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# ON THE NEAR-INFRARED EXCESSES OF VERY COOL SUPERGIANTS

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## ABSTRACT

Spectroscopic and narrow-band photometric observations of ~15 G, K, and M supergiants with large infrared excesses have been made to search for line weakening and chromospheric near-infrared emission of the form proposed by Humphreys and Gilman to be present in the peculiar M stars S Per, VY CMa, and VX Sgr. The results indicate that the line weakening of S Per and VX Sgr is probably photospheric in origin and temporally variable, while that of VY CMa may be constant. None of the other supergiants show significant line weakening. There are no near-infrared excesses evident in the photometry of any of these objects; overestimates of interstellar extinction and TiO opacity may have led to a mistaken identification of chromospheric $H^-$ bound-free emission from S Per and VX Sgr.

Veiling of the 4.8 $\mu$m absorption feature in late-type supergiants with extremely large infrared excesses implies that the 3.5–8 $\mu$m excesses are formed above the molecular photospheres and are probably thermal reradiation from the circumstellar shells rather than free-free emission. In addition, the K supergiants RW Cep, W Cep, and IRC +60370 have significantly less blue and ultraviolet flux than is normal for their spectral types. This missing flux may be the energy supply for the infrared excesses radiated by their circumstellar shells.

*Subject headings:* infrared: sources — stars: circumstellar shells — stars: late-type — stars: supergiants

## I. INTRODUCTION

The discovery of circumstellar emission at infrared wavelengths from late-type stars has stimulated extensive observational and theoretical research over the past decade. It now appears that the strength of the emission feature centered at 10 $\mu$m, commonly attributed to silicate grains, correlates with both the total luminosity and the photospheric temperature of the underlying star (see, e.g., Humphreys, Strecker, and Ney 1972; Cohen and Gaustad 1973). Moreover, the most luminous G, K, and M-type supergiants show additional emission between 3.5 and 8.6 $\mu$m. The most extreme members of this group, such as S Per, have a flux distribution between 2 and 8 $\mu$m paralleling that of optically thin free-free radiation.

Recently, Humphreys (1974) (see also Herbig 1969; Wallerstein 1971*a*) reported strong absorption-line weakening or veiling in the near-infrared spectra of three M supergiants with large infrared excesses: S Per, VY CMa, and VX Sgr (hereafter referred to as S Per *et al.*). She argued that photometry of these three stars indicated large near-infrared radiation excesses as the cause of the veiling. She and Gilman (1974) identified these excesses as optically thin chromospheric $H^-$ free-bound emission and also suggested that accompanying optically thin free-free radiation may be responsible for the 3–8 $\mu$m emission. Gilman found that his theoretical models of S Per *et al.* required their chromospheres to provide more than *half* their total fluxes.

I undertook a spectroscopic and photometric study to examine more closely the near-infrared line veiling and proposed radiation excesses of these three stars, and to establish whether these phenomena are exhibited by other luminous G, K, and M-type supergiants with large infrared excesses. If immensely luminous chromospheres proved to be a general property of these stars, this would greatly affect ideas concerning their atmospheric structure and mass-loss mechanisms. However, my results suggest that the line weakening of S Per and VX Sgr is variable and is more likely to be caused by photospheric peculiarities than by chromospheric emission.

## II. NEAR-INFRARED ABSORPTION LINE VEILING

In her paper on excess radiation from peculiar M supergiants, Humphreys (1974) reported strikingly evident absorption-line veiling in near-infrared spectra of S Per *et al.* which she attributed to overlying chromospheric $H^-$ free-bound emission. The spectra of the more normal M supergiants HD 97671 and AH Sco (Humphreys and Ney 1974*a*) indicated that weaker line veiling might be present in those stars also. From isodensity tracings of metallic absorption lines near λ8400, she determined the ratio of chromospheric excess to photospheric continuum emission by comparison with normal M supergiants. These ratios ($\equiv E/C$) varied from 0.6 for S Per to approximately 1.0 for VY CMa and VX Sgr. Application of $\chi^2$ statistics to Humphreys's measurements indicates that the apparent line veiling is significant at greater than the 99% confidence level (see Table 1).

I have made similar absorption-line measurements of my coudé spectra of G, K, and M supergiants with

TABLE 1

EXCESS-TO-CONTINUUM RATIOS

| Star | [3.5] − [11] | Observation Date | Spectral Type | Observer* | Best Fit $E/C$ | 99% Confidence Limits | Best Fit $\chi^2$ | No. Lines |
|---|---|---|---|---|---|---|---|---|
| S Per........ | 3.2 | 1971 | M4p | H | 0.6 | +0.4 −0.3 | 7.3 | 8 |
| | | 1973 Oct. | M6 | F | 0.0 | +0.3 | 10.0 | 7 |
| | | 1974 Aug. | M4.5 Ia | F | 0.0 | +0.2 | 16.1 | 8 |
| | | 1975 Nov. | M7 | F | 0.0 | +0.3 | 14.4 | 7 |
| VY CMa..... | 3.8 | 1971–1972 | M4–5 | H | 1.0† | +0.5 −0.5 | 4.9 | 8 |
| | | 1973 Sept. | M5 | F | 0.2‡ | +0.3 −0.2 | 4.3 | 7 |
| | | 1974 Feb. | M5 | F | 0.2‡ | +0.4 | 20.4 | 7 |
| | | 1975 Nov. | M5 | F | 0.2‡ | +0.3 −0.2 | 21.9 | 7 |
| VX Sgr...... | 3.4 | 1971–1972 | M4p | H | 1.0 | +0.5 −0.4 | 5.9 | 8 |
| | | 1973 Sept. | M9 | F | 0.0: | ... | ... | 4 |
| | | 1974 Aug. | M8.6 | F | 0.0: | ... | ... | 4 |
| HS Cas...... | ... | 1974 Aug. | M4 Ia | F | 0.2 | +0.2 | 5.6 | 8 |
| KW Sgr...... | 2.8 | 1974 Aug. | M4 Ia | F | 0.2 | +0.2 | 7.6 | 8 |
| PZ Cas...... | 2.7 | 1974 July | M3 Ia | F | 0.0 | +0.2 | 2.3 | 8 |
| BC Cyg...... | 3.5 | 1974 July | M3.5 Ia | F | 0.0 | +0.2 | 12.8 | 8 |
| U Lac....... | 2.3 | 1974 Aug. | M3 Ia | F | 0.0 | +0.1 | 38.2 | 8 |
| W Per....... | 2.6 | 1974 July | M3 Iab | F | 0.0 | +0.2 | 13.8 | 8 |
| | | 1975 Nov. | M5 I | F | 0.0 | +0.4 | 42.3 | 7 |
| AH Sco...... | 3.0 | 1974 Aug. | M4 Ia | F | 0.0 | +0.2 | 16.1 | 8 |
| UY Sct...... | 2.7 | 1974 Aug. | M4 Ia–Iab | F | 0.0 | +0.2 | 14.3 | 8 |

* H = Humphreys (1974); F = this paper.

† Using M4 supergiants as reference objects.

‡ Using $\alpha$ Her (M5 Ib) as reference object.

large 10 $\mu$m excesses, and, for comparison purposes, MK standards (Morgan and Keenan 1973) and additional reference stars. The spectra extend from 7600 to 8700 Å at a dispersion of 35 Å mm$^{-1}$. They were taken at Lick Observatory during 1973–1975 with either the 3.05 m reflector or the 50 cm coudé auxiliary telescope, using a Varo S-20 image intensifier optically coupled to 103a-D or baked IIIa-J plates. Each spectrum was scanned with the Berkeley PDS microphotometer and reduced to relative intensities with the aid of calibrated exposure strips present on each plate. I determined characteristic curves by a modified de Vaucouleurs method (1968). The modification was to redefine the opacitance $\omega$ to be $(1/T)^\alpha - 1$. De Vaucouleurs set $\alpha = 1$, which works well for 103a-D emulsion; but I found that IIIa-J emulsion required using $\alpha \sim 0.25$ to produce a linear relationship between $\log I$ and $\log \omega$. The resultant characteristic curve rms fitting errors were normally less than 0.02 in $\log_{10} I$ up to density 2.3.

### *a*) *M1–4 MK Supergiant Standards*

I measured absorption-line residual intensities ($\equiv R\lambda$) in the near-infrared spectra of eight MK supergiant standards (BU Gem [M1–2 Ia–Iab], HD 202380 [M2 Ib], 119 Tau [M2 Ib], $\mu$ Cep [M2 Ia], HD 190788 [M3 Ib], RW Cyg [M3 Ia], SU Per [M4 Iab], and AZ Cyg [M3–4 Iab]). The individual lines (Fe I $\lambda\lambda$8327, 8387; Ti I $\lambda\lambda$8382, 8412, 8426, 8435; Ca II $\lambda\lambda$8498, 8542) were chosen for their low $R\lambda$'s ($\lesssim 0.75$) in early M supergiants; five of the eight lines are common to Humphreys's (1974) list. The dispersion in $R\lambda \approx 0.03$ for a specific line. If $\chi^2$ statistics are applicable, a radiation excess whose $E/C = 0.25$ will be detectable in the near-infrared spectrum of an early M supergiant at greater than the 99% confidence level.

### *b*) *M3–4 Ia Supergiants*

A large percentage of all known M3–4 Ia supergiants between $l^{\mathrm{II}} \sim 0°$ and $l^{\mathrm{II}} \sim 120°$ constitute the first set of program stars. These supergiants were selected for their large 10 $\mu$m excesses; the MK standard RW Cyg would also belong to this group. Log intensity (photographic) tracings of most of these objects, and, for comparison, the MK standards $\mu$ Cep and AZ Cyg, are shown in Figure 1. The residual intensity measurements, summarized in Table 1, reveal that two of the nine program supergiants, HS Cas and KW Sgr, show some evidence of line weakening. Both objects are best fitted by $E/C = 0.2$, relative to the MK standards. The other seven supergiants, including S Per (1974 August observation: M4.5 spectral type) and AH Sco (1974 July observation: M4), are best fitted by $E/C = 0.0$ with $E/C$'s greater than 0.2 ruled out statistically.

UY Sct, S Per, and AH Sco have noticeably weaker Ca II $\lambda\lambda$8498, 8542 lines than do the MK standards, though their other absorption lines are of comparable strength. The Ca II lines are weak in HS Cas and KW Sgr also. One explanation for this weakness is that the

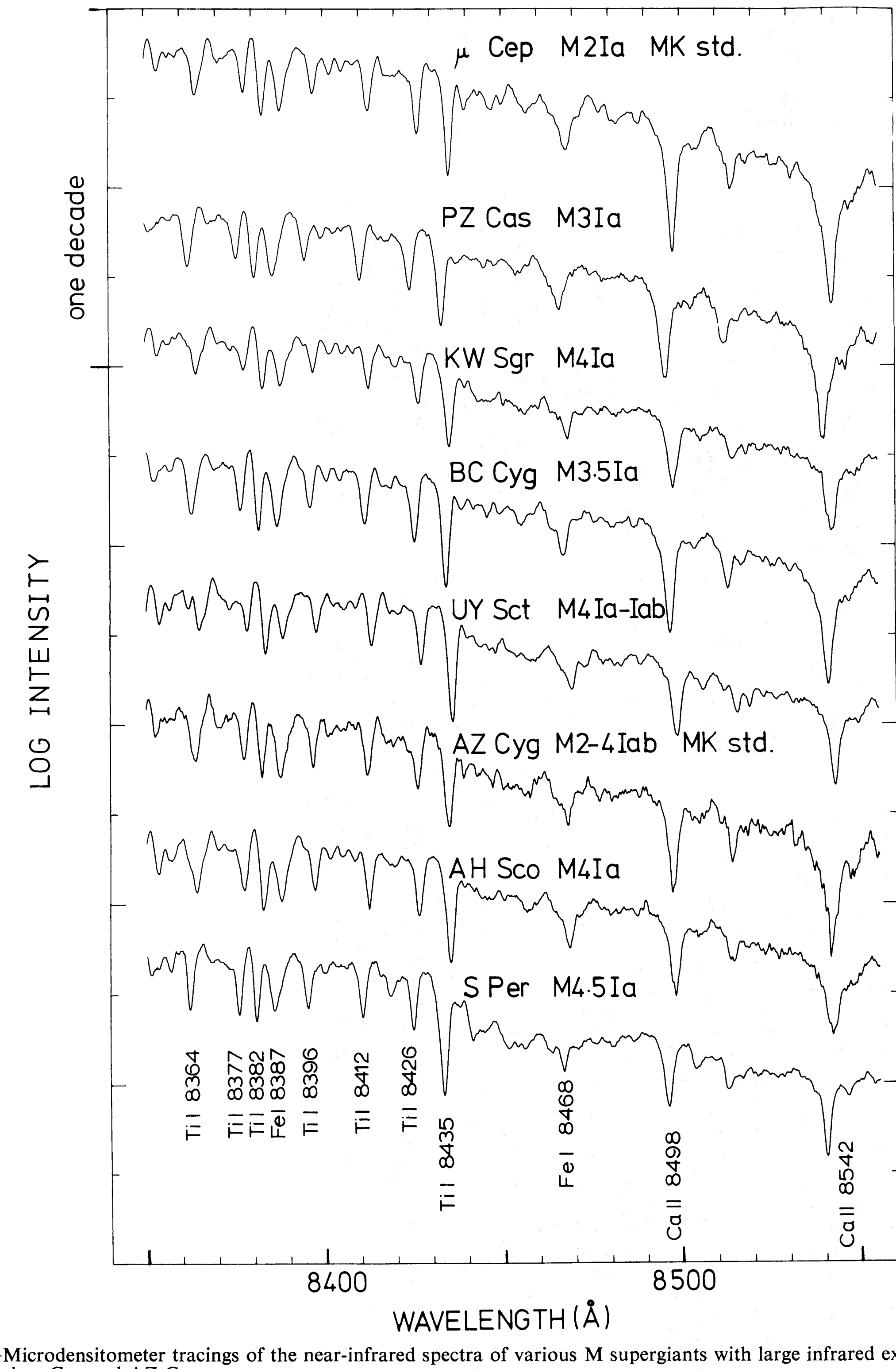


FIG. 1.—Microdensitometer tracings of the near-infrared spectra of various M supergiants with large infrared excesses and the MK standards $\mu$ Cep and AZ Cyg.

outer photospheres of these stars may be cooler than normal. The Ca II infrared triplet rapidly decreases in strength with decreasing temperature between spectral types M3 and M6 and is thus very sensitive to boundary effects. Another possibility is that chromospheric line emission, similar to that which occurs at the H and K Ca II lines, could partially veil the infrared triplet. However, Anderson (1974), who used much higher resolution, did not observe any emission at λ8498 in late-type stars of various luminosities and K line emission strengths. I stress that possible emission is suggested only in the calcium infrared triplet, and therefore cannot be due to a process such as $H^-$ free-bound emission which would weaken all the near-infrared absorption lines.

### *c) M5–8 Reference and Program Stars*

The rapid decline of absorption-line strength in the λ8400 region due to increasing molecular absorption after spectral type M4 makes it both more difficult to

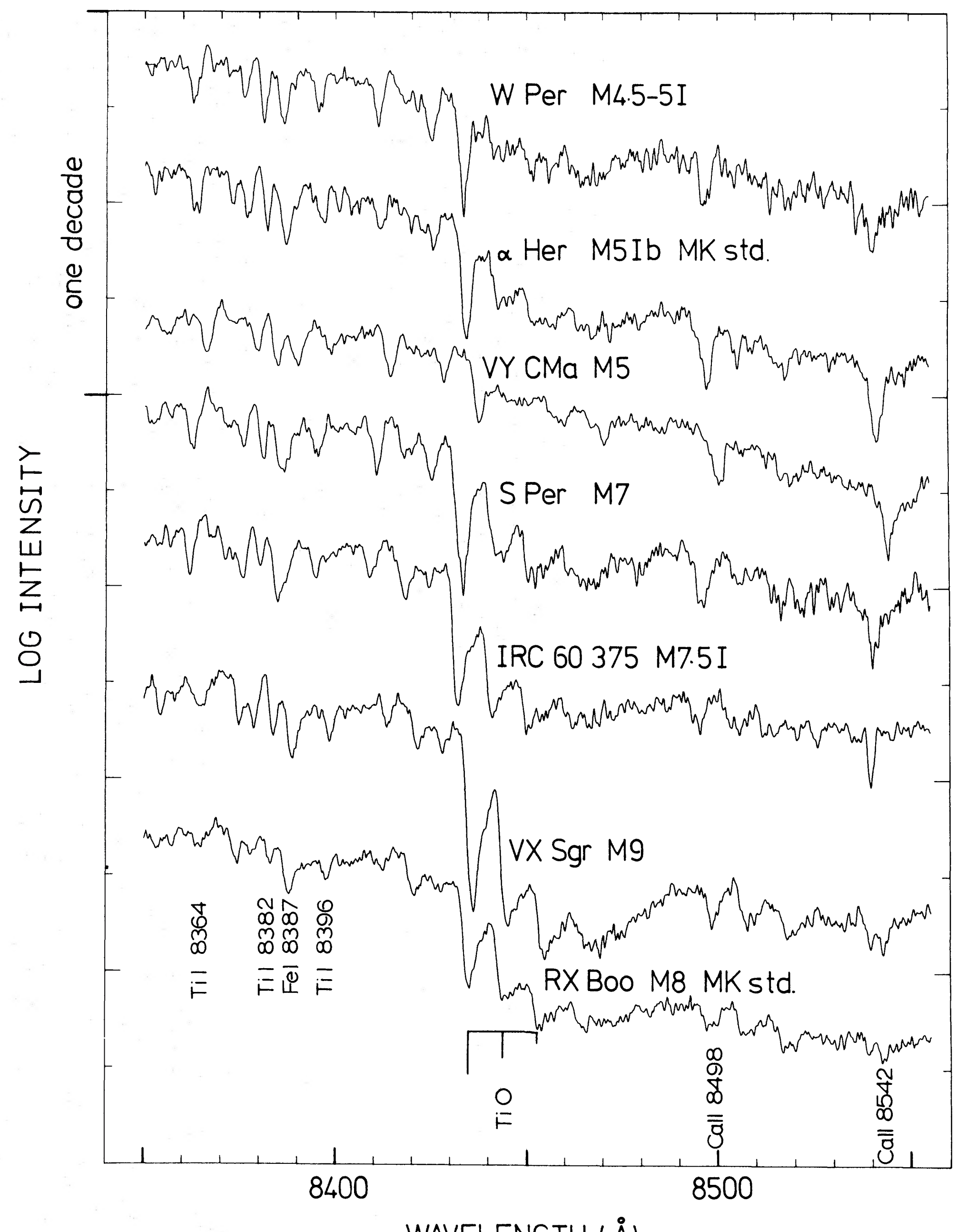


FIG. 2.—Same as Fig. 1. Alpha Her and RX Boo are MK standards.

detect line veiling in M5–8 stars and much more critical to use reference stars of the correct temperature for comparison purposes. As reference stars I have chosen $\alpha$ Her (M5 Ib), 30 Her (M6 III), HD 207076 (M7 III), RX Boo (M8e), Y UMa (M7 II–III), and IRC +60375 (M7.5 I). The first four stars are MK standards, and the last star is classified as a supergiant from its membership in an open cluster (Fawley and Cohen 1974). There are no MK supergiant standards of later spectral type than M5. From measurements of six spectra each of $\alpha$ Her and HD 207076, the rms dispersion in $R\lambda$ for a single line $\leqslant 0.03$. This dispersion will be used in the $\chi^2$ statistics of Table 1 for W Per, S Per, and VY CMa.

#### i) *W Persei and S Persei*

Normally, the Per OB1 supergiant W Per has an M3 spectral type, but a 1975 November (Fig. 2) near-infrared spectrum and 1975 October spectrophotometry (§ III) correspond to ~M5. Relative to $\alpha$ Her, W Per has normal line strengths except for a weak Ca II infrared triplet.

The 1973 October and 1975 November (Fig. 2) spectra of S Per exhibit later spectral types (M6, M7) than its normal classification of M4e Ia. Relative to the M6–7 reference stars, these two spectra have normal line strengths and are best fitted by excess to continuum ratios of 0.0. Thus, neither these spectra nor that of 1974 August (M4.5 Ia, Fig. 1) shows evidence of the line veiling ($E/C \approx 0.6$) seen previously (1971–1972) by Humphreys, which implies that such veiling must be highly variable in strength.

#### ii) *VY Canis Majoris*

My three near-infrared spectra of VY CMa from 1973 to 1975 all indicate an M5 spectral type according to the TiO band head strength at $\lambda\lambda$7820 and 8440. This classification agrees with the near-infrared TiO spectrophotometric type of M5–5.5 obtained in 1974 February (§ III). It also coincides with Hyland *et al.*'s (1969) M5 classification based upon numerous blue, red, and near-infrared 15 Å $\mathrm{mm}^{-1}$ spectra of VY CMa.

Relative to $\alpha$ Her (M5 Ib), the absorption-line $R\lambda$'s of all three spectra of VY CMa are best fitted by veiling strengths of $E/C = 0.2$. Statistical limits of $E/C \leq 0.6$ can set at the 99% confidence level. Though this veiling strength is much smaller than that ($E/C \approx 1.0$) found two years earlier by Humphreys, this difference probably arises from her use of M4 rather than M5 supergiants as comparison objects, and not from temporal variability. The comparison of VY CMa with M4 supergiants, which have stronger absorption lines than do M5 supergiants, would lead to much larger veiling strengths. For example, if my 1973 September spectrum of VY CMa is compared with M3–4 supergiant standards rather than with $\alpha$ Her, it is best fitted by an $E/C = 0.7$, which is comparable to Humphreys's value. Therefore, it is likely that if she had compared her spectra of VY CMa with $\alpha$ Her, as was done in this paper and Hyland *et al.*, she too would have found an $E/C \approx 0.2$.

Besides absorption-line weakening, VY CMa's near-infrared spectra show emission at the $\lambda\lambda$7667, 7749, and 8435 TiO band heads, and also at several VO and ScO band heads similar to that previously reported by Herbig (1969), Hyland *et al.* (1969), and Wallerstein (1971*c*, 1977). Herbig suggested that a cool (~1000 K) equatorial disk of gas and dust surrounding the central star of VY CMa is responsible for both the molecular band head emission and the line weakening seen at red and near-infrared wavelengths.

#### iii) *VX Sagittarii*

Despite extremely late spectral types, my 1973–1974 spectra of VX Sgr (Fig. 2) exhibit surprisingly strong absorption lines, especially $\lambda\lambda$8377, 8382, 8387, 8396, and 8426, relative to IRC +60375 and RX Boo. This suggests that the line veiling of VX Sgr, like that of S Per, is temporally variable. Humphreys's VX Sgr spectra that show blue and near-infrared line veiling occur near maximum light, whereas my spectra span the 1973 September minimum (Celis 1975).

### *d) G and K Supergiants*

HR 6392, AX Sgr, RW Cep, W Cep, and IRC +60370 are a group of highly luminous G and K supergiants with large infrared excesses identical in nature to those of M supergiants (Dyck *et al.* 1971; Humphreys, Strecker, and Ney 1972; Humphreys and Ney 1974*b*). For reference, I obtained coudé spectra of a few G and K supergiants that had no detectable 10 $\mu$m excesses according to Hackwell and Gehrz (1974). Residual intensity measurements show no evidence of systematic absorption-line veiling or weakening in G and K supergiants with large infrared excesses relative to those without such excesses.

In summary, the strong near-infrared line veiling observed by Humphreys in S Per *et al.* is not characteristic of luminous late-type supergiants with large infrared excesses. Moreover, the line veiling in S Per and probably VX Sgr is temporally variable, while that of VY CMa may be constant with $E/C \approx 0.2$. Humphreys also detected some variability in line-veiling strength, especially at blue wavelengths, in two years of observations of VY CMa and VX Sgr. She commented upon the similar behavior of long-period Mira variables (Merrill, Deutsch, and Keenan 1962), which also show variable line weakening of unknown causes. This point is further discussed in § VI.

## III. PHOTOMETRIC OBSERVATIONS AND MOLECULAR INDICES

### *a) Narrow-Band Observations*

Three sets of narrow-band photometry were obtained in 1974 and 1975 with the Lick Observatory 91 cm Crossley reflector, using the prime focus scanner (Wampler 1966). Near-infrared observations of VY CMa on the Wing (1967) system with 32 Å bandpasses were made in 1974 February. In 1974 August and 1975 October, data on numerous G, K, and M supergiants were taken at visual and near-infrared wave-

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TABLE 2A

NARROW-BAND PHOTOMETRY: K STARS

| Star<br>Obs. Date<br>Sp. Type | HD 38427<br>1975 Oct.<br>G8 Iab | AX Sgr<br>1974 Aug.<br>G8 Ia | HR 8321<br>1975 Oct.<br>K0 Ib | HD 45829<br>1975 Oct.<br>K0 Iab | HD 221861<br>1975 Oct.<br>K0 Iab | RW Cep<br>1975 Oct.<br>K0 Ia | W Cep<br>1974 Aug.<br>K0 Ia | W Cep<br>1975 Oct.<br>K0 Ia | IRC +60370<br>1975 Oct.<br>K4.5: Ia |
|---|---|---|---|---|---|---|---|---|---|
| Wavelength (Å) | | | | | $-2.5 \log (F_\lambda/F_0)$* | | | | |
| 4036...... | 8.36 | ... | 6.60 | 8.29 | 7.74 | 9.50 | ... | 9.40 | ... |
| 4167...... | 8.40 | ... | 6.61 | 8.34 | 7.76 | 9.25 | ... | 9.23 | ... |
| 4785...... | 6.93 | ... | 5.47 | 6.91 | 6.29 | 7.26 | ... | 7.81 | ... |
| 5262...... | 6.74 | ... | 5.38 | 6.74 | 6.00 | 6.82 | ... | 7.34 | 9.82 |
| 5556...... | ... | 7.52 | ... | ... | ... | ... | 7.10 | ... | ... |
| 5820...... | 6.29 | 7.25 | 4.99 | 6.29 | 5.45 | 5.96 | 6.84 | 6.61 | 9.08 |
| 6100...... | 6.31 | 7.17 | 5.05 | 6.35 | 5.47 | 5.93 | 6.74 | 6.58 | 8.94 |
| 6456...... | ... | 7.06 | 5.08 | ... | 5.45 | 5.87 | 6.64 | 6.49 | 9.77 |
| 7010...... | 6.31 | 6.83 | 5.08 | 6.36 | 5.37 | 5.68 | 6.48 | 6.31 | 8.32 |
| 7144...... | 6.30 | ... | 5.07 | 6.37 | 5.35 | 5.63 | ... | 6.24 | 8.37 |
| 7550...... | 6.24 | 6.65 | 5.06 | 6.32 | 5.28 | 5.52 | 6.35 | 6.20 | 7.97 |
| 8090...... | 6.40 | 6.64 | 5.19 | 6.50 | 5.37 | 5.59 | 6.43 | ... | 7.87 |
| 8370...... | ... | 6.55 | ... | ... | ... | ... | 6.33 | 6.09 | ... |
| 8804...... | 6.34 | 6.42 | 5.24 | 6.43 | 5.29 | 5.39 | 6.22 | ... | 7.40 |
| 9960...... | ... | 6.22 | ... | ... | ... | ... | 6.13 | 6.00 | ... |
| 10400...... | 6.37 | 6.22 | 5.37 | 6.48 | 5.26 | 5.26 | 6.09 | 6.02 | 6.90 |
| 10564...... | 6.39 | 6.21 | 5.40 | 6.51 | 5.29 | 5.28 | 6.04 | ... | 6.88 |
| 10870...... | ... | 6.32 | ... | ... | ... | ... | 6.16 | ... | ... |
| 10976...... | 6.65 | 6.55 | 5.64 | 6.85 | 5.58 | 5.49 | 6.44 | 6.30 | 7.30 |

* $F_0 = 3.39 \times 10^{-12}$ W cm$^{-2}$ $\mu$m$^{-1}$ (Hayes and Latham 1975).

lengths to measure both continuum fluxes and Wing molecular indices by using 48 Å bandpasses shortward and 32 Å longward of 0.5 $\mu$m. Air-mass corrections were determined empirically each night; however, no reference star was observed at greater than 2.0 air masses, necessitating extrapolation for the 1974 observations of AH Sco at air mass 3.0. Monochromatic flux calibration was done through observations of $\alpha$ Lyr and other Hayes (1970) standard stars by using the recent revision by Hayes, Latham, and Hayes (1975) to $\alpha$ Lyr's absolute flux distribution. I have also used a near-infrared flux calibration of $\alpha$ Lyr kindly provided by Dr. R. Wing. Internal photometric errors were 0.02 mag or less unless otherwise indicated. The rms repeatability errors between adjoining nights were 0.03 mag.

TABLE 2B

NARROW-BAND PHOTOMETRY: M STARS†

| Star<br>Obs. Date<br>Sp. Type | BC Cyg<br>1974 Aug.<br>M3.5 Ia | PZ Cas<br>1974 Aug.<br>M3 Ia | PZ Cas<br>1975 Oct.<br>M3.5 | UY Sct<br>1974 Aug.<br>M4 Ia–Iab | AH Sco<br>1974 Aug.<br>M4 Ia | S Per<br>1974 Aug.<br>M4.5 Ia | S Per<br>1975 Oct.<br>M7 | W Per<br>1975 Oct.<br>M5 | VY CMa<br>1974 Feb.<br>M5 | VX Sgr<br>1974 Aug.<br>M8.6 |
|---|---|---|---|---|---|---|---|---|---|---|
| Wavelength (Å) | | | | | $-2.5 \log (F_\lambda/F_0)$ | | | | | |
| 5556...... | 8.69(0.05) | 8.54(0.08) | ... | 9.06(0.04) | 6.88(0.04) | 9.31(0.05) | ... | ... | ... | 10.41(0.06) |
| 5820...... | 8.32(0.04) | 8.18(0.04) | 8.27 | 8.81(0.04) | 6.67 | 9.02(0.05) | 9.48 | 9.46 | ... | 10.04(0.05) |
| 6100...... | 7.77 | 7.82 | 7.92 | 8.38 | 6.34 | 8.57(0.04) | 8.93 | 9.02 | ... | 9.81(0.04) |
| 6456...... | 7.41 | 7.36 | 7.61 | 7.85 | 5.94 | 8.15 | 8.50 | 8.70 | ... | 8.80(0.04) |
| 7010...... | 6.67 | 6.78 | 6.86 | 7.06 | 5.39 | 7.32 | 7.48 | 7.85 | ... | 7.61 |
| 7144...... | ... | ... | 7.36 | ... | ... | ... | 8.41 | 8.54 | ... | ... |
| 7550...... | 6.02 | 6.29 | 6.28 | 6.40 | 4.77 | 6.57 | 6.61 | 7.16 | 5.79 | 6.52 |
| 7812...... | ... | ... | ... | ... | ... | ... | ... | ... | 5.98 | ... |
| 8090...... | 5.81 | 6.16 | 6.14 | 6.15 | 4.69 | 6.38 | 6.30 | 6.99 | 5.68 | 5.91 |
| 8370...... | 5.76 | 6.05 | ... | 6.03 | 4.66 | 6.31 | ... | ... | 5.63 | 5.70 |
| 8804...... | 5.37 | 5.77 | 5.71 | 5.71 | 4.38 | 5.99 | 5.85 | 6.61 | ... | 5.29 |
| 8880...... | ... | ... | ... | ... | ... | ... | ... | ... | 5.55 | ... |
| 9960...... | 4.89 | 5.41 | ... | 5.33 | 4.08 | 5.66 | ... | ... | 5.06 | 4.54 |
| 10400...... | 4.75 | 5.27 | 5.20 | 5.22 | 4.02 | 5.54 | 5.25 | 6.09 | 4.91 | 4.26 |
| 10564...... | 4.69 | 5.23 | 5.17 | 5.16 | 4.05 | 5.50 | 5.36 | 6.15 | 5.00 | 4.84 |
| 10870...... | 4.74 | 5.30 | ... | 5.29 | 4.19 | 5.58 | ... | ... | 5.00 | 4.42 |
| 10976...... | 4.95 | 5.50 | 5.59 | 5.59 | 4.64 | 5.83 | 5.48 | 6.30 | 4.97 | 4.74 |

† Internal photometric errors ≥ 0.04 mag are listed in parentheses.

TABLE 2C

INTERMEDIATE-BAND PHOTOMETRY†

| Star | $y$ | $(b-y)$ | $(v-b)$ | $(u-v)$ |
|---|---|---|---|---|
| HD 38427..... | 6.58 | 1.02 | 1.70 | 1.93 |
| AX Sgr....... | 7.54 | 1.43 | 1.97 | 2.61 (0.06) |
| HR 8321...... | 5.18 | 0.86 | 1.51 (0.05) | 1.72 |
| HD 45829..... | 6.60 | 1.02 | 1.66 | 1.93 |
| HD 221861.... | 5.81 | 1.18 | 1.72 | 2.03 |
| RW Cep...... | 6.49 | 1.58 | 2.25 | 2.51 (0.04) |
| W Cep........ | 7.07 | 1.49 | 1.78 | 1.16 (0.04) |
| IRC +60370... | 10.06 | 2.25 (0.04) | 2.6 (0.25) | ... |

† Internal photometric errors ≥0.04 mag are listed in parentheses.

### b) *Intermediate-Band Observations*

Strömgren *uvby* photometry of G and K supergiants was obtained in 1975 with the Leuschner Observatory 76 cm reflector by using standard filters and a refrigerated 1P-21 photomultiplier tube. For calibration each night, I observed six or more standard stars from the list of Crawford and Barnes (1970), including at least one at greater air mass than all the program stars. Standard star rms errors were 0.02 mag or less for $(b-y)$, $c_1$, and $m_1$, and 0.03 mag for $(u-b)$.

I have used this intermediate-band data to provide both color and flux measurements. The latter were derived by using the results of Breger (1974) and the indices of standard stars common to the lists of both Hayes (1970) and Crawford and Barnes (1970). No color or hydrogen line corrections were applied. As the reddest Crawford and Barnes standard star has a $(b-y) \sim 0.8$ and $(u-b) \sim 3.0$, it was necessary to extrapolate color coefficients for stars such as RW Cep whose $(b-y) \approx 1.6$ and $(u-b) \approx 4.8$.

Tables 2A–2C present the reduced photometry in the form of monochromatic magnitudes together with the date of observation. The notation 0.00 mag corresponds to $3.39 \times 10^{-12}$ W cm$^{-2}$ $\mu$m$^{-1}$ (Hayes and Latham 1975).

### c) *Molecular Indices*

Applying the methods of Wing (1967, 1974), I have computed color temperatures, TiO (7144), (7812), (8880), VO (10564), and CN (10976) indices from the scanner observations. The color temperatures correspond to blackbody fits to the observed fluxes at $\lambda$7550 and $\lambda$10400. I have redefined the TiO (7144) index to be

$$100 \times \{[m_\lambda(7144) - m_\lambda(7010)] - 0.25 \times [m_\lambda(7550) - m_\lambda(7010)]\} .$$

The other indices measure depressions from the blackbody fits. Table 3 gives the derived temperatures, molecular indices, and $I(104)$ magnitudes.

The large CN (10976) indices of all the G and K supergiants are in accord with their luminosity classifications. Their lack of TiO $\lambda$7144 absorption, excepting IRC +60370, implies spectral types of K3 or earlier. The 0.1 mag depression at $\lambda$7144 in IRC +60370 corresponds to a spectral type of K4.5; however, this depression may be due in part to contamination by the (4, 1) band of CN, given the large CN (10976) strength.

The M supergiants of Table 3 also have the large CN indices indicative of high luminosity. Of particular interest is my confirmation of Wing's (1974) discovery of simultaneously strong VO and CN absorption in VX Sgr. VY CMa, W Per, and S Per (1975 October

TABLE 3

MOLECULAR INDICES

| Star | Obs. Date | $T_{color}$ | $I(104)$ | TiO (7144) | VO (10564) | CN (10976) | TiO Spectral Type | VO Spectral Type |
|---|---|---|---|---|---|---|---|---|
| HD 38427...... | 1975 Oct. | 3610 | 4.42 | 0 | 3 | 21 | ≲K3 | ... |
| HR 8321....... | 1975 Oct. | 4100 | 3.42 | 0 | 0 | 18 | ≲K3 | ... |
| HD 45829...... | 1975 Oct. | 3650 | 4.53 | 2 | 2 | 30 | ≲K3 | ... |
| HD 221861..... | 1975 Oct. | 3250 | 3.31 | 0 | 2 | 27 | ≲K3 | ... |
| AX Sgr........ | 1974 Aug. | 2620 | 4.27 | −3* | −1 | 34 | ≲K3 | ... |
| RW Cep....... | 1975 Oct. | 2850 | 3.31 | −1 | 2 | 22 | ≲K3 | ... |
| W Cep......... | 1974 Aug. | 2850 | 4.14 | ... | −5 | 34 | ... | ... |
| | 1975 Oct. | 2930 | 4.05 | −3 | 2 | 28 | ≲K3 | ... |
| IRC +60370.... | 1975 Oct. | 1980 | 4.95 | 16 | 1 | 51 | K4.5 | ... |
| PZ Cas........ | 1974 Aug. | 2060 | 3.32 | ... | −1 | 32 | ... | ... |
| | 1975 Oct. | 2020 | 3.25 | 64 | 0 | 35 | M3.5 | ... |
| BC Cyg........ | 1974 Aug. | 1890 | 2.80 | ... | 0 | 41 | ... | ... |
| UY Sct........ | 1974 Aug. | 1940 | 3.27 | ... | −2 | 48 | ... | ... |
| AH Sco........ | 1974 Aug. | 2270 | 2.07 | ... | 5 | 68 | ... | ... |
| W Per......... | 1975 Oct. | 2020 | 4.14 | 87 | 9 | 31 | M4.5 | M7.0 |
| S Per.......... | 1974 Aug. | 2060 | 3.59 | ... | −1 | 38 | ... | ... |
| | 1975 Oct. | 1840 | 3.30 | 116 | 15 | 37 | M5.5 | M7.5 |
| VY CMa....... | 1974 Feb. | 2160 | 2.96 | ... | 11 | 43 | M4† M5.0 | M7.0 |
| VX Sgr........ | 1974 Aug. | 1420 | 2.31 | ... | 66 | 74 | ... | M8.6 |

* TiO (7144) observation made in 1975 Oct.

† TiO spectral types from depressions at $\lambda\lambda$7812, 8880, respectively.

observation) show similar behavior, though their VO strengths correspond to earlier spectral types. Wing has suggested that abnormally large CN strength in a late M star indicates high luminosity because normal M0–8 giants and Mira variables have CN (10976) indices of 15 or less. These observations of S Per and W Per, whose kinematic membership in Per OB1 establishes their high luminosity, tend to confirm this hypothesis. IRC +60375 (M7.5 I) does not have an especially large CN (10976) index (see Fawley and Cohen 1974) but also differs from the aforementioned stars in apparently being constant in spectral type.

Wing (1974) also noted an abnormal TiO/VO ratio in VX Sgr, relative to M giants of the same spectral type. W Per, VY CMa, S Per, and IRC +60375 are similar to VX Sgr in that their VO strengths indicate later spectral types than their TiO strengths.

Recently S Per, normally of M4 spectral type, has shown extreme spectral variability similar to that of VX Sgr. From an M6 near-infrared spectral type in 1973 October, S Per changed to a M4.5 near-infrared spectral type in 1974 August and then to a M7 near-infrared spectral and spectrophotometric type in 1975 October–November. Finally, a 1976 January Lick 3 m image-tube scanner (Robinson and Wampler 1972) spectrum of S Per covering $\lambda\lambda$4200–6700 kindly obtained by Dr. L. Kuhi shows an *M8* spectral type according to the strength of six TiO band heads. To my knowledge, this is the latest spectral type ever observed for S Per. Unless the star changed significantly between 1975 November and 1976 January, this visual spectral type indicates that the November M7.5 VO (10564) spectral type is indeed correct, and that the CN (10976) strength is abnormally large.

## IV. NEAR-INFRARED AND VISUAL FLUX DISTRIBUTIONS

### *a) Interstellar Extinction Corrections and Flux Distributions of S Persei, VX Sagittarii, and VY Canis Majoris*

Humphreys (1974) in her study of S Per *et al.* argued that, after making TiO opacity and interstellar extinction corrections, there was broad-band photometric evidence for large near-infrared excesses from these peculiar M stars. In § IV*b*, I show that $H^-$ bound-free emission "bumps" mimic interstellar extinction over corrections. Humphreys's photometric evidence for such emission therefore strongly depends upon the accuracy of her TiO opacity and interstellar extinction corrections for S Per *et al.* For S Per and VX Sgr, her use of the TiO corrections grossly violates flux conservation and is suspect on this ground alone. Her $A_V$'s were deduced from estimates of intrinsic $(B - V)$'s and $M_V$'s by using distances derived from kinematic and cluster membership considerations. However, the spectral peculiarities of S Per *et al.* make such estimates quite uncertain, especially because $(B - V)$ colors and $M_V$'s are properties of the exponential part of these cool stars' flux distributions. There is additional uncertainty if circumstellar extinction differs from interstellar extinction in wavelength dependence. Most important, the small amount of independent evidence available indicates that Humphreys overestimated $A_V$ by $\gtrsim 1$ mag for S Per and VX Sgr.

1) Humphreys used an $A_V \sim 3$ mag for S Per, though Wildey's (1964) *UBV* observations of stars lying extremely close to S Per suggested an $A_V$ of 1.9 mag. The lower figure is more compatible with the general $A_V = 1.8$ mag found by Crawford, Glaspey, and Perry (1970) for h and $\chi$ Per, which lie 1°.5 south of S Per. The $A_V$'s of three nearby early-type supergiants [HD 13476 (A3 Iab), 1°.2 W, $A_V = 1.6$ mag; HD 13744 (A0 Iab), 1° SW, $A_V = 2.1$ mag; HD 14947 (O5.5f), 0°.6 NE, $A_V = 2.0$ mag; photometry reference: Blanco *et al.* 1968; Crawford 1975] also agree with Wildey's value. At a distance of 2 kpc S Per has a $\log L/L_\odot = 5.1 + 0.1(A_V - 2)$, using the photometry of this paper and Cohen and Gaustad (1973).

2) I have made *uvby* observations of six B stars lying within 15′ of VX Sgr. If one assumes main-sequence luminosities for these blue stars, their distances range from 0.48 to 1.33 kpc. Their measured $A_V$'s are 0.68–0.84 mag. At a distance of 1.33 kpc, VX Sgr at maximum light would have $\log L/L_\odot \sim 5.3 + 0.1(A_V - 1)$. Unless it is superluminous, its distance is almost certainly less than 2.5 kpc; even a distance of 1.0 kpc is quite compatible with supergiant luminosity. Therefore, it appears probable that the $A_V$ of VX Sgr is less than 2 mag unless it suffers obscuration by a discrete ($<10'$) interstellar dust cloud. Humphreys used an $A_V \sim$ 3–4 mag.

3) Since ~90% of VY CMa's stellar flux below 1 $\mu$m is absorbed and thermally reradiated by its dust shell (or disk), it is impossible to determine separately the interstellar extinction component from $M_V$'s or $E(B - V)$'s without extensive knowledge of the optical properties of the circumstellar dust. If the central star has an $I(104) - 0.755\ \mu$m color temperature of 2700 K, the observed color implies a total interstellar plus circumstellar *reddening* equivalent to an $A_V \sim$ 1–1.5 mag. This value is comparable with that suggested by Herbig (1970) and Humphreys (1974). If VY CMa is associated with NGC 2362 at a distance of 1.5 kpc as proposed by Herbig, it has $\log L/L_\odot = 5.7 + 0.02(A_V - 1)$, using the photometry of this paper and Hyland *et al.* (1969).

In Figure 3, I plot the continuum wavelength scanner data corrected for interstellar extinction for S Per ($A_V = 2$ mag), VX Sgr ($A_V = 2$ mag), and VY CMa ($A_V = 1$ mag). I have also included the 2.2 $\mu$m flux (S Per [1975 November]: $K = +1.14$, Cohen, private communication; VX Sgr, $K = -0.25 \pm 0.3$, *estimated* from $I(104)$ magnitude and phase by using past $I(104)$ and $K$ measurements kindly provided by G. Lockwood and in the literature; VY CMa, $K = -0.62$, Hyland *et al.* 1969).

The rapid rise of flux between 0.5 and 1 $\mu$m in Figure 3 for S Per and VX Sgr rules out the presence of any significant $H^-$ bound-free emission because such emission peaks at or below 0.8 $\mu$m. These negative photometric results agree with the spectroscopic upper limits of § II. There is no indication whatsoever of a "bump" at 0.7 $\mu$m in S Per's or VX Sgr's flux

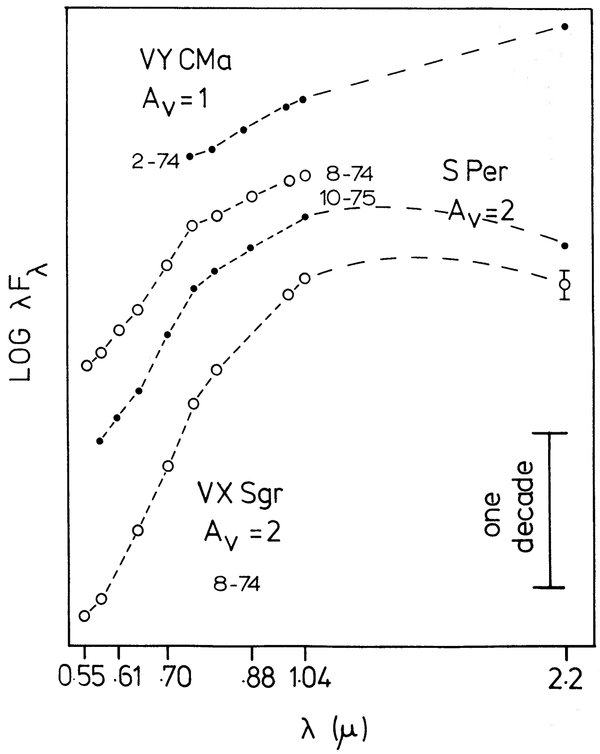


FIG. 3.—The corrected visual and near-infrared energy distributions of VY CMa, S Per, and VX Sgr. The curves have been arbitrarily displaced in ordinate.

distributions, in sharp contrast to those presented in Humphreys's (1974) Figures 6*b*–6*d*. These differences are *not* caused by variability, inasmuch as my observed 0.701 − 0.88 $\mu$m colors for S Per and VX Sgr are within a couple of tenths of Humphreys's observed ($R-I$)'s (her Fig. 6*c*), but by her $A_V$ overestimates and incorrect use of TiO opacity blanketing estimates.

The flux distribution of VY CMa is less steep between 0.75 and 1 $\mu$m and is similar to that presented in Humphreys's Figure 6*f*. Considered alone, this flux distribution could contain a significant $H^-$ component, but the 1974 February spectrum limits any excess emission to $\leqslant 0.2$ stellar continuum strength at 0.84 $\mu$m.

### *b*) *The "Mimic" Nature of* $H^-$ *Emission*

To minimize errors from miscorrections for interstellar extinction and molecular absorption, I have used a method employing monochromatic continuum flux ratios to detect peculiarities in late-type supergiants' visual and near-infrared flux distributions. This method graphically illustrates how interstellar extinction over corrections can lead to a spurious identification of $H^-$ bound-free emission.

Interstellar extinction normally follows a $1/\lambda$ law between 0.45 and 1.25 $\mu$m. Thus if two stars have the same intrinsic flux distribution but suffer different amounts of interstellar absorption, one can make a *linear* fit to a plot of difference in monochromatic magnitude versus reciprocal wavelength. This is illustrated by Figure 4*a* where I compare two normal K0 Iab supergiants, HD 45289 and HD 221861. The data below 0.45 $\mu$m have had their abscissa position

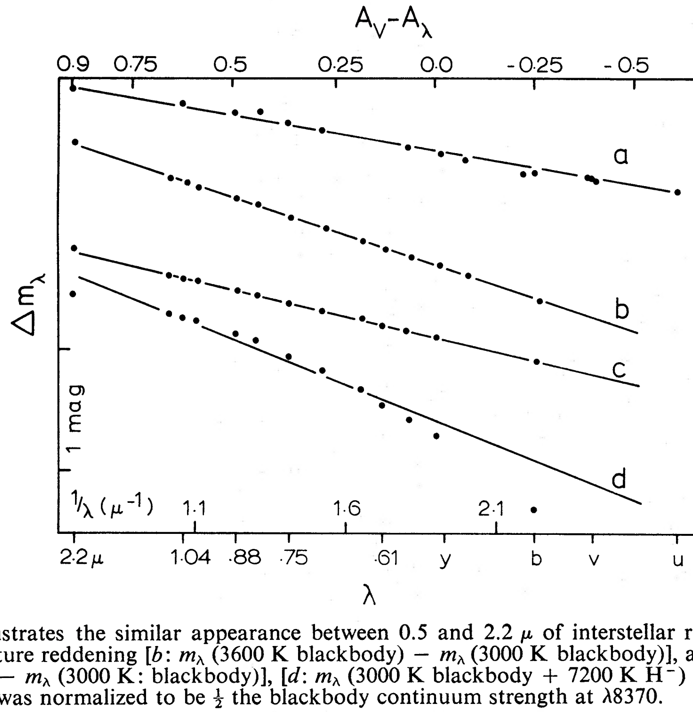


FIG. 4.—This figure illustrates the similar appearance between 0.5 and 2.2 $\mu$ of interstellar reddening [*a*: $m_\lambda$ (HD 45829) − $m_\lambda$ (HD 221861)], temperature reddening [*b*: $m_\lambda$ (3600 K blackbody) − $m_\lambda$ (3000 K blackbody)], and $H^-$ emission [*c*: $m_\lambda$ (3000 K blackbody + 4500 K $H^-$) − $m_\lambda$ (3000 K: blackbody)], [*d*: $m_\lambda$ (3000 K blackbody + 7200 K $H^-$) − $m_\lambda$ (3000 K blackbody)]. The $H^-$ emission contribution was normalized to be $\frac{1}{2}$ the blackbody continuum strength at $\lambda$8370.

adjusted to reflect the change in the interstellar extinction law below this wavelength by using the results of Crawford (1975). The plot also includes the $K$(2.2 $\mu$m) point, whose abscissa position corresponds to $A_K/A_V = 0.1$. For the wavelength and temperature ranges considered here, differences in photospheric temperature will also appear linearly on this type of plot. This is shown in Figure 4*b* where a 3600 K blackbody is compared with one of 3000 K.

Surprisingly, the wavelength extent of $H^-$ free-bound emission is such as to nearly perfectly mimic the behavior of interstellar extinction and photospheric temperature differences in the wavelength region 0.5–2.2 $\mu$m. This is apparent in Figure 4*c*, *d* where I plot the monochromatic magnitude differences between a normal 3000 K blackbody and a 3000 K blackbody with overlying $H^-$ emission, the latter component normalized to be one-half the blackbody strength at $\lambda$8370. For the two examples shown, the $H^-$ temperatures were 4500 K and 7200 K, the first approximately equal to that used by Gilman (1974) for his models of S Per, VY CMa, and VX Sgr.

Between 0.47 and 2.2 $\mu$m $m_\lambda$ (4500 K $H^-$ + 3000 K blackbody) $-$ $m_\lambda$ (3000 K blackbody) is a nearly perfect linear function of reciprocal wavelength. The 7200 K $H^-$ example is not quite as linear, but still can be fitted with a straight line whose maximum deviations are $\leqslant$0.2 mag between 0.55 and 2.2 $\mu$m. These examples emphasize the following points:

Overcorrections for interstellar extinction or underestimates of photospheric temperature can lead one to misidentify $H^-$ emission by broad- and/or narrow-band photometry of cool stars. The linear fit of the 4500 K $H^-$ example corresponds to an $A_V$ of 0.9 mag. Put in another way, overestimating the $A_V$ of a normal M star by 1 mag will lead to a flux excess which then can be well fitted by optically thin $H^-$ emission with an excess-to-continuum ratio of 0.6 at $\lambda$8400. This explains why Gilman (1974) could so accurately fit Humphreys's visual and near-infrared flux distributions of S Per and VX Sgr with an $H^-$ chromospheric emission component despite her probable $A_V$ overestimates.

Though the lack of significant near-infrared line veiling argues against the presence of strong $H^-$ emission in any of the G, K, and early M supergiants of § II, it is worthwhile nonetheless to check their near-infrared flux distributions for peculiarities, as the scanner data give much higher resolution than does broad-band photometry.

### *c*) *M Supergiant Flux Ratios*

Figure 5 plots the observed monochromatic magnitude differences between various M supergiants against reciprocal wavelength. In nearly all cases, a straight-line fit may be made with mean deviations $\leqslant$0.1 mag, implying that all these objects have similar near-infrared flux distributions. There is no evidence of any significant ($\geqslant$0.25 mag) emission "bumps" between 0.55 and 1.1 $\mu$m. VX Sgr's depression at $\lambda$6100 is due to VO absorption not present in the warmer S Per. Therefore all these stars appear to have had normal near-infrared continua in 1974–1975.

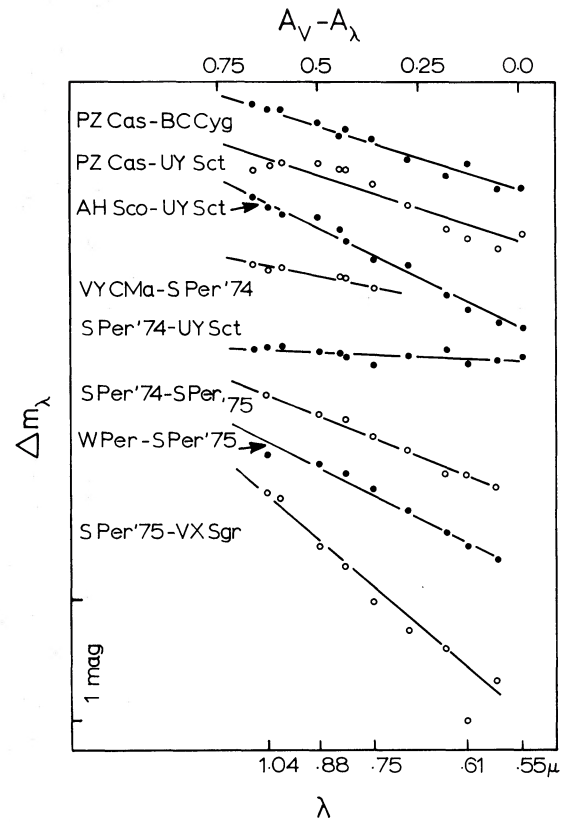


FIG. 5.—The $\Delta m_\lambda$ plots for the M supergiants of Table 2. The PZ Cas observations are from 1974 August, while those of S Per are from both 1974 August and 1975 October.

### *d*) *G and K Supergiant Flux Ratios*

In 1975 summer, I obtained photometry of a few G and K supergiants with large infrared excesses on the Strömgren system because the system's characteristics are well defined through spectral type K5 and its response to interstellar reddening is accurately determined (Crawford 1975). Upon reducing the initial data, I noticed that the ratios of $E(b-y)/E(u-b)$ and $E(b-y)/E(v-b)$ for these stars were peculiarly low. I then made narrow-band scanner measurements at four additional wavelengths below 0.55 $\mu$m, which confirmed the abnormal reddening affecting the blue light of K supergiants with large infrared excesses.

In Figure 6, I compare HD 221861 (K0 Iab) with RW Cep (K0 Ia), W Cep (K0 Iab), and IRC +60370 (K4.5: Ia). HD 221861, together with HD 45829 (K0 Iab), HD 38427 (G8 Iab), and HR 8321 (K0 Ib), were selected from the list of Hackwell and Gehrz (1974) as "control" supergiants without any detectable circumstellar emission at infrared wavelengths. The plots of $m_\lambda$ (HD 45829) $-$ $m_\lambda$ (HD 221861) (Fig. 4*a*) and $m_\lambda$ (HR 8321) $-$ $m_\lambda$ (HD 221861) (Figure 6*a*) exhibit normal interstellar reddening laws except for a 0.2 mag dimming at $u$ (0.35 $\mu$m) of HD 221861 relative to HR 8321.

However, the $\Delta m_\lambda$ plots (Fig. 6*b–e*) of RW Cep,

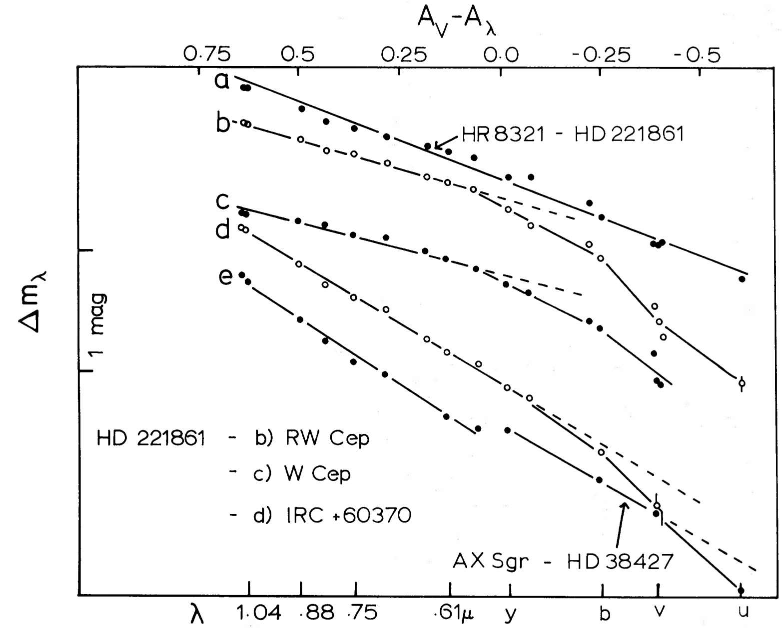


FIG. 6.—The $\Delta m_\lambda$ plots for the G and K supergiants of Table 2. The ordinate scale should be multiplied by two for [$m_\lambda$ (HD 221861) − $m_\lambda$ (IRC +60370)]. The data on AX Sgr (*e*) below 0.55 were obtained one year later than the near-infrared data; the W Cep observations are from 1975 October.

W Cep, IRC +60370, and AX Sgr all appear peculiar. Between 0.58 and 1.06 $\mu$m, $m_\lambda$ (HD 221861) − $m_\lambda$ (RW Cep) is well fitted by a straight line. But below 0.58 $\mu$m, this line must curve increasingly downward, an effect shown by *both* the narrow ($\Delta\lambda = 48$ Å) and intermediate ($\Delta\lambda \approx 200$ Å) band data. By 0.35 $\mu$m, RW Cep has *one* magnitude less flux relative to HD 221861 than would be expected from an extrapolation of the interstellar extinction corresponding to the line between 0.58 and 1.06 $\mu$m.

At the time of the 1975 October photometric observations, W Cep exhibited a strong ultraviolet excess. Generally, this excess has been attributed to a hot companion (see Swings and Struve 1940), though it may be intermittent because it was not observed by Wallerstein (1971*b*). After measuring the strength of the line veiling apparent in a coudé spectrum obtained in 1975 November centered at λ4100, I removed the contribution of the hot continuum to the narrow- and intermediate-band photometry by assuming it was described by a Rayleigh-Jeans law. The interstellar extinction was estimated as 2.9 mag by assuming W Cep's intrinsic flux distribution between 0.7 and 1.1 $\mu$m is identical to that of HD 221861 and by taking an $A_V = 2.18$ mag for the latter. When this correction is made to the observed fluxes, W Cep shows the same behavior in the blue as does RW Cep.

The comparison of IRC +60370 with HD 221861 also shows the same reddening effects below 0.5 $\mu$m, but the measurement errors are quite large. Because the scanner data on IRC +60370 were badly contaminated by the light of the nearby B5 II optical companion, below 0.5 $\mu$m I have plotted only the Leuschner *vby* observations which were intentionally obtained with a small enough aperture to include only the K supergiant. Relative to HD 221861, IRC +60370 is underluminous 0.25 mag at *b* and 0.5 mag at *v*.

Unfortunately, one year separated the *uvby* and near-infrared scanner observations of AX Sgr, in which time AX Sgr brightened visually by ~0.2 mag. Nonetheless, Figure 6*e* indicates that AX Sgr has ~0.4 mag less flux at *u* than would be expected from the *vby* and near-infrared measurements.

The peculiarly low blue and ultraviolet fluxes of these G and K Ia supergiants may result from the extended and turbulent nature of their photospheres compared with those of Iab supergiants. The differences in atmospheric structure, line blanketing, and radiation dilution factors could significantly change the spectral distribution of the outgoing radiation. However, this effect appears only weakly in the comparison of a K Iab (HD 221861) with a K Ib (HR 8321) supergiant (Fig. 6*a*). A second explanation is that RW Cep, W Cep, and IRC +60370 all may be carbon-rich relative to normal K supergiants. One could then account for the excess blue and ultraviolet opacity by invoking absorption by molecules such as CN. However, only IRC +60370 has an unusually large λ10976 CN index compared with HD 221861 and HD 45829.

A final, very intriguing possibility is Rayleigh scattering and absorption by small grains and molecules present in the circumstellar shells of these objects. If this explanation is correct, one can compare the magnitude of the "missing" blue flux with that of the excess infrared flux. This has been done in Table 4 for RW Cep and W Cep. The excess infrared fluxes,

TABLE 4

COMPARISON OF MISSING BLUE AND EXCESS INFRARED FLUXES

| Star | $A_V$* | Missing Flux 0.3–0.6 $\mu$ (W cm$^{-2}$) | Excess Flux 2–20 $\mu$ (W cm$^{-2}$) |
|---|---|---|---|
| RW Cep.... | 3.1 mag | $3.5 \times 10^{-15}$ | $6.2 \times 10^{-15}$ |
| W Cep...... | 2.9 mag | $4.5 \times 10^{-15}$ | $2.8 \times 10^{-15}$ |

* Estimated by assuming that RW Cep's and W Cep's intrinsic flux distributions between 0.7 and 1.2 $\mu$m are identical to those of HD 221861, and by using an $E(B - V) = 0.68$ mag and $A_V = 2.18$ mag for the latter. Light of hot companion of W Cep was subtracted out by assuming that it was not contained within the dust shell of the red star.

corrected for reddening, were summed between 2 and 20 $\mu$m, though there are large uncertainties in the amplitude of the excess between 2 and 4 $\mu$m. For both RW Cep and W Cep, the missing flux in the blue-ultraviolet and the excess flux in the infrared are comparable in size. Thus a dust-scattering absorption and reradiation model is reasonably in accord with the photometric data, but certainly not demanded by them.

## V. FREE-FREE EMISSION AND THE 3–8 $\mu$m RADIATION EXCESSES

Much of the impetus for the identification of $H^-$ emission from the spectra and photometry of S Per *et al.* came from the similarities of their flux distribution between 2 and 8 $\mu$m to that of optically thin free-free radiation. This suggested that if there were chromospheric free-free emission, there might also be $H^-$ emission. It is thus useful to investigate whether free-free emission is actually present in late-type supergiants with free-free–like infrared flux distributions.

Hackwell and Gehrz (1974) in their infrared survey of supergiants noted that beginning at spectral type G5, a ~0.3 mag depression in the 4.8 $\mu$m filter appeared. They attributed this absorption to CO and/or CN. By measuring any veiling of this molecular feature, one can place spatial constraints upon the region of emission. For Gilman's models of the chromospheres of S Per *et al.*, the free-free and $H^-$ emission must occur *below* the molecular photosphere. This was required by both the absence of any veiling of the TiO, VO, and CN features in the near-infrared, and by the lack of unabsorbed Balmer-line emission accompanying the hypothesized free-free emission. Both VX Sgr and VY CMa on occasion have Balmer-line emission obscured by overlying molecular absorption (see Humphreys and Lockwood 1972; Table 1 of Humphreys 1974; Wallerstein 1977).

As a rough photometric measure of the 4.8 $\mu$m depression, I derived an index relating the observed 4.8 $\mu$m flux to that expected from the observed 3.5 and 8.6 $\mu$m fluxes. This required correcting the 8.6 $\mu$m flux for any silicate emission contained within the filter bandpass. Using the high-resolution spectroscopy of Treffers and Cohen (1974), Gilman's (1974) calculations of $Mg_2SiO_4$ emissivity, and photometry of $\alpha$ Ori and $\alpha$ Sco, I estimated the observed silicate emission within the 8.6 $\mu$ filter to be about one-sixth that contained within the 10.7 or 11.3 $\mu$m filters. It is then possible to correct the observed 8.6 $\mu$m flux for this emission if one knows the [8.6] − [10.7] or [8.6] − [11.3] colors, assuming the underlying continuum follows either a Rayleigh-Jeans or free-free slope. For [3.5] − [8.6] $\leqslant$ 2.0, there will be only a very small ($\leqslant$0.04 mag) difference in this index between assuming a Rayleigh-Jeans and a free-free continuum, and for [8.6] − [10.7] $\geq$ 1.2 mag, I have used an average of the two. Therefore,

$$D[4.8] \equiv [4.8] - (0.65[3.5] + 0.35[8.6]_{\mathrm{adj}})$$

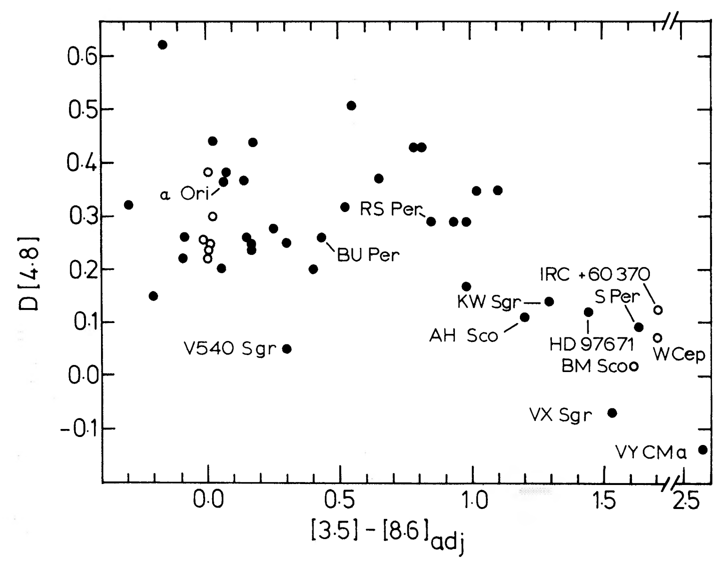


FIG. 7.—$D$(4.8), a measure of the 4.8 $\mu$m molecular absorption feature, is plotted against [3.5] − [8.6], a measure of the 3–8 $\mu$m radiation excess, for various late-type supergiants. *Open circles*, K supergiants; *closed circles*, M supergiants.

will measure the difference between the observed 4.8 $\mu$m flux and that expected from the observed 3.5 and adjusted 8.6 $\mu$m fluxes.

In Figure 7 I plot $D[4.8]$ versus $[3.5] - [8.6]_{\mathrm{adj}}$. The latter quantity is a good measure of the excess radiation between 3 and 8 $\mu$m as for a blackbody, it would be zero. These observations of both K and M supergiants were taken from Humphreys, Strecker, and Ney (1972), Cohen and Gaustad (1973), Humphreys and Ney (1974*a*, *b*), and Hackwell and Gehrz (1974). The 4.8 $\mu$m filter bandwidths, which greatly affect the sensitivity to the CO/CN absorption, were similar in all these observations.

The resulting plot confirms Hackwell and Gehrz's 0.3 mag estimate for the 4.8 $\mu$m absorption strength in normal late-type supergiants. The few negative $[3.5] - [8.6]_{\mathrm{adj}}$ colors are probably due to overcorrection for the silicate emission at 8.6 $\mu$m or, perhaps, photometric errors. However, for stars with large $[3.5] - [8.6]_{\mathrm{adj}}$ colors, it is evident that the 4.8 $\mu$m absorption becomes veiled. The stars with free-free–like infrared flux distributions, S Per, VY CMa, VX Sgr, AH Sco, HD 97671, W Cep, and BM Sco, fall in this category. All of these stars have $D[4.8] < 0.15$ mag, whereas all but one of the supergiants with 0.0 mag $< [3.5] - [8.6]_{\mathrm{adj}} < 1.0$ mag have $D[4.8] \geq 0.2$ mag. These results support the explanation of Dyck, Lockwood, and Capps (1974) and Jones and Merrill (1976) for the 3–8 $\mu$m excesses: as the circumstellar dust shell becomes progressively optically thicker at 10 $\mu$m, it begins to emit significant radiation at shorter wavelengths, such as 4.8 $\mu$m, thus veiling photospheric molecular absorptions at these wavelengths.

Further evidence for veiling in the 4–5 $\mu$m region can be found in the observations of VY CMa, VX Sgr, and NML Cyg by Geballe, Wollman, and Rank (1973), and Wollman *et al.* (1973). No photospheric 4.7 $\mu$m CO lines are present in VY CMa or NML Cyg despite quite strong CO absorption at 2.3 $\mu$m. Moreover, no 4.05 $\mu$m SiO lines are visible in VX Sgr or NML Cyg, though these lines are strong in both normal M giants and supergiants of spectral types as late as M7.

Therefore, the 3–8 $\mu$m radiation excesses of late-type supergiants partially or fully veil absorption features near 5 $\mu$m and cannot be free-free emission radiated from below the molecular photospheres, in contradiction to Gilman's models for such excesses.

## VI. DISCUSSION

### *a*) *S Persei and VX Sagittarii*

None of the narrow-band photometry (§ IV) of S Per and VX Sgr display the $H^-$ bound-free excesses proposed by Humphreys (1974) and Gilman (1974). Their excesses were probably spurious and originated in $A_V$ overestimates and TiO opacity miscorrections. Apart from lower photospheric temperatures, S Per and VX Sgr resemble warmer M supergiants in their continuum flux distributions. The veiling (§ V) of photospheric molecular features near 5 $\mu$m suggests that thermal circumstellar radiation rather than free-free emission causes the 3–8 $\mu$m excesses of these two stars and other late-type supergiants with free-free–like infrared flux distributions. No photometric evidence remains for large chromospheric near-infrared or infrared radiation excesses from either S Per or VX Sgr.

An alternative explanation for the variable line weakening of these objects is that it is photospheric in origin. As luminous M supergiants, S Per and VX Sgr are unique in their Mira-like temperature variations. Their abnormal (relative to warmer, less variable M supergiants) temperature and pressure structures may on occasion lower the ratio of line to continuum plus quasi-continuous molecular opacity, resulting in an apparent absorption-line weakening. In addition, the large spectral variations and extensive mass loss of S Per and VX Sgr suggest that their outer photospheres are hydrostatically unstable and poorly described by a single effective temperature. These conditions may lead to the peculiar observed TiO/VO and CN/VO index ratios.

Merrill, Deutsch, and Keenan (1962) also suggested increased molecular opacity as being at least partially responsible for the variable line weakening seen at blue wavelengths in long-period Mira variables. In Miras, the degree of line weakening varies from cycle to cycle, but remains relatively constant with respect to phase within a given cycle. It is important to establish whether the variable line weakening of S Per and VX Sgr shares these characteristics. Wallerstein (1977) cautions, however, that S Per and VX Sgr differ from Miras in the velocity structure of their hydrogen and OH emission, and also in the relative strengths of various nonhydrogenic emission lines.

### *b*) *VY Canis Majoris*

This object differs from S Per and VX Sgr by its more constant spectral type and by the larger fraction of radiation emitted by its circumstellar shell. As Gilman (1974) noted, thermal reradiation models (e.g., Herbig 1970; Schwartz 1975) are more successful than free-free emission models in explaining VY CMa's infrared excess. The veiling of the 4.7 and possibly 2.2 $\mu$m (cf. Hyland *et al.* 1969) CO lines supports reradiation models. VY CMa's near-infrared line veiling may be due either to overlying emission, such as $H^-$, or to Doppler weakening from multiple-path photon scattering in the surrounding circumstellar shell (or disk). Schwartz (1975) preferred the 4500 K $H^-$ explanation in order to fit VY CMa's observed fluxes without resorting to high dust temperatures in his models. His models assumed a wavelength-independent scattering albedo; if this assumption were to be dropped, it might not be necessary to invoke warm $H^-$ emission or hot dust to explain the near-infrared fluxes. It is unclear (see § II) whether VY CMa's line veiling is variable or constant in strength.

### *c*) *G, K, and Early M Supergiants*

Neither the residual intensity measurements of § II nor the narrow-band photometry of § IV suggests that any of these supergiants have significant line veiling or large radiation excesses in the near-infrared.

RW Cep, W Cep, and IRC +60370, three K Ia supergiants with large infrared excesses, have significant excess opacity sources below λ5000 relative to supergiants of similar photospheric temperatures without circumstellar shells. This opacity may occur in the dust shell itself and provide the means for powering their infrared excesses.

Finally, I suggest that it is worthwhile to investigate more extensively the nature of the 3–8 μm infrared excesses and extinction properties of circumstellar shells. The advent of InSb detectors permits high-resolution studies of the possible veiling of photospheric molecular features in the 1.6–5 μm region by circumstellar thermal reradiation. Additional narrow- and intermediate-band photometry below 1.25 μm of G and K supergiants with large infrared excesses, including HR 5171 and BM Sco in the southern hemisphere, could be extremely helpful in determining circumstellar dust extinction properties. This is especially true if the interstellar extinction to these objects can be accurately determined. Similar spectrophotometry of M supergiants with large infrared excesses could provide even more information because the infrared excesses of the cooler supergiants are much greater relative to their visual fluxes. However, it is essential to obtain simultaneous TiO and VO spectral types, and, if possible, infrared photometry to minimize uncertainties due to variability.

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