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INFRARED EMISSION FROM UNUSUAL BINARY STARS

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ABSTRACT

Infrared emission between 2 and 22 microns has been photometrically observed for nine binary stars, ϵ Aur, ζ Aur, W Cep, Z And, UV Aur, υ Sgr, HD 30353 (KS Per), η Gem, and RZ Cnc. A model is developed for ϵ Aur. There are indications of free-free emission in some objects without H emission lines, confirming a suggestion by Dyck and Milkey. The continuum in υ Sgr is interpreted as due to a shell of graphite. A peak resembling that in carbon stars occurs near 11 μ. Limited systematics of this peak suggest that it correlates with high nitrogen abundance, and is probably due to Si_3N_4.

Subject headings: binaries — circumstellar shells — infrared sources

I. INTRODUCTION

In earlier papers (e.g., Humphreys, Strecker, and Ney 1972; Deutsch 1960; Swings and Allen 1972), there have been questions raised whether the presence of a close companion to a star might modify the circumstellar medium expected if the star were single. In principle there might seem to be three relevant factors. The presence of a companion to a star might so lower the surface potential that matter could escape to large distances, and this matter might give rise to infrared emission. Or if a stellar wind arises because of radiation pressure on dust condensing near a star, then the presence of a heat input from another star might hinder dust condensation, and so reduce the infrared emission. Humphreys *et al.* have called attention to a few cases that may be examples of this phenomenon. Finally, if a hot companion does not interfere with particle formation, it might either modify the chemical nature of the solids formed, or ionize the gas flow, so that the spectral distribution of the infrared radiation is modified.

Thus close binaries perform experiments on the nature of the processes that give rise to circumstellar emission. It will also appear in this paper that because of the abnormal chemical composition of some binary stars, they also provide clues to the interpretation of normal circumstellar emission. And in one case, the star ϵ Aurigae, the observations seem to provide help in chosing a model of the system that can explain this star's light curve.

General discussions of the phenomena that have been observed in circumstellar envelopes have been given elsewhere (Woolf 1971, 1972). It suffices here to say that silicate particles are detected by a double emission peak centered at 9.7 and 20 μ. Certain carbon stars of type N appear to have a single emission peak at 11 μ that is interpreted as either silicon nitride or silicon carbide (Hackwell 1972). Few evolved stars earlier than type G0 show circumstellar emission. A smooth blackbody-like continuum around R CrB and RY Sgr is generally accepted as due to carbon. Continua of unknown origin exist around 89 Her and υ Sgr. Hot stars with hydrogen lines in emission tend to show a portion of continuum with $F(\nu)$ approximately constant, from free-free emission; then at larger wavelengths this becomes opaque and the emission falls off, tending toward a blackbody-like long-wavelength tail.

Silicate emission always occurs for normal composition stars later than G0 Ia$^+$, G8 Ia, M2 Iab, M5 Ib–II, M6 III. Some pulsating stars of earlier type show emission,

TABLE 1

MAGNITUDES OF BINARY STARS

STAR	TYPE	PERIOD (days)	WAVELENGTH (microns) 2.2	3.6	4.8	8.6	11.3	12.2	18	22
ϵ Aur.......	A8 Ia	9883	+1.5	+1.4	+1.3	+0.7	+0.6		+0.5:	
ζ Aur.......	K4 Ib + B7 V	972	+0.2	+0.1	+0.3	+0.1	+0.0		+0.2	
W Cep......	K0 Iaep + O?	...	+2.3	+1.5	+0.9	−0.9	−1.8	−1.3	−2.3	−3.0:
Z And......	M2 III + W	≈700?	+4.8	+4.9	+4.4		+4.1::		+1.0:	+1.3::
UV Aur.....	C8ep	...	+2.2	+1.9	+1.4	+0.5	−0.6	−0.2	−0.3	
HD 30353...	A5p	360	+5.9	+5.7	+5.7::	+4.4::	+3.5:		> +1.8	
υ Sgr........	A0p	138	+2.4	+1.1	+0.5	−0.5	−1.3	−1.3	−1.3	−1.3
RZ Cnc.....	K2 IIIe + K5 III	21.6	+5.9	+5.7	+4.9:	+4.0:	+3.3:		> +2.4	
η Gem......	M3 III	2983	−1.5	−1.6	−1.5	−1.8	−2.0	−2.2:	−2.0	
μ Gem......	M3 II–III	Not binary	−1.9	−2.1	−1.9	−2.2	−2.3	−2.3	−2.3	

NOTE.—A colon corresponds to an observation of standard error between 0.1 and 0.3 mag; a double colon corresponds to an observation that is only 1–3 standard errors in amplitude.

but no nonvariable ones have yet been found. Some of the observed stars were selected because they are just a little too hot for typical silicate emission to be found. The binaries include ζ Aur (K4 Ib + B7), RZ Cnc (K2 III + K5 III), and η Gem (M3 III + ?). Two stars, Z And and UV Aur, have been included because both late stars and planetary-nebula shells show excess infrared emission, and these objects have optical spectra resembling a late star with a planetary nebula. Two hydrogen-deficient binary stars, υ Sgr and HD 30353 (KS Per), were included. And finally two supergiants were included, ϵ Aur because no infrared radiation had previously been detected from its companion, and W Cep because Wallerstein (1971) had thought from earlier limited infrared observations, and from visual spectroscopic observations, that there should be an infrared free-free continuum.

II. OBSERVATIONS

The stars were observed with the 60-inch (152-cm) University of Minnesota–University of California, San Diego, telescope of Mount Lemmon Infrared Observatory. A 2–22 micron photometer had passbands with typically $\lambda/\Delta\lambda \simeq 10$. Most stars were observed on more than one occasion, and observations averaged without regard to phase of the binary in its orbit. For most observations the internal standard error

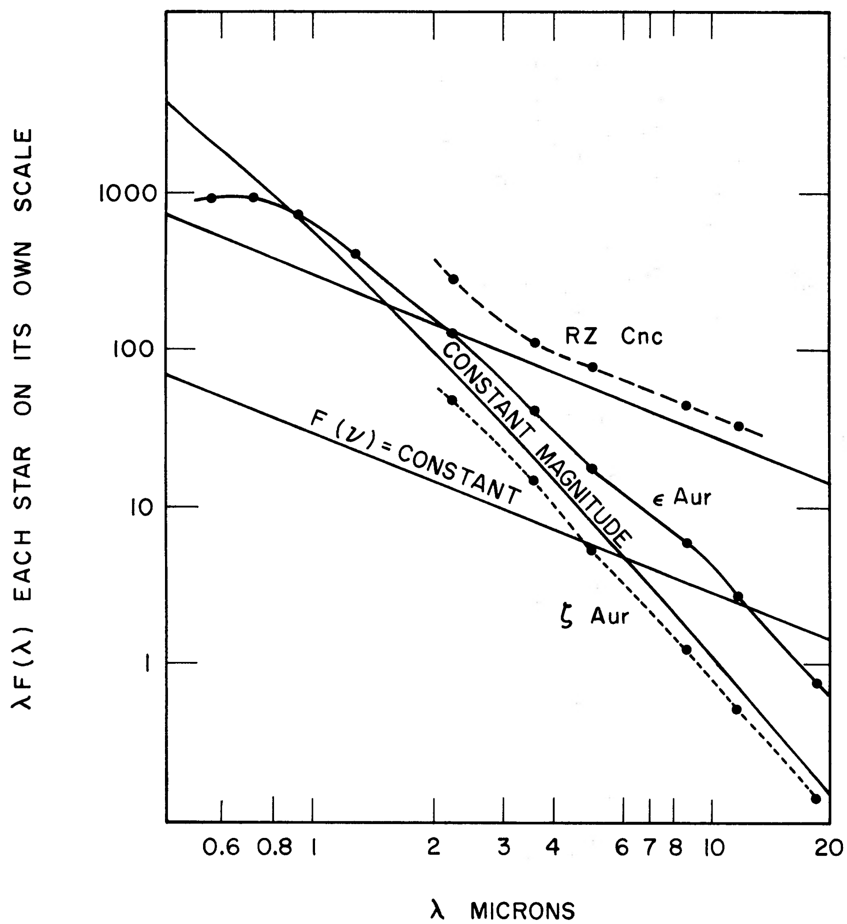

FIG. 1.—The energy distributions of ζ Aur, ϵ Aur, and RZ Cnc. It can be seen that ζ Aur resembles a hot blackbody, RZ Cnc emission resembles optically thin free-free emission, and the continuum for ϵ Aur is slightly elevated from 8 to 20 μ.

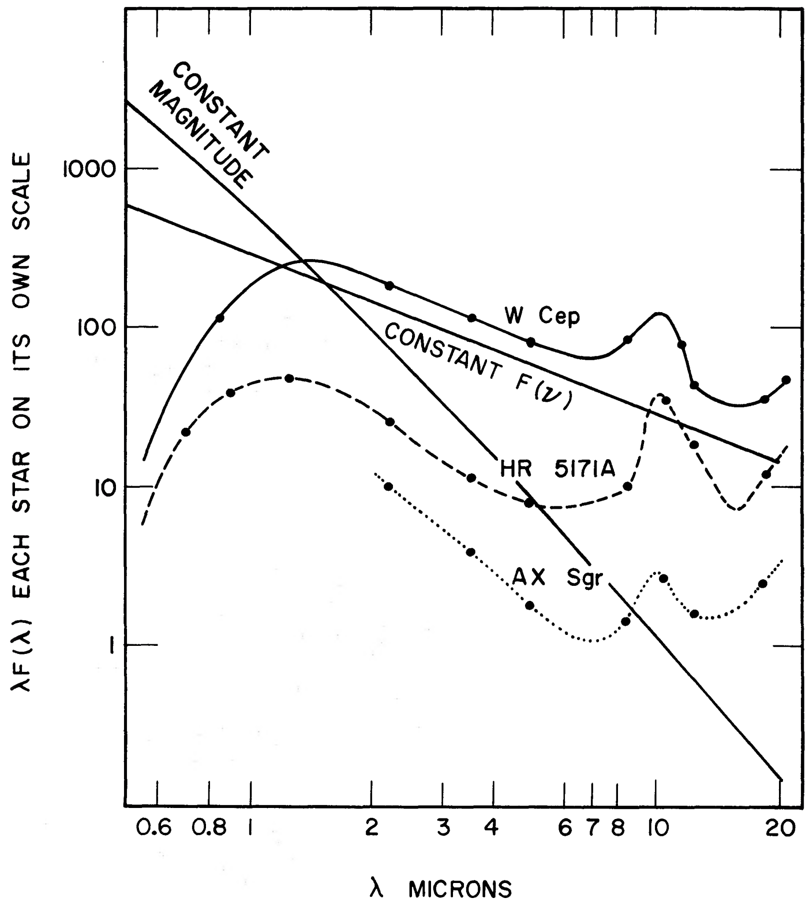

FIG. 2.—The energy distribution for W Cep. It can be seen that in the otherwise similar stars AX Sgr and HR 5171 A, the energy from 2 to 8 μ is reduced as though another component, of energy distribution $F(\nu) \simeq$ constant, is weakened or missing.

was less than 0.1 mag. Those cases where the error was between 0.1 and 0.3 mag are indicated in table 1 by a colon. In a few interesting cases observations exist of uncertainty between 1 σ and 3 σ. These observations are indicated by a double colon. The consistency of the observations indicates that the external error of the observations is also about ± 0.1 mag.

In figures 1–3 observations of these stars are plotted with arbitrary vertical displacement to permit ease of comparison. Additional observations at short wavelengths have been taken for υ Sgr and HD 30353 from Lee and Nariai (1967, 1969). For ϵ Aur they are from Johnson *et al.* (1964) while Mount Lemmon comparison-object observations have been used together with short-wavelength data from Gillett, Hyland, and Stein (1970) and other comparison observations by Humphreys, Strecker, and Ney (1971).

III. ϵ AURIGAE

This binary star with a 27-year period has only one optically observable component, type A8 Ia. The problems of interpreting the light curve and spectrum of the system have been discussed by Kuiper, Struve, and Strömgren (1937), Struve (1956), Hack (1959), and Huang (1965). Some broad-band infrared measures have previously been reported by Low and Mitchell (1964). The new observations are shown in figure 1.

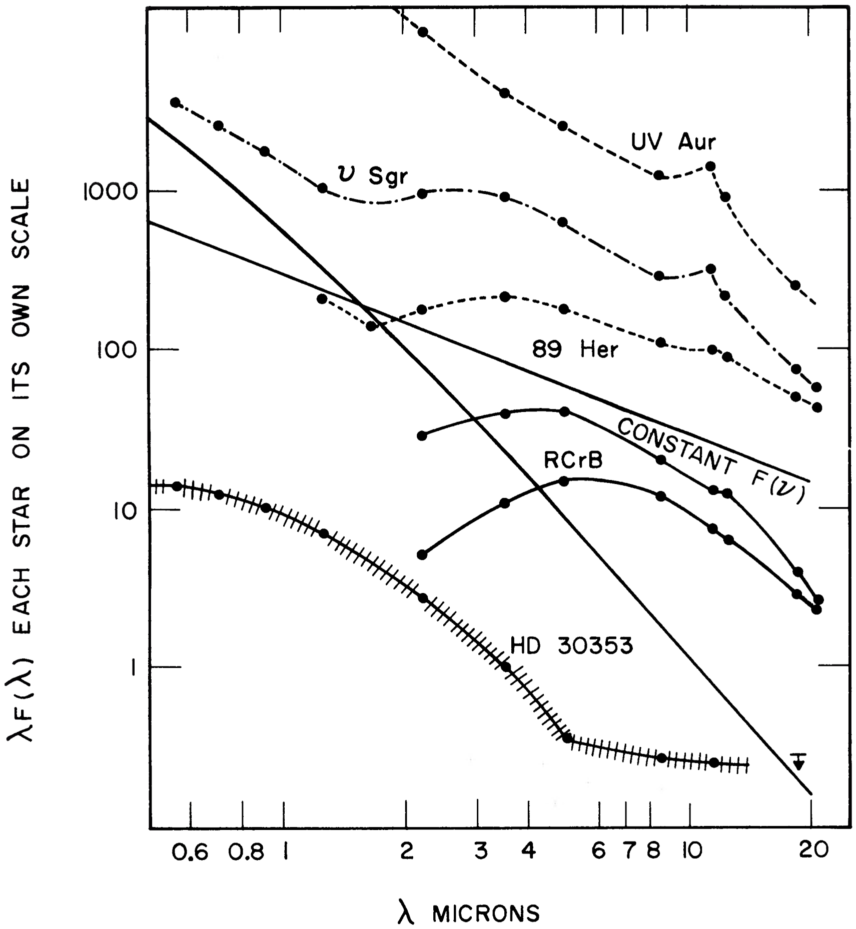

FIG. 3.—The energy distributions of UV Aur, υ Sgr, and HD 30353. Note the elevated continuum in υ Sgr, and compare this with the continua in 89 Her and R CrB, but absent in HD 30353. Note the 11-μ peak that appears in UV Aur, υ Sgr, and possibly weakly in 89 Her.

The shape of the spectral energy distribution from the visual to 5 μ is appropriate for a late A star suffering about 1.3 mag of visual extinction. Longward of 10 μ the energy distribution is elevated by about a factor of 2. The 18-μ observation sets a severe limit on the presence of any large cool star in the system. And the dimensions of the system, together with the heating by the A star, imply a temperature of more than some hundreds of degrees for any companion. Thus a companion should not be expected to show up at longer wavelengths, and we must take the 5–18 μ excess as probably being radiation from the companion.

If so, we can suggest that the radiation from the companion behaves as though $F(\nu)$ is approximately constant at a level of about 10 flux units between 5 and 10 μ, and at longer wavelengths it falls off like a blackbody with a total radiation in this tail slightly larger than that produced by the A star. This radiation could be similar to the radiation observed from the envelopes around Be stars (Woolf, Stein, and Strittmatter 1970). And Huang has already suggested that the circumstances of the eclipse are consistent with the A star being occulted by a disk three times the diameter of the A star and 0.4 of its height. Thus the projected surface area of the disk is about equal to the surface area of the A star. The equality of 10–18 μ emission of these components suggests that the disk is a cloud of partially ionized gas with temperature similar to that of the A star.

If we then ask at what electron density such a disk would become opaque to free-free radiation near 10 μ, we find $\eta_e \simeq 10^{11}$ cm^{-3}. At such a density the disk would also have an optical depth $\tau \simeq 3$ from electron scattering. This would explain how the disk occults the A star.

From spectra of the A star at the end of the eclipse, Hack (1959) has derived the electron pressure by two separate ways. She finds an electron density $\eta_e \approx 2 \times 10^{11}$ cm^{-3}, and the dilution factor is about 0.1. The consistency of the derived densities, expected electron-scattering optical depth, shell temperature found from the infrared observations, and shell temperature indicated by its spectral absorption features seem convincing. The worries that Hack had because the outer part of the shell is substantially neutral and should therefore also have appreciable H^- opacity are overcome by Huang's disk model. It is predicted that near 10 μ there will be a long secondary eclipse of depth $\sim$0.2 mag.

IV. ζ AURIGAE

This 972-day binary consists of a K4 Ib supergiant and a B star. Spectroscopically there is evidence for an extended atmosphere around the K star (Wilson 1960). Thus it seemed natural to see whether this star showed silicate emission.

In normal cool stars the magnitude at 3.6 and 8.6 μ is usually a good measure of the continuum level, whereas the radiation at 11 and 18 μ is a measure of any silicate emission. The averages of these two sets of magnitudes are the same. Therefore, there is no detectable silicate emission to within about 0.1 mag. This is far less than the smallest emission detected with certainty up until now, α Her with 0.4 mag of silicate excess.

V. W CEPHEI

This K0 Ia star apparently has a much fainter O-type companion. From earlier observations of limited spectral range by Gehrz and Woolf (1970), Wallerstein had suggested that part of the continuum might be due to free-free emission. And his spectroscopic observations of shell iron emission lines were consistent with this interpretation. From the new observations shown in figure 2, it seems that the entire energy output between 2 and 5 μ might be dominated by optically thin free-free emission at a level of 70 flux units. This is comparable with the amount suggested by Wallerstein.

Free-free emission at such high levels is not present in any other G–K Ia or Ia$^+$ supergiant observed to date. Such stars include RW Cep, AX Sgr, HR 5171 A, and HR 6392. In figure 2, comparison spectra from Humphreys *et al.* show AX Sgr (G8 Ia), fairly typical of most of these stars, and HR 5171 A (G8 Ia$^+$), whose energy distribution is most close to W Cep in possibly showing some (smaller) amount of free-free emission.

It is tempting to conclude that the presence of the O-type companion is responsible for the ionization producing the free-free emission. The silicate emission is very strong, and it seems as if the presence of the hot star has not prevented the formation of solid particles as it may have in VV Cephei–type stars.

VI. Z ANDROMEDAE

In an earlier study (Woolf 1969) Z And was observed to see if it could shed some light on the phenomena producing infrared emission of some planetary nebulae. At that time only upper limits could be placed on its infrared emission. The new observations of table 2 are now useful for placing constraints on the free-free emission of the gas (no more than 1 flux unit), on the emission of solid particles embedded in the nebula, and on any silicate emission from the late-type star in the system.

The observations in table 2 show a continuum that from 2 to 11 μ rises only a factor of 2 above that expected from a blackbody. This continuum can mainly be attributed to the M2 III star that has been postulated by Boyarchuk (1968). The color difference of about 5 mag between visual and infrared is entirely appropriate for such a star.

Observations of low weight at 18 and 22 μ seem to suggest a sharply rising continuum of the type that might be associated with the planetary nebula component. Further observations of this object will be made next season. The absence of any large flux near 11 μ shows that the M star is not coaxed into silicate particle emission despite the small size of the binary system (period $\sim$700 days).

VII. UV AURIGAE

UV Aurigae is a system with a late-type star and a planetary nebula, resembling R Aqr, except in this case the late star is a carbon star (Sanford 1949). The energy distribution of this star appears in figure 3. It is virtually identical to the spectra of other carbon stars studied by Hackwell (1972).

The single peak at 11 μ in stars like UV Aur has been attributed to either silicon carbide or silicon nitride. Later discussion of the hydrogen-deficient stars has bearing on this question. There is no sign of any infrared component associated with the planetary nebula.

VIII. υ SAGITTARII AND HD 30353 (KS PER)

Although the visual spectra of these two hydrogen-deficient binary stars are very similar, their infrared energy distributions as shown in figure 3 are very different. In υ Sgr there seem to be three components. Shortward of 1.5 μ there is the visually observed star. From 1.5 to 18 μ there is a smooth continuum, resembling a blackbody at a temperature of about 900° K, but broader. At 11 μ there is a peak that is surprisingly reminiscent of that in UV Aur. In this connection it is interesting to note that in an analysis by Hack (1966) of υ Sgr, she derives relative abundances of light elements N > C > O. Thus υ Sgr is a hot hydrogen-deficient carbon star, and its resemblance to UV Aur may be meaningful. HD 30353 on the other hand seems to have an energy distribution quite smooth from the visible to 5 microns. Contrary to suggestions by Lee and Nariai there appears no obvious separation of a hot and a cool stellar component. Indeed, if one allows for about 1.5 mag of visual extinction, the energy distribution would not permit any substantial fraction of the energy to come from a late-type star.

Longward of 5 μ there are low-grade observations that suggest the presence of some excess radiation, but its spectral distribution is quite uncertain. An analysis of the spectrum of HD 30353 by Wallerstein, Green, and Tomley (1967) shows that, although it is like υ Sgr in that nitrogen is again the most abundant light element, it is unlike υ Sgr in that N > O > C. Thus this is not a carbon star. And one immediately is impressed with the notion that the continuum present in υ Sgr and absent in HD 30353 might be due to carbon.

In figure 3 for further comparison, the infrared spectrum of R CrB (Stein *et al.* 1969) is shown. Two spectra are shown, corresponding to two different times. It is seen that the energy distributions for R CrB are very similar to that in υ Sgr except that the 11-μ peak is missing. Now in Searle's (1961) analysis of R CrB, he suggests that though the carbon abundance is high, the nitrogen abundance is normal. Danziger (1965) has analyzed the very similar star RY Sgr, and finds there C > O > N. Thus we are now finding our supposition that the smooth continuum in υ Sgr is due to carbon tends to be confirmed. And there is a suggestion that the presence or absence of the 11-μ peak is linked to the high or low abundance of nitrogen. Such a linking might seem probable if the peak is due to Si_3N_4, or a nitrogen impurity band in graphite, but most unlikely if it is due to SiC.

In figure 3 one last star is shown for comparison, 89 Her. This F2 Ia supergiant has an infrared excess found by Gillett, Hyland, and Stein (1970). Other F supergiants losing mass, such as ρ Cas, do not show such a continuum, nor do other spectroscopically similar stars such as ι Sco. Now the energy distribution of 89 Her is remarkably like that of υ Sgr though it appears that an 11-μ peak is rather weaker. It is tempting to conclude that the peculiarity of 89 Her which permits it to have an infrared excess is that it is a carbon star, with a somewhat milder nitrogen excess than υ Sgr. An infrared energy distribution is no substitute for a spectroscopic abundance analysis. Such an analysis would be most useful in confirming or denying the apparent implications of figure 3.

In summary, it is tentatively suggested that there are a set of carbon rich stars of type earlier than G0; and if they eject mass, they can be distinguished by their production of clouds of graphite in a circumstellar shell. If they also have a high abundance of nitrogen, they will produce an 11-μ emission peak.

IX. η GEMINORUM

This star is most unusual in being both an intrinsic variable and an eclipsing binary star (McLaughlin and van Dijke 1943). The evidence that actual eclipses take place is rather slight. It seems much more likely that the star is an ellipsoidal variable. If one tries to interpret the visual light curve as an eclipse, the secondary should be an even later M giant. But there is no sign of the presence of such a star.

In this study η Gem (M3 III) has been compared with the nearby single star μ Gem (M3 II–III). If we analyze these the same way as we analyzed ζ Aur, we find a silicate excess of emission of 0.15 mag for μ Gem and 0.3 mag for η Gem. These values are about 0.1 mag larger than suggested by some earlier published observations of these stars. The difference between the stars repeats in the sense that η Gem seems to have a very slightly greater excess than μ Gem. The total amount of silicate emission for either star is extremely small and is at the limit of precision for these measurements. If there is an effect of the binary system in increasing the silicate emission of η Gem, it is small.

X. RZ CANCRI

This unusual binary consists of a pair of K giants revolving in a 21-day period. Hiltner (1946) has spectroscopically shown that Ca II emission is associated with the pointed ends of the prolate K2 star. The infrared observations seem to indicate (fig. 1) an optically thin ionized gas. This is quite surprising, in that this system is not known to show hydrogen emission lines. The circumstance of infrared indications of free-free emission while hydrogen is not in emission recalls our interpretation of ϵ Aur which has a similar phenomenon. There is a hydrogen emission line in ϵ Aur, but it is associated with the A star. Such emission from mildly ionized gas has been predicted by Dyck and Milkey (1972).

XI. SUMMARY

The results of this paper fit into a number of separate categories. Thus the infrared observations of ϵ Aur have been useful in developing a model in which the A star is eclipsed by a partially ionized disk, with $n_e \simeq 10^{11}$ cm^{-3}, $T_e \simeq 7000°$ K.

Free-free emission is seen from this disk, from RZ Cnc and W Cep. In these stars the free-free emission from mildly ionized matter seems consistent with prediction that such emission should occur by Dyck and Milkey (1972). The free-free emission from the two latter stars are the only phenomena of this group of stars that are clearly linked to the binary nature of the systems.

Stars like ζ Aur and η Gem seem to have no special dust production, despite the extended atmosphere of the first and the ellipsoidal shape of the second. Two combinations of a cool star and a planetary-nebula–like object also seem to show no abnormal emission. However, the tentative identification of 20-μ emission in Z And should be reexamined.

The observations of hydrogen-deficient stars seem to indicate that those stars with high infrared continua are carbon rich, and so the continuum is probably due to graphite. An 11-μ peak appears in υ Sgr, resembling that found in some carbon stars but not R CrB. It is suggested that this peak is found in nitrogen-rich objects, and is probably due to Si_3N_4. Optical observations of 89 Her might help confirm this.

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