Mon. Not. R. astr. Soc. (1986) **222,** 357–364

IRAS observations of R Cor Bor stars

N. Kameswara Rao *Indian Institute of Astrophysics, Bangalore 560034, India*
K. Nandy *Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ*

Accepted 1986 May 1. Received 1986 April 22; in original form 1985 October 9

Summary. The *IRAS* observations of R Cr B, SU Tau and V 348 Sgr indicate the existence of a cool dust component of temperature ~30 K in R Cr B and SU Tau and ≤ 100 K in V 348 Sgr, in addition to the hot dust. It is suggested that this cool dust shell is a remnant of the stage when these stars were red giants for the first time.

Although R Cr B was observed by *IRAS* during a visual light minimum no significant IR flux increase was apparent.

1 Introduction

R Cr B is the brightest member, and the prototype, of the group of hydrogen-deficient carbon-rich irregular variables. Loreta (1934) and O'Keefe (1939) have suggested that the deep, irregular, visual light minima are due to the formation of carbon dust around the star. The discovery of IR excesses by Stein *et al.* (1969) and later by Forrest, Gillett & Stein (1971, 1972) not only indicated the presence of dust but also showed that there was no real correspondence between visual light minima and variation in the infrared flux. The ground-based IR photometry indicated that the IR energy distribution is smooth (featureless) and behaves like a blackbody varying between 600 and 900 K (Forrest 1974). UV observations suggest that the dust consists of amorphous carbon particles (Holm, Wu & Doherty 1982). When *IRAS* was launched observations of these stars were proposed to study the properties of the dust and its distribution from IR excess at longer wavelengths. Another reason was that to account for the extreme hydrogen deficiency in these objects, it has recently been proposed (Iben *et al.* 1983; Iben 1984) that R Cr B stars are born-again asymptotic giant-branch stars, i.e. after being once on the asymptotic giant branch the star moved to the left in the H–R diagram and ejected or lost the hydrogen envelope (planetary nebulae-like) and moved again to the right to a red giant phase. In such a case following the analogy of the planetary nebulae we expect to see the remnant of the ejected nebular material and also the cold dust (≤100 K) associated with it. In this paper we present some of the *IRAS* observations regarding the cold dust component. Walker (1985) has used *IRAS* survey band observations to infer the presence of hotter dust as is indicated by the ground-based observations.

2 *IRAS* observations

A description of the *IRAS* survey instrument and details of observations have already been given by Neugebauer *et al.* (1984). The observations of R Cr B, S Aps, and UW Cen discussed here were obtained in the UK guest observers programme in deep survey mode (Additional observations – AO). These observations have been converted from in-band powers to flux densities using the conversion factors and colour correction procedures given in the guide to interpreting *IRAS* additional observations made with the survey array (Miley 1983). The additional observations of UW Cen and S Aps were made with a macro different from that used for R Cr B and SU Tau and this macro took no data on the source in the 60 and 100 μm bands.

The observations obtained on two SOPs (Satellite Operation Plan) are in good agreement. The flux densities and the *IRAS* positions along with the survey data on two other R Cr B stars, SU Tau and V348 Sgr, are given in Table 1, along with the signal to noise ratio for the observations made in the AO mode. This represents the ratio of the signal to local noise. The observations of SU Tau and V348 Sgr are from the survey observations contained in the catalogue of *IRAS* point sources. Walker (1985) pointed out that the 60 and 100 μm flux of some of the R Cr B stars could be due to the confusion with background or foreground sources.

Table 1. *IRAS* observations of R Cr B stars.

Star	Observed coordinates (1950)		Observed flux densities (Jy)				SOP	Date
	RA	DEC	12 μm	25 μm	60 μm	100 μm		
	h m s	° ′ ″						
UW Cen	12 40 25.9	−54 15 08.7	7.35 (244)	4.76 (145)			360	83 July 24
			7.20 (201)	4.74 (119)			362	83 July 25
S Aps	15 15 20.4	−71 52 17.4	2.77 (143)	0.98 (95)			63	83 Feb 26
			2.72 (157)	1.05 (89)			65	83 Feb 27
R Cr B	15 46 30.3	+28 18 28.4	31.11 (13)	13.18 (21)	2.78 (15)	2.44 (19)	459	83 Sep 12
			32.28 (20)	12.97 (19)	3.01 (11)	2.48 (21)	461	83 Sep 13
SU Tau	5 46 07.6	+19 03 27	9.5	4.14	1.52	2.78		
V 348 Sgr	18 37 17.3	−22 57 20	5.56	3.02	2.83	1.3		

Su Tau: it had a 51 per cent likelihood of variability. The 100 μm flux is unusually high but it seems legitimate having a signal-to-noise ratio of 5.2.
No data at 60 and 100 μm exist for UW Cen and S Aps in the AO mode.
The signal to local noise ratio is given in parentheses for the observations obtained in AO mode.

We have examined the field of about 50 arcmin (Fig. 1) around R Cr B and could identify two galaxies and a star close to R Cr B. The star is only seen in the 12 and 25 μm bands whereas the galaxies are only prominent in the 60 and 100 μm bands. The fluxes from R Cr B in 60 and 100 μm are comparable to those of the galaxies. These data indicate that the 100 μm flux of R Cr B is real and not due to cirrus or a background source. The 100 μm position of R Cr B agrees within the positional accuracy (±10 arcsec) with the astrometric position of R Cr B. For all the stars in Table 1 the positional agreement is within ±15 arcsec.

These *IRAS* observations of R Cr B were obtained (1983 September 12 – 13) when the star was undergoing a visual light minimum. The visual magnitude was $V \sim 10.2$ (Böhme 1983) on the descending part of the light curve after roughly 30 days from the start of the minimum.

3 Results and interpretation

Fig. 2 shows the *IRAS* observations along with other ground-based observations obtained by Forrest (1974) on two occasions; when the star was at infrared maximum (JD 2441033 – crosses)

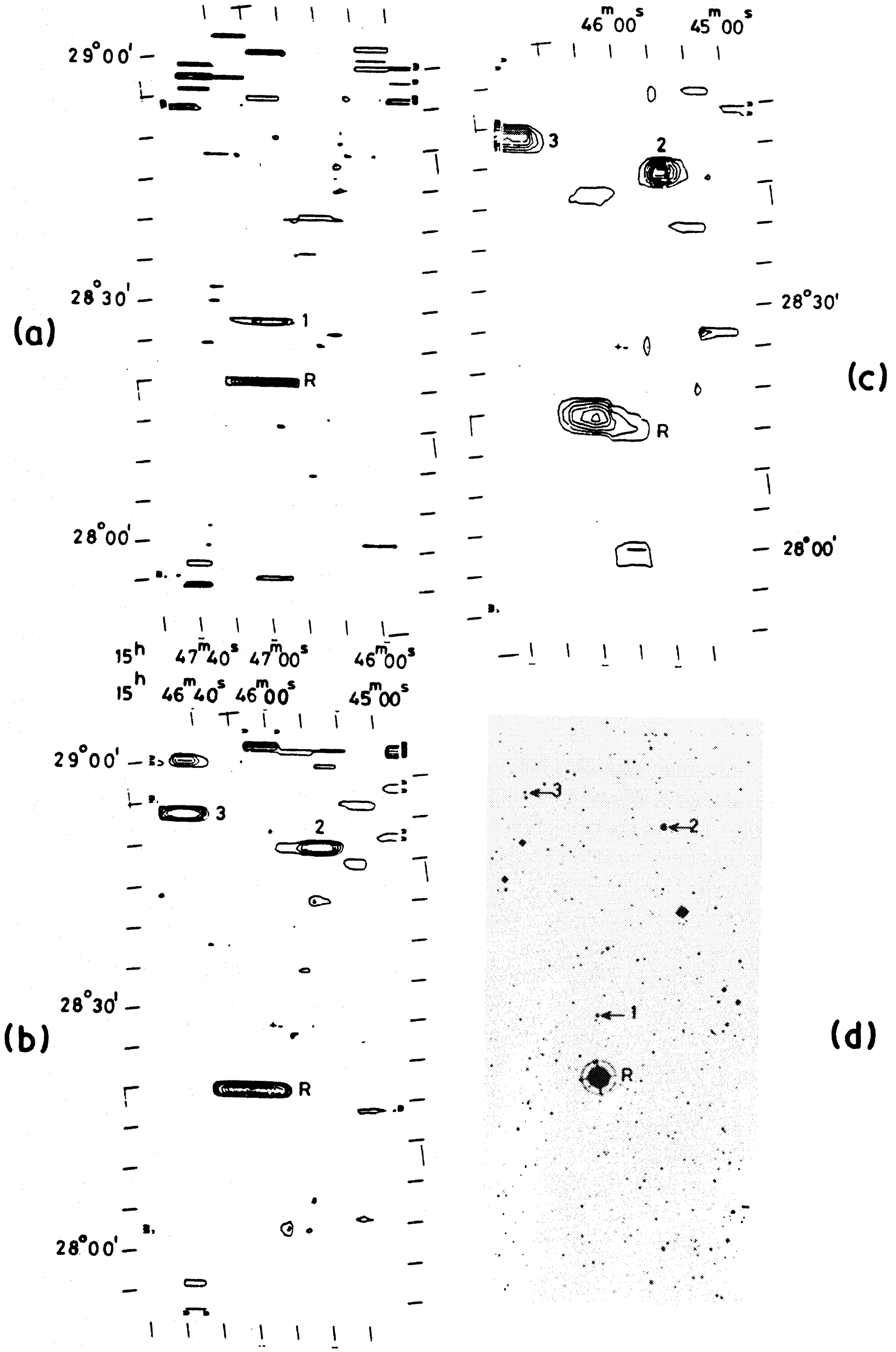

Figure 1. The field of R Cr B; (a) in 25 μm band, (b) 60 μm band, (c) 100 μm band, and (d) from Palomar Sky Survey E print. R denotes R Cr B and No. 1 in (a) is 11 mag star, No. 2 seen in the 60 and 100 μm bands is the galaxy NGC 6001 and No. 3 is an elliptical galaxy corresponding to ZWG 166.059. These objects are identified in the POSS plate. (POSS print reproduced by permission of the California Institute of Technology.)

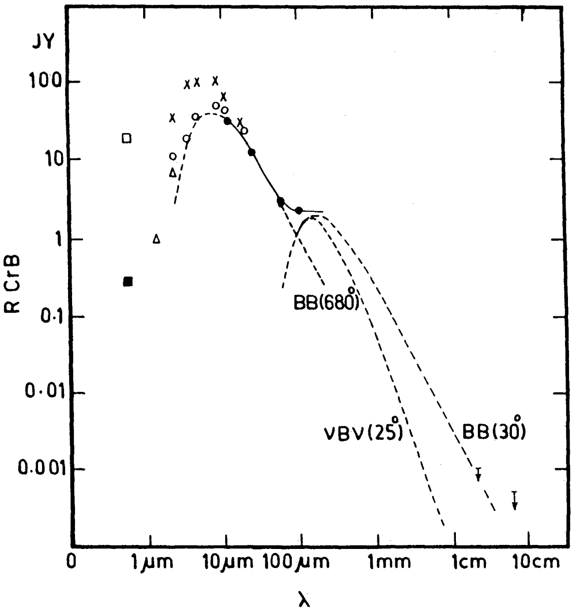

Figure 2. Shows the energy distribution of R Cr B. Dots are the *IRAS* observations. The dark square represents the visual magnitude at the time of the *IRAS* observations. The open square is the normal light maximum. Open circles and crosses are the ground-based observations on two different occasions, IR minimum and maximum respectively (Forrest 1974). Open triangles are observations of Ashok *et al.* (1984) during the same visual minimum but at a later date than the *IRAS* observations. The arrows indicate upper limits to the radio flux at 2 and 6 cm. The line shows the combination of 680 K blackbody +30 K blackbody and a $\nu B\nu$ (25 K) type energy distribution.

and at infrared minimum (JD 2441740 – open circles). The near-IR (J, K) measurements of Ashok, Chandresekher & Bhatt (1984) obtained in the same visual minimum as *IRAS* but when the star was at $m_V \sim 11.5$ on the rising branch are also shown for comparison. The flux calibration given by Forrest has been used. The *IRAS* 12, 25 μm fluxes fall very close to the IR minimum fluxes given by Forrest and probably indicate that the star was going through the IR minimum phase. No IR observations are available just prior to the onset of visual minimum for a comparison. The *IRAS* observations follow a 680 K blackbody energy distribution very accurately from 12 to 60 μm with an effective radiating solid angle of 6.84×10^{-15} sr. This is in conformity with the previous ground-based IR observations that although the total IR flux varies, at any given time the energy distribution can be well represented by a blackbody. The F^{exc} (680 BB)= 2.6×10^{-15} W cm^{-2} corresponds to $L \simeq 0.15\ L_*$ (assuming $M_V = -5$ for R Cr B, and distance of 1380 pc). However 100 μm *IRAS* observations show significant excess flux (~1.3 Jy) over the 1 Jy expected from the 680 K blackbody energy distribution. Since there are no obvious emission features around 100 μm either in the cool gas or the carbon dust usually associated with R Cr B stars this emission is assumed to be due to dust continuum. If it is further assumed to behave like a blackbody – a temperature of ~30 K with a radiating solid angle of 3.97×10^{-12} sr is obtained which is about 580 times the surface area of the 680 K material (an upper limit of 10 per cent flux density at 60 μm is assumed to be due to the cool component).

There appear to be two distinct components for the infrared emission; one from a component characterized by a 680 K blackbody and the other cool dust component which may be at 25–30 K. The *IRAS* measurements of SU Tau (star very similar to R Cr B) and V348 Sgr, a hotter R Cr B star surrounded by visible nebulosity (Herbig 1958; Dahari & Osterbrock 1984) reinforce this conclusion. The *IRAS* measurements along with the ground-based observations for these two stars are shown in Fig. 3. SU Tau can be fitted with a blackbody temperature 600 K until 60 μm,

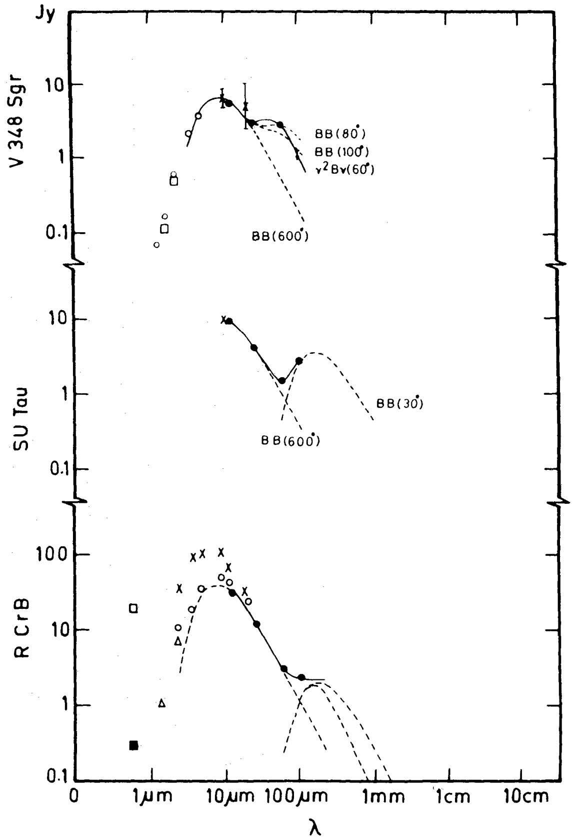

Figure 3. The measured IR flux densities are plotted as a function of wavelength for V 348 Sgr (top), SU Tau (middle) and R Cr B. The dots represents the *IRAS* observations. For V 348 Sgr, the crosses are the ground-based observations at 10.2 and 20 μm by Feast & Glass (1973), and the open circles are at other epochs. For SU Tau the cross represents the 10.2 μm flux measurement. The plot for R Cr B is the same as shown in Fig. 2 and for V 348 the line represents a combination of 600 K blackbody $+\nu^2 B\nu$ (60 K) energy distribution; the dashed lines show T_{BB} (600 K) +80 and 100 K blackbody distributions. For SU Tau the line represents a combination of a 600 K blackbody and a 30 K blackbody.

but at 100 μm shows a large excess particularly the increase of flux at 100 μm over 60 μm (this has further been confirmed from AO observations also – Walker 1986). Again V348 Sgr shows this dual nature: a hotter component a 600 K blackbody, with excess flux at 60 μm (beyond 25 μM), probably due to a cooler dust component. Radio observations at 2 and 6 cm (Rao, Venugopal & Patnaik 1985) show that this is not due to the free–free emission from the surrounding nebula. The nature of the dust distribution of V348 Sgr will be dealt with in a separate paper (Rao & Nandy 1986). S Aps and UW Cen could only be detected at 12 and 25 μm by *IRAS* and these observations agree with the ground-based observations of Kilkenny & Whittet (1984) and confirm that they follow a 750 K blackbody.

The energy distribution of R Cr B beyond 60 μm (Fig. 2) can be characterized by a blackbody of 30 K with a total flux in the infrared of about 3.3×10^{-4} L_*. If the dust emissivity is taken as $\propto\nu$ or ν^2 then the characteristic temperature T_d is 25 K ($L=2.6\times10^{-4}$ L_*) and 22 K respectively. In the case of V348 Sgr although the *IRAS* observations longward of 25 μm show better agreement with dust emissivity proportional to ν^2 (T_d of 60 K), it is still consistent with emissivity proportional to ν (with T_d of 70 K). But fits with 90 K to 100 K blackbodies cannot be ruled out. This behaviour is consistent with emission from dust which is optically thin at these wavelengths.

3.1 THE HOT DUST

The nature of the hot-dust emission of R Cr B has been discussed by various authors (Forrest 1974; Rao 1974; Hartmann & Apruzese 1976; Hecht *et al.* 1984) in the context of patchy cloud models, where optically thick dust clouds are formed around the star giving rise to infrared excess and the visual light minima are caused whenever such a cloud is formed in the line-of-sight. Hartmann & Apruzese (1976) could explain with roughly the same dust mass ($4.6\times10^{-7}m_\odot$) both the maximum (crosses in Fig. 2) and minimum (open circles) of IR emission with a model of both clumped as well as dispersed dust shells with density increasing outwards ($\varrho\propto\gamma$ or γ^2 material will be concentrated in a thin shell). In particular the minimum IR emission, which agrees with the present *IRAS* observations, could be matched by a dispersed dust-shell model of 571 R_* and density increasing as $\varrho\propto\gamma^2$. Since the present *IRAS* observations occur during a visual minimum, a clumped dust-shell model with similar temperature distribution to the dispersed model seems possible, with a dust-shell radius of 200 R_*. All these models are optically thick in the visual (~5) but thin in IR. In order to infer the composition, Hartmann & Apruzese also obtained the variation of opacity with wavelength which could satisfy the energy distribution both for IR maximum and minimum. This opacity behaviour was very similar to that of small spherical graphite particles as calculated by Gilman (1974). Recently Hecht *et al.* (1984) discussed the nature of the dust around R Cr B on the basis of UV spectra (a depression at λ2400), and favoured glassy or amorphous carbon particles of 30–60 nm size. However, the models discussed above cannot explain the excess beyond 60 μm as a natural extension: one has to invoke either a different grain size, chemical composition or distribution. Thus another cool-dust component is required.

3.2 COOL DUST

The mass and angular extent of the cool dust would depend on its composition, size and the emissivity at long wavelengths (100 μm). If this cool dust is assumed to be distributed in a thin shell in thermal equilibrium with the central star (which is likely, since the hot dust seemed to be distributed in patchy clouds – Forrest 1974) then the angular diameter θ_d of the shell is given by

$$\frac{\theta_\mathrm{d}}{\theta_*}=0.5\left(\frac{\varepsilon_\mathrm{vis}}{\varepsilon_\mathrm{IR}}\right)^{1/2}\left(\frac{T_*}{T_\mathrm{d}}\right)^2,$$

where (θ_*, T_*) are the angular diameter and effective temperature of the star and ε's are the emissivities. Because the R Cr B spectrum indicates a high carbon abundance and because of the smooth featureless IR continuum, it was suggested by several investigators that the dust is composed of small graphite grains. However, recently it was suggested by Hecht *et al.* (1984) that glassy or amorphous carbon grains are more likely to occur than graphite. The emissivity of small graphite particles in the long-wavelength range is supposed to be proportional to ν^2 or even steeper, whereas small amorphous carbon particles (200–500 Å) show emissivity proportional to ν (Koike, Hasegawa & Manabe 1980). As mentioned earlier this behaviour is quite consistent with *IRAS* energy distributions of R Cr B, SU Tau, and V348 Sgr. For R Cr B we take a distance of 1.38 kpc and $T_*=7000$ K (Cottrell & Lambert 1982). For the case of amorphous carbon grains the cool-dust emissivity $\varepsilon_\mathrm{vis}/\varepsilon_{100\mu\mathrm{m}}=Q_\mathrm{abs.\,vis}/Q_{\mathrm{abs.}\,100\mu\mathrm{m}}$ is $\sim10^2$ (Koike *et al.* 1980) and a T_d of 25 K leads to a radius of the cool-dust shell of 2.2×10^{18} cm. In the case of graphite grains $Q_\mathrm{abs.\,vis}/Q_{\mathrm{abs.}\,100\mu\mathrm{m}}=6.5\times10^2$ (Draine 1984) leads to a radius of 5.6×10^{18} cm. However, there seems to be another difficulty regarding the small graphite particles: because of the low opacity at the long wavelengths, too much dust mass seems to be needed to account for the IR emission. If the dust is optically thin, the dust mass M_d is given as $M_\mathrm{d}=F_\lambda D^2/K_\lambda B_\lambda(T_\mathrm{d})$ where F_λ is the excess flux at 100 μm (3.94×10^{-20} W cm^{-2} μm^{-1}) and K_λ is the opacity (~3.5 cm g^{-1} at 100 μm) leading to a dust mass of 0.01 $m_\odot$ (a total mass of ~1 $m_\odot$ with gas to dust ratio of 100) which seems to be too high; whereas for amorphous carbon, the other possible grain material, the opacity seems to be 750 cm^2 g^{-1} at 100 μm (fig. 1 of Koike *et al.* 1980) which leads to a dust mass of 4.8×10^{-5} $m_\odot$, a more reasonable value. According to Forrest, McCarthy & Houck (1980) a recent redetermination of far-IR optical constants of graphite would indicate $\varepsilon_\lambda \propto \nu^3$ beyond 20 μm with a bump around 95 μm; in addition the opacity per unit mass is much lower, as much more dust mass would be needed. It appears that small graphite grains are not good candidates for the far-IR emissivity in R Cr B. Small amorphous carbon grains are expected to show spectral features at 8 μm (Koike *et al.* 1980) and may be at 3.4 μm (Duley & Williams 1983), etc. and graphite grains are expected to show a sharp feature at 11.5 μm (Draine 1984) which have not been reported in the spectrum of R Cr B. However, better resolution observations are needed to investigate this aspect. The other likely candidates are large spherical or elongated grains of graphite which could cause higher emissivity in the far-IR but graphite formation in the circumstellar envelopes seems to be a less likely process (Czyzak, Hirth & Tabak 1982).

4 Discussion

The *IRAS* survey observations (Walker 1985, 1986) of several R Cr B stars which have enough flux density to be detectable seem to show excess flux at 60 and 100 μm indicative of cool dust, which might be a general feature of R Cr B stars, e.g. RY Sgr, WX CrA, etc. The survey observation of UW Cen also shows excess at 60 and 100 μm, however, no data from AO mode exist in these bands for UW Cen and S Aps. As pointed out by Walker (1985) confusion with background sources might be a problem. However, the presence of cool dust in R Cr B, etc. appears to be real. This dust does not seem to be a part of the hotter dust which apparently formed at the time of the irregular light minima. In this case we expect to see a continuous range of temperatures for the dust and a smooth and broader flux distribution, unlike the distinct increase influx beyond 60 μm in R Cr B, SU Tau. Thus this cool dust component must have formed in a different way. The *IRAS* observations of V348 Sgr, the hotter R Cr B star, show many similarities with planetary nebulae (Rao & Nandy 1985) and further, there seems to be a continuity in the properties between V 348 Sgr and R Cr B. Both are hydrogen-deficient irregular variables and V348 Sgr is of spectral type B1I and R Cr B is F8Ib. V 348 Sgr has an optical nebulosity and R Cr B shows λ3727 of [O II] emission whenever the star is visually fainter than ~13 mag (Herbig 1949, 1968), probably indicating the existence of a very low surface-brightness nebula. Apart from the hotter dust, both have cool dust which is characterized by $\leqslant$100 K in V 348 Sgr and ~30 K in R Cr B. The nebula has a radius of 3×10^{17} cm in V 348 Sgr (Rao & Nandy 1985) and in R Cr B the cool-dust shell has a radius of 2.2×10^{18} cm. This radius places R Cr B on the extension of the relation between the dust temperature and nebular radius for planetary nebulae (Pottasch *et al.* 1984 plot the relationship for nebulae only up to $T_d \simeq 40$ K) and might indicate that the remnant nebula is also roughly the same size. Thus R Cr B indicates a later stage in the evolution of the nebula and dust shell relative to V 348 Sgr. R Cr B being a cooler star shows that it is probably at the red giant stage for a second time and the cool-dust shell is a remnant of the first red giant phase. Recently Walker (1986) analysed the additional observations for the spatial extent of the dust shells around R Cr B, SU Tau and RY Sgr at 100 μm. Both R Cr B and SU Tau show the presence of dust shells whereas RY Sgr does not. The full width at half maximum of the spatial profiles for R Cr B and SU Tau are 5.20±0.08, 4.31±0.20 arcmin as compared to a point source (NGC 6543) of 3.03±0.04 arcmin.

It is important to detect both the nebulae and the cool dust around R Cr B stars for estimation of the time-scales. Further long-wavelength observations in the mm wave range are needed to establish the energy distribution of these stars for the study of the nature of the dust.

5 Conclusions

The *IRAS* observations of R Cr B, SU Tau and V 348 Sgr indicate the existence of a cool-dust component of temperature ≤100 K around these stars apart from the hot dust. This cool-dust shell is probably a remnant of the stage when these stars were red giants for the first time.

Acknowledgments

We thank Dr Helen Walker for preprints and for useful discussions and also Professor S. R. Pottasch for supplying the *IRAS* fluxes of SU Tau and V 348 Sgr. NKR thanks the Royal Astronomical Society, Edinburgh for the financial grant which enabled his visit to ROE during the preparation of this paper.

References

Ashok, N. M., Chandrasekhar, T. & Bhatt, H. C., 1984. *Inf. Bull. Var. Stars,* 2510.

Böhme, D., 1983. *Inf. Bull. Var. Stars,* 2442.

Cottrell, P. L. & Lambert, D. L., 1982. *Astrophys. J.*, **261,** 595.

Czyzak, S. J., Hirth, J. P. & Tabak, R. G., 1982. *Vistas Astr.*, **25,** 337.

Dahari, O. & Osterbrock, D. E., 1984. *Astrophys. J.*, **277,** 648.

Draine, B. T., 1984. *Astrophys. J.*, **277,** L71.

Duley, H. W. & Williams, D. A., 1983. *Mon. Not. R. astr. Soc.*, **205,** 67P.

Feast, M. W. & Glass, I. S., 1973. *Mon. Not. R. astr. Soc.*, **161,** 293.

Forrest, W. J., 1974. *Thesis*, University of California.

Forrest, W. J., Gillett, F. C. & Stein, W. A., 1971. *Astrophys. J.* **170,** L29.

Forrest, W. J., Gillett, F. C. & Stein, W. A., 1972. *Astrophys. J.*, **178,** L129.

Forrest, W. J., McCarthy, J. F. & Houck, J. R., 1980. *Astrophys. J.* **240,** L37.

Gilman, R. G., 1974. *Astrophys. J.*, **188,** 87.

Hartmann, L. & Apruzese, J. P., 1976. *Astrophys. J.*, **203,** 610.

Hecht, J. H., Holm, A. V., Donn. B. & Wu, C. C., 1984. *Astrophys. J.*, **280,** 228.

Herbig, G. H., 1949. *Astrophys. J.*, **110,** 143.

Herbig, G. H., 1958. *Astrophys. J.*, **127,** 312.

Herbig, G. H., 1968. *Mem. Soc. R. Sci. Liège*, **17,** 353.

Holm, A. V., Wu, C. C. & Doherty, H. R., 1982. *Publs astr. Soc. Pacif.*, **94,** 548.

Iben, I. Jr, 1984. *Astrophys. J.*, **277,** 333.

Iben, I. Jr, Kaler, J. B., Truran, J. W. & Renzini, A., 1983. *Astrophys. J.*, **264,** 605.

Kilkenny, D. & Whittet, D. C. B., 1984. *Mon. Not. R. astr. Soc.*, **208,** 25.

Koike, C., Hasegawa, H. & Manabe, A., 1980. *Astrophys. Space Sci.*, **67,** 495.

Loreta, E., 1934. *Astr. Nach.,* **254,** 151.

Miley, G., 1983. *A Guide to Interpret IRAS Additional Observations.*

Neugebauer, G. *et al.*, 1984. *Astrophys. J.*,**278,** L1.

O'Keefe, J. A., 1939. *Astrophys. J.*, **90,** 294.

Pottasch, S. R., Baud, B., Beintema, D., Emerson, J., Habing, H. J., Harris, S., Houck, J., Jennings, R. & Marsden, P., 1984. *Astr. Astrophys.*, **138,** 10.

Rao, N. K., 1974. *Thesis*, University of California.

Rao, N. K. & Nandy, K., 1986. *Workshop on V 348 Sgr*, held at Liège, April 1985, in press.

Rao, N. K., Venugopal, V. R. & Patnaik, A. 1985 *J. Astrophys. Astr.*, **6,** 150.

Stein, W. A., Gaustad, J. E., Gillett, F. C. & Knacke, R. F., 1969. *Astrophys. J.*, **155,** L3.

Walker, H. J., 1985. *Astr. Astrophys.*, **152,** 58.

Walker, H. J., 1986. *IAU Coll. 87, Hydrogen Deficient Stars and Related Objects,* Reidel, Dordrecht, Holland, in press.