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INFRA-RED PHOTOMETRY OF R CORONAE BOREALIS TYPE VARIABLES AND RELATED OBJECTS

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SUMMARY

Infra-red photometry (*J*, *H*, *K*, *L*) is given for 12 RCB stars, three HdC stars and two helium stars. *N*, *Q* observations are given for six of the RCB stars. Most of the RCB stars show infra-red excesses. Although the HdC and helium stars are related spectroscopically to the RCB stars they do not show IR excesses. Evidently the occurrence of an IR excess is intimately connected with the RCB phenomenon rather than being a general property of hydrogen deficient, carbon-rich objects. This is understandable if the circumstellar shell is periodically replenished by particles ejected by the variables at minimum. The very hot RCB star, MV Sgr has an IR excess which indicates a hotter shell (1200°–1500°) than that found in other RCB stars (800°–900°). V348 Sgr, a peculiar carbon-rich hydrogen-poor variable, has a large infra-red excess. This strengthens its similarity to the RCB stars. Recently proposed models for the RCB phenomenon are considered. Ejection of particles at minima rather than geometrical eclipses by circumstellar dust blotches seems required by the observations.

1. INTRODUCTION

This is the fifth in a series of papers aimed at improving our understanding of the physical state and evolutionary status of the R Coronae Borealis (RCB) variables. Previous papers (Feast 1969, Paper I; Lee & Feast 1969, Paper II; Alexander *et al.* 1972, Paper III) have dealt in some detail with the pulsating RCB star RY Sgr and another paper (Feast 1972, Paper IV) has discussed the spectra and absolute magnitudes of RCB stars in the Large Magellanic Cloud.

The purpose of the present paper is to present and discuss infra-red photometry on the Johnson system for a number of RCB stars and related objects. Infra-red photometry of RY Sgr was discussed in Paper II and infra-red observations of R CrB itself have been published by Stein *et al.* (1969), Forrest, Gillett & Stein (1971) and Wing *et al.* (1972). Both these stars are hydrogen deficient, carbon-rich objects which show marked infra-red excesses attributed to black-body radiation from (carbon) dust particles in circumstellar shells. Analysis of spectroscopy and *UBV* photometry of RY Sgr (Paper III) gives good evidence for the existence, during a minimum, of circumstellar reddening presumably associated with the shell. Extention of this work to a larger sample of RCB stars is desirable for a number of reasons. For instance, the possibility was raised in Paper II that an infra-red excess might be present at most epochs in RCB stars and this suggestion can be tested on a larger sample. Furthermore, RY Sgr and R CrB are both

TAI

Observations of RCB

(a) RCB stars

	Date 1972	*J*	*H*	*K*	*L*
S Aps	June 4, June 28	7·80	7·26	6·81	5·28
UW Cen	June 29	8·57	8·01	6·94	4·65
DY Cen	June 29	11·9±0·4	11·1±0·2	10·9±0·2	>8·88
V Cr A	June 6	8·98	8·47	7·55	5·47
	June 29	8·84	8·35	7·47	5·45
	June 30				
WX Cr A	June 29	9·18	8·63	8·05	6·70
RT Nor	June 29	8·89	8·66	8·16	6·42
RZ Nor	June 29	9·14	8·57	8·49	8·01±0
RY Sgr	June 2, June 28	8·54	6·97	5·19	2·59
GU Sgr	June 5, June 30	8·70	8·22	7·59	6·08
MV Sgr	June 4	10·7±0·4	9·98±0·11	8·76	7·6±0
	June 29	11·11	9·85	8·95	7·32±0
V348 Sgr	June 5, June 28	11·3±0·2	10·1±0·3	8·08	5·40
RS Tel	June 5	10·98±0·16	10·39±0·15	9·27	6·9±0
	June 27	10·92	9·97	9·07	7·03
	June 28				

(b) HdC stars

	Date 1972	*J*	*H*	*K*	*L*
HD 148839	June 4	7·36	7·28	7·15	6·93±0
HD 173409	June 5	8·59	8·48	8·43	>7·51
HD 182040	June 6	5·53	5·29	5·13	4·73

Note: The standard error of these measuren

rather similar stars (apart from being hydrogen deficient and carbon rich, they are similar to late F or early G type supergiants). Other RCB stars cover a wide variety of spectra (all however characterized so far as is known by hydrogen deficiency and carbon richness). They range from R type stars with very strong C_2 bands to the very hot object MV Sgr. It is desirable to know whether infra-red excesses are present in this whole range of objects.

MV Sgr is similar in spectrum to the hydrogen-deficient B type stars (the helium stars) which are also known to be carbon rich (e.g. Hill 1965). The cooler RCB stars are similar in spectrum to the (non-variable) hydrogen deficient carbon stars (HdC stars) (cf. Bidelman 1953; Warner 1967). We have therefore included some helium and HdC stars in our work for comparison with the RCB stars.

d related objects

(a) RCB stars

N	*Q*	Magnitude range and spectral type	Spectroscopic notes etc.
		9·6–15·2 vis. R3	C_2 strong
2·0±0·3			
		9·6–>13 pg K	C_2 uncertain
		12·0–>16·4 pg	Pec. (all lines including *H*, *K* quite weak)
		9·4–>14·0 pg Ro	C_2 present
2·1±0·2			
		11·0–>16·5 pg R5	C_2 strong
		11·3–16·3 pg R	C_2 present
		11·1–>12·5 pg	C_2 uncertain
		6·5±14·0 vis. Goep	Star faint when observed
0·4±0·2	−0·8±0·5		
		11·3–15·0 pg	C_2 present
3·0±0·3	1·4±0·7		
		12·0–15·6 pg B(He)	He I, C II etc., absorption (Herbig)
1·9±0·3	0·7±0·8	10·6–17 pg Pec	C II emission etc. (Herbig, Houziaux)
>2·1	>−2·8	9·3–>13·0 pg R8	Pec (star faint when observed). C_2 absorption and He I 3888 emission suspected

(c) Helium stars

D 124448	June 29	10·28	10·47	10·41±0·19	>8·75
D 168476	June 4	9·36	9·39±0·15	9·35±0·12	

$\leqslant \pm 0^{m}{\cdot}1$ unless another value is given.

2. OBSERVATIONS

The observations were made in June 1972 with an infra-red photometer (Glass, to be published) mounted at the Cassegrain focus of the Radcliffe 74-inch (1·88-m) reflector.

The results are listed in Table I. For the majority of the stars observations were obtained at *J*, *H*, *K* and *L* (1·25, 1·65, 2·2 and 3·5 μ). For a selection of the stars, observations were also made at *N* and *Q* (10 and 20 μ) with a liquid helium cooled bolometer. Standard stars were selected from the photometry of Johnson *et al.* (1966).

Table I also contains other relevant data from Kukarkin *et al.* (1969) and spectroscopic notes. These notes depend unless otherwise stated on 150 Å mm^{-1}

Carnegie image tube spectra taken with the Radcliffe reflector near the time of the infra-red observations (in June/July 1972). The main purpose of the spectroscopy was to confirm as far as possible from the presence of C_2 bands that the objects were typical RCB stars. Of the stars studied, RY Sgr and RS Tel were definitely well below maximum light at the time of the observations.

3. GENERAL DISCUSSION

A useful way to present some of the observations is a (*J–K*), (*K–L*) plot as in Fig. 1. This diagram shows the present observations of RCB stars together with

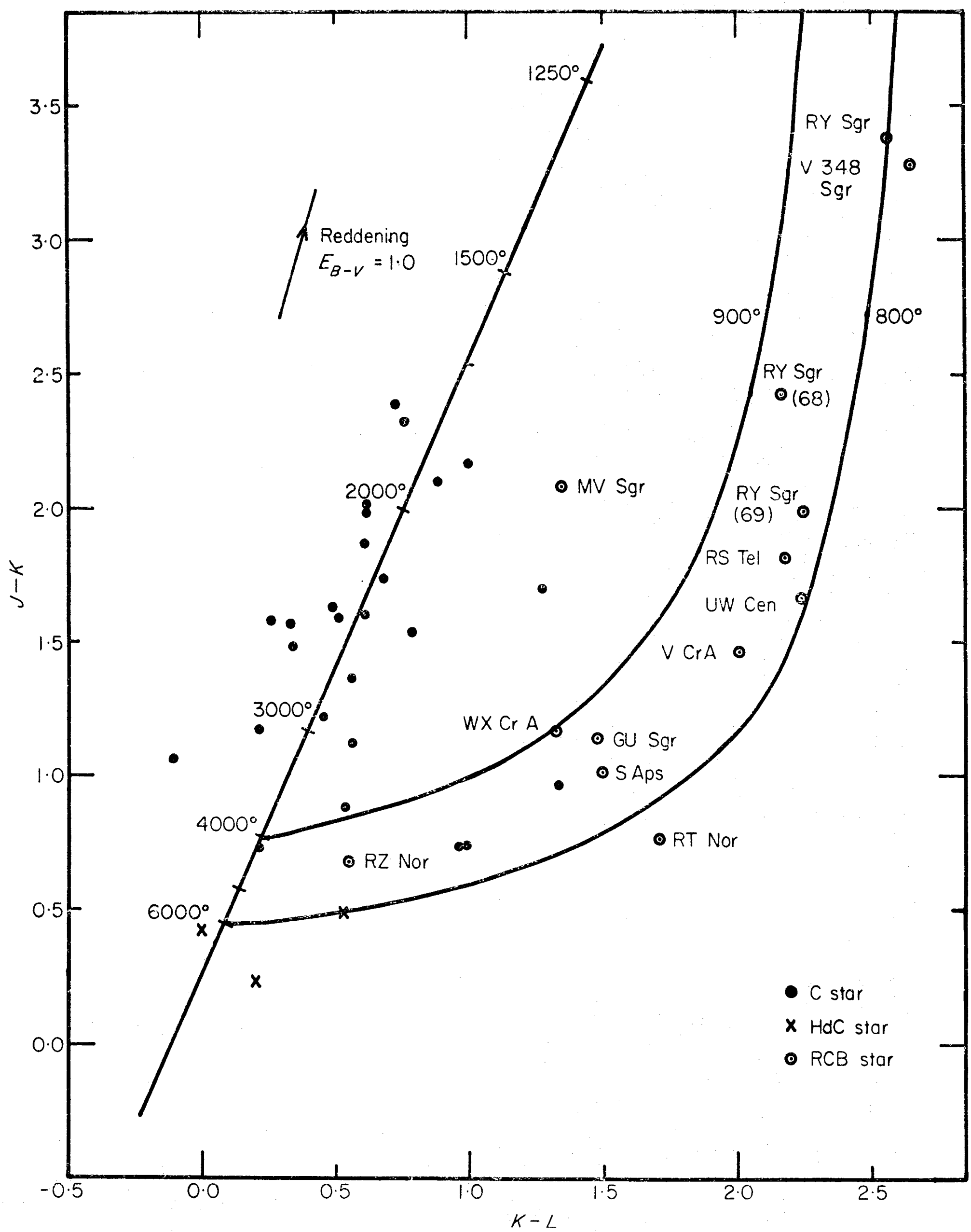

FIG. 1. (J–K), (K–L) *diagram; filled circles carbon stars from Mendoza & Johnson* (1965)*; crosses HdC stars; open circles, RCB stars. The black-body line and the reddening line* (*length corresponding to* E_{B-V} = 1·0) *are shown. The curves show the loci of combinations of black-bodies at* (*a*) 4000° *and* 900°, (*b*) 6000° *and* 800°.

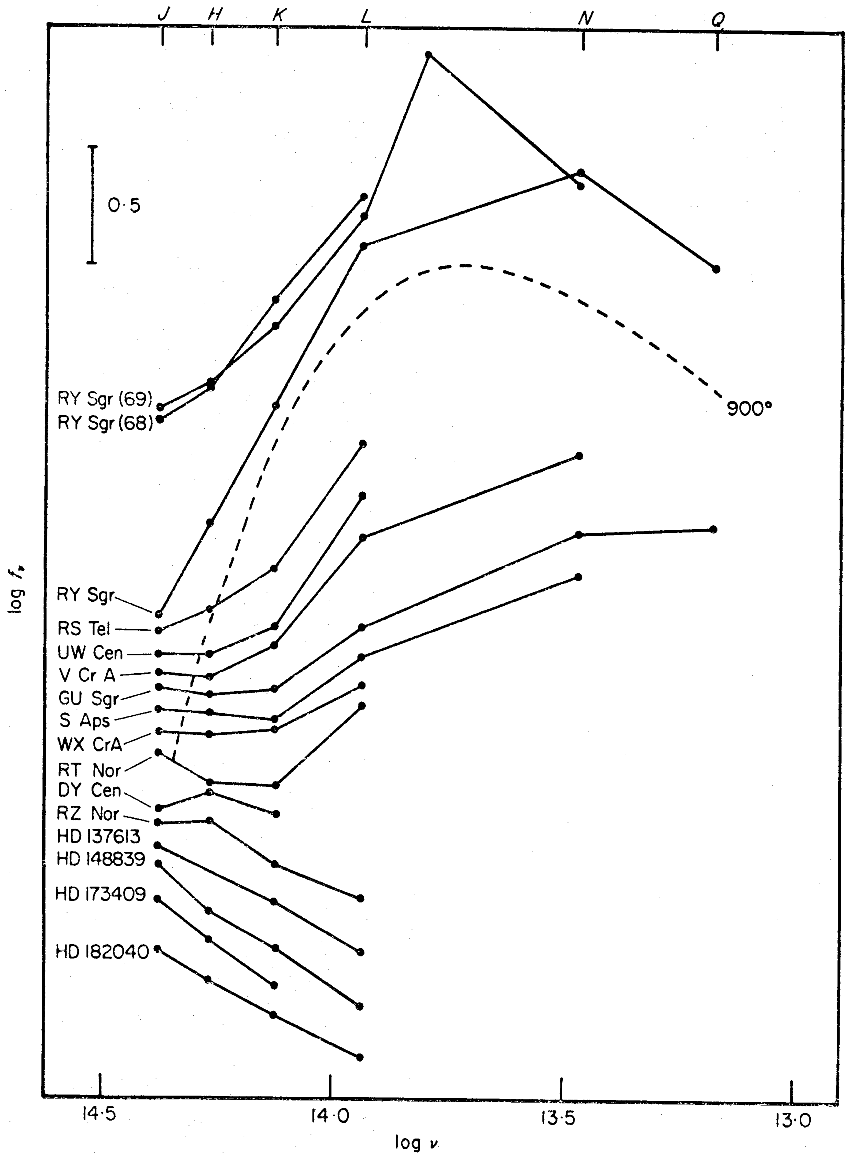

FIG. 2. *Log* F_ν – *log* ν *diagram for RCB and HdC stars. Ordinate arbitrary except that the observations of RY Sgr in* 1968, 1969 *and* 1972 *are correctly placed relative to one another. A* 900° *black body is shown for comparison.*

1968 and 1969 observations of RY Sgr from Paper II and carbon stars from Mendoza & Johnson (1965). Also plotted are the HdC stars. The theoretical black-body line is shown with temperatures marked at intervals along it. Also shown is the reddening line corresponding to van de Hulst's curve no. 15 (cf. Johnson 1968). The length of the reddening line corresponds to $E_{B-V} = 1{\cdot}0$. The normal carbon stars, with a few exceptions, lie close to the black-body line as do the HdC stars. Since the black-body and reddening lines are nearly parallel, interstellar reddening merely shifts the carbon stars along the black-body line (and slightly above it).

Leaving aside for the moment RZ Nor and the hot RCB star MV Sgr, it is evident that the other RCB stars fall well off the black-body line. Their position in the diagram cannot be explained by their being reddened carbon stars. However their position is that expected for objects with infra-red excesses. This is illustrated in Fig. 1 by the two curves which show, (1) the loci of all possible combinations of a black-body at 6000 K (the star) with another at 800 K (the shell) and (2) similar results for combinations of black bodies at 4000° and 900°. It is clear that the region of the RCB stars is well defined by the curves shown. Earlier work indicated a temperature of ~900 K for the circumstellar shells of RY Sgr and R CrB (cf. Stein *et al.* 1969, and Paper II).

Fig. 2 shows a $\log F_\nu$ (W Hz^{-1} m^{-2}) against $\log \nu$ plot for RCB stars and HdC stars. This figure shows that there is no evidence for a marked infra-red excess in the HdC stars, a conclusion already inferred from Fig. 1. In Fig. 2 the ordinate is arbitrary except that the 1968, 1969 and 1972 observations of RY Sgr are correctly positioned relative to one another. It is clear that in 1972 RY Sgr had a similar (large) infra-red excess to that observed in 1968 and 1969 and that the energy distribution was roughly similar to that of a black body at 900 K.

The other RCB stars all show evidence for infra-red excesses except DY Cen and RZ Nor. As indicated in Table I, DY Cen has a peculiar spectrum. This star is being further investigated spectroscopically but the possibility should be borne in mind that it is not an RCB star. In the past, stars have fairly often been erroneously assigned to the RCB class. C_2 has not yet been positively identified in RZ Nor and pending further work it should be considered only a doubtful member of the class.

The present observations cover a random sample of RCB stars at an arbitrary epoch. Most of these RCB stars (perhaps all of them) show infra-red excesses which may be attributed to radiation from a circumstellar shell. It seems reasonable to conclude therefore that typical RCB stars show radiation from such shells at most epochs if not at all times. As shown in Table I the *N* and *Q* (10 and 20 μ) observations frequently have quite large standard errors as is not unusual in this wavelength region. Thus it is probably premature to discuss possible deviations of the infra-red emission (as shown in Fig. 2) from a black body.

The similarity in chemical composition and temperature range of the majority of RCB variables and the HdC stars is compelling evidence that a close relationship exists between these two groups of objects. Since the HdC stars studied do not have infra-red excesses it seems reasonable to conclude that the presence of an infra-red emitting shell is intimately connected with the RCB phenomenon and is not a general property of all hydrogen poor, carbon rich objects. It seems probable that the RCB phenomenon is associated with the ejection of particles at each minimum thus replenishing the circumstellar shell. We cannot yet distinguish between the three following possibilities: (1) the HdC stars are RCB variables undergoing an extended period of quiescence, (2) The HdC stars avoid RCB type instability entirely in some way, and (3) The HdC stars represent an evolutionary stage just before or just after the RCB stars.

If we are correct in concluding that RCB stars have infra-red emitting shells at most epochs, it seems likely that these stars will also be affected at most epochs by a certain amount of circumstellar reddening. This will make the intrinsic *UBV* colours of the stars difficult to determine and may introduce some scatter in the effective absolute magnitudes of these objects.

One of the carbon stars observed by Mendoza & Johnson (1965), HD 166097, lies near one end of the region defined by the RCB stars in Fig. 1 and two others, HD 113801 and +17° 3325, lie near this region. These three stars deserve further study.

4. MV SGR

MV Sgr is a very hot RCB star discovered by Hoffleit (1958). Its spectrum was discussed by Herbig (1964) who found it to be similar to the helium stars (he compared it in particular to BD +10° 2179). As noted earlier the helium stars have the temperatures of OB type stars but are hydrogen poor and carbon rich. MV Sgr is distinguished from the helium stars by having a few emission lines in the visual region. Because of the apparently close connection of MV Sgr and the helium stars, two of the brightest helium stars, HD 124448 and HD 168476, were included in the present work. Fig. 3 shows these stars and MV Sgr in a log $F_\nu - \log \nu$ plot. This figure includes *UBV* values for MV Sgr by Paczynski (quoted by Herbig 1964) which presumably refer to near maximum light. *UBV* values for HD 168476 and HD 124448 were taken from Blanco *et al.* (1970). In the case of MV Sgr, in addition to the uncorrected observations, we plot fluxes corrected for a reddening of $E_{B-V} = 0{\cdot}44$ which was the value adopted by Herbig on the assumption that the

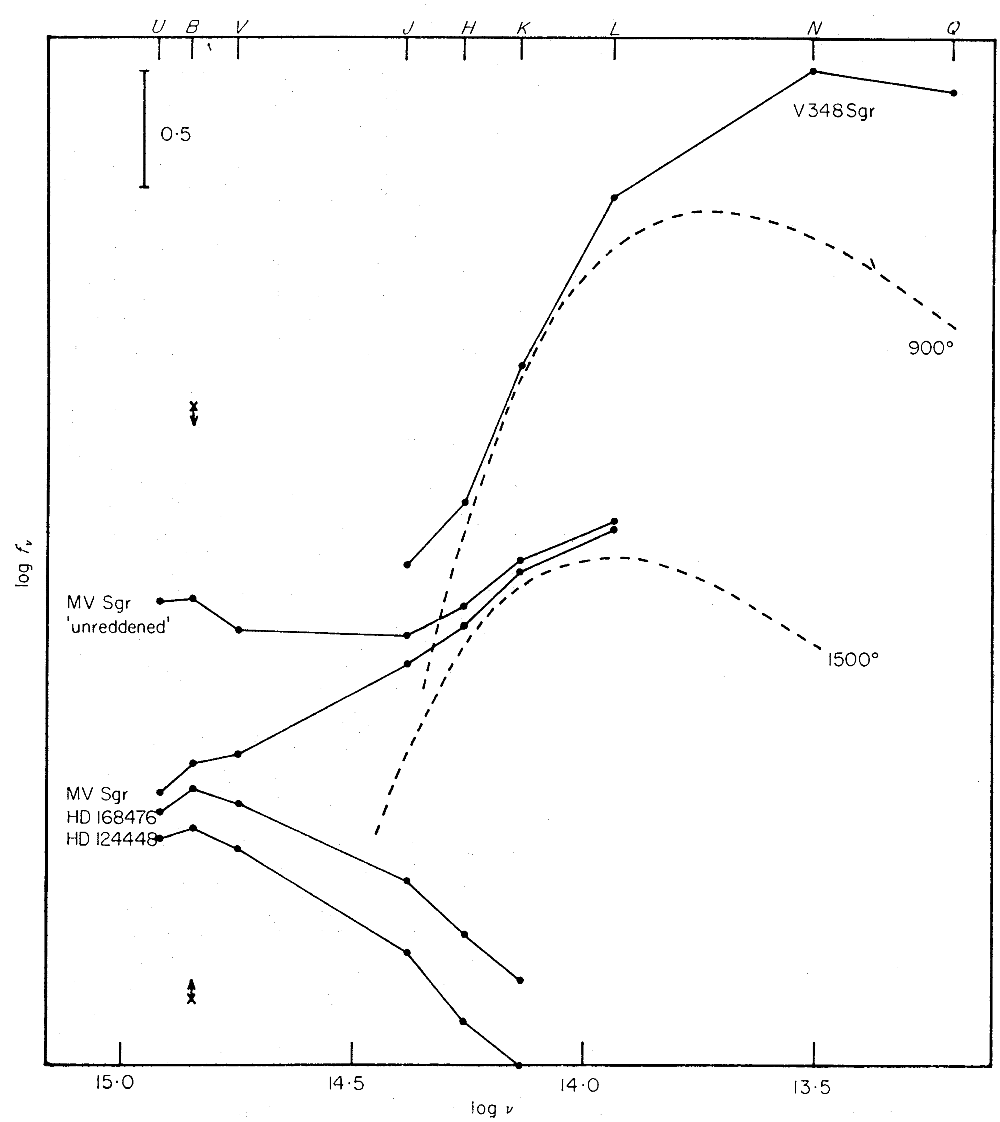

FIG. 3. *Log* F_ν − *log ν plot for helium stars, MV Sgr and V*348 *Sgr. The crosses indicate the approximate B flux of V*348 *Sgr at maximum and at minimum. Black-body fluxes at* 900° *and* 1500° *are shown for comparison.*

intrinsic (B–V) colour of the variable was the same as that of the helium stars BD +13° 3224 and +10° 2179. Whilst the ordinate in Fig. 3 is arbitrary the uncorrected and corrected plots of MV Sgr are correctly positioned relative to one another. Fig. 3 shows that whilst MV Sgr has a marked infra-red excess none is evident for the two helium stars. As in the discussion of the HdC stars we conclude that the presence of an infra-red excess is intimately connected with the occurrence of the RCB type of variability. Large infra-red excesses apparently do not occur in closely related non-variable objects.

In Fig. 1, MV Sgr is seen to lie at a somewhat different position from the other RCB stars. In fact it is relatively close to the black-body line but at a temperature of 2000°–1500° rather than at ~20 000° (the order of magnitude of the temperature of the star as indicated by its spectrum (Herbig 1964)). This suggests that the (J–K) and (K–L) indices are measuring mainly the colour of the shell without any large contribution from the star. This conclusion is reinforced by Fig. 3. It is clear that if the *UBV* fluxes of MV Sgr are extrapolated into the infra-red parallel to the helium stars, the contribution of the star to the observed infra-red fluxes will be small. Furthermore, Fig. 3 shows that the J, H, K, L fluxes of MV Sgr are roughly parallel to those of a black-body at 1500 K. It appears therefore that the very hot RCB star MV Sgr has a hotter circumstellar shell than the more normal RCB stars.

It may be noted that the two measures of MV Sgr in Table I do not agree particularly well. A mean of the two has been used in the discussion and there would be no significant change in the conclusions if either of the two values had been adopted. However the possibility exists that the infra-red magnitudes of this star may vary on a relatively short time scale (~1 month).

5. V 348 SGR

V 348 Sgr is a remarkable object which was described by Herbig (1958) and whose spectrum has been discussed in detail by Houziaux (1968). It varies between 10·6 and 17 pg with a quasi-period of 200 days; spending most of its time at either maximum or minimum. Its spectrum at maximum consists primarily of emission lines of C II. At minimum a normal nebular emission spectrum is seen. The strength of C II emission and the absence of hydrogen in the spectrum at maximum strongly suggest a hydrogen deficient, carbon-rich object and a close relation to the RCB stars, though the character of the light variations is atypical of the group. When observed in the present survey the star was definitely not at minimum. As shown in Figs 1 and 3 the object shows a large infra-red excess. There is a rough resemblance to 900 K black-body with a slight indication of excess emission at the longest wavelengths measured. The infra-red measurements are consistent with the association of V 348 Sgr with the RCB variables and suggest that the minima are produced in the same manner (obscuration by a circumstellar shell).

6. MODELS FOR THE RCB PHENOMENON

In Paper III the detailed photometric and spectroscopic observations of RY Sgr during minimum were discussed in terms of two possible models. (a) An eclipse of the star by a cloud of particles ejected by the star in the direction of the observer, and (b) the ejection of a more or less uniform spherical shell. The latter model was favoured because the evidence then available suggested that the bolometric magnitude of star and shell together remained constant during a minimum (cf. Paper II and Stein *et al.* 1969). Work by Forrest *et al.* (1971) suggests considerable deviations from constancy of the bolometric magnitude for R CrB and presumably indicate that the shell is rather irregular. Quite recently Wing *et al.* (1972) have suggested that large departures from constancy of bolometric magnitude can take place for R CrB. They conclude that an appropriate model is one in which an irregular cloud (giving rise to infra-red emission) is present at all times and that the minima of the star are caused by dense regions of this cloud ('blotches') crossing the observed face of the star.

As noted earlier, the present observations are indeed consistent with a model for RCB stars in which an infra-red emitting circumstellar shell is present at all, or most, epochs. However there are a number of reasons why a model of the type proposed by Wing *et al.* cannot apply to minima such as the one of RY Sgr analysed in detail in Paper III.

(1) If the initial decline of RY Sgr in 1967 (for example) is to be explained on the blotchy model, a blotch about the size of the stellar disc must move rather rapidly in front of the star (the photospheric light decays on a time scale of $\leqslant 5$ days). The blotch must then remain more or less stationary in front of the star, producing a geometrical eclipse, since the chromospheric emission spectrum of RY Sgr is seen at this time. The size of the blotch must then change gradually so that the characteristic development with time of the chromospheric spectrum is accounted for. The blotch model appears rather unlikely to be able to plausibly comply with these requirements. Furthermore the 1967–70 minimum of RY Sgr was typical of the RCB phenomenon in that whilst there was an initial rapid drop in light, the recovery was quite slow, occupying the order of 2 years. It is not clear why such a characteristically strong asymmetry in the light curve should follow from the blotchy model.

(2) It was shown in Paper III that during the rise from minimum of RY Sgr its position in the V, $(B-V)$ diagram at epochs of normal spectra lay along a reddening line. As discussed in Paper III this is evidence against any gross non-uniformity in the part of the obscuring shell covering the observed face of the star (e.g. totally opaque clouds produce extinction without reddening).

(3) The rapid initial decline of RY Sgr in 1967 was accompanied by the ejection of gas at ~ 200 km s^{-1} (Paper III). It is not clear why this physical effect should be associated with the geometrical eclipse of the star by a blotch some distance from it.

As already mentioned, the eclipse model considered in Paper III was one where a cloud was ejected from the star towards the observer (presumably small magnitude drops at other epochs might be attributed to clouds ejected at an angle to the line of sight). The main attraction of this model is that in principle it allows the development of the chromospheric spectrum of RY Sgr to be explained in exactly the same way as the development of the solar chromospheric spectrum during a solar eclipse; that is, by gradual variation of the height above the star of the observed chromospheric region. The objections to the blotchy model do not necessarily apply to this eclipse model. However this model does place rather definite restrictions on the size of the ejected cloud and its development with time. It is not clear whether in reality a particle cloud could meet these restrictions. Observations of different minima of R CrB (Herbig 1949; Payne-Gaposchkin 1963) show that the spectroscopic changes were rather similar in both cases to those observed for RY Sgr. Thus it appears necessary to look for some model which does not rely too heavily on the chance occurrence of a rare situation. The principal difference between the eclipse model discussed in Paper III and the uniform shell model is that in the latter case the development of the chromospheric spectrum is interpreted in terms of the decay of an emitting region cut off from its primary source of excitation. So far as the physics of the RCB phenomenon is concerned the ejection of a cloud in the direction of the observer is not basically different from the ejection of a uniform shell.

It appears that the available evidence requires the ejection of a shell at minima of RCB stars. Whether or not there are very marked non-uniformities in this shell is not yet entirely clear. Concurrent *UBV* and infra-red photometry as well as spectroscopy is needed to settle this point. It should also be possible to devise ways of distinguishing between the two models of chromospheric development discussed in Paper III.

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