$ Pup, we set an upper limit to the brightness of any hypothetical WN component, $M_v \gtrsim -2.3$. Since this is considerably fainter than the accepted absolute magnitudes of WN stars, we conclude that the W-R characteristics exhibited by $\zeta$ Pup in the visual spectrum are intrinsic to it.

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