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ISOPHOT observations of R CrB: a star caught smoking*

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Abstract. R CrB is a very unusual star, being extremely hydrogen deficient and undergoing irregular deep minima in its visible light. R CrB started to undergo a fading episode in October 1995. The Infrared Space Observatory (ISO) observed the star after it had faded by 7 magnitudes. The inner, warm dust shell has been observed by ISOPHOT, using the long wavelength camera mode (from 60μm to 200μm). The dust shell was observed using the low resolution spectrometer (from 2.5μm to 5μm and 5.8μm to 11.6μm). The energy distribution peaks around 6 – 8 μm, indicative of a 650K dust shell with an unusual shape to the observed spectrum. The long wavelength photometry, when compared to IRAS data, shows the temperature of the warm dust shell is unaffected by the ejection of a new cloud of carbon from the central star. The dust cloud is probably composed of pure carbon, but other materials cannot be excluded. There is no evidence of hydrogenated carbon molecules.

Key words: Circumstellar matter – Stars:individual – Stars:variable – Stars:AGB and post-AGB – Infrared:stars

1. Introduction

R Coronae Borealis (R CrB) is a very unusual star, and the class standard for a group of about 40 stars (Clayton, 1996). Their major identifying characteristics are that they are extremely hydrogen deficient, very carbon-rich, and they suffer irregular periods of minimum light when the star has faded by several magnitudes in visible light (typically 7 magnitudes for R CrB; Mayall, 1960). The first recorded fading of R CrB occurred 200 years ago (Pigott, 1797). The stars are evolved late-type (F or G) supergiants. All the R CrB stars (Clayton, 1996) have proved to be semi-regular variables (in addition to the fadings), periods have been determined for very few members. R CrB has also proved to be remarkable in the infrared, with the discovery using the Infrared Astronomical Satellite (IRAS, 1987) of the very large, cold, 'fossil' dust shell (Gillett et al., 1986; Rao and Nandy, 1986; Walker, 1985). Walker (1994) re-examined IRAS survey data and showed that at least four R CrB stars have 'fossil' shells. All the group members have an inner warm dust shell, with a temperature of several hundred degrees Kelvin. Clayton (1996) comments that searches have produced no obvious correlation between infrared brightness (from this warm dust shell) and the declines in visual brightness.

The cause of the fading is the expulsion of a cloud of carbon from the star which obscures the starlight, causing the visual magnitude to decline, at first, over a period of a few days (Feast 1986), then the cloud gradually dissipates over a period of months and the visual magnitude slowly returns to its maximum value. The exact mechanism of the expulsion of the cloud of carbon is unknown. Dick and Walker (1991) examined the fadings and found that for four R CrB stars (including R CrB itself), the data suggested that the fadings were random. Since the condensation temperature of carbon is around 1500K, it was proposed that the dust cloud (a 'puff' of carbon) formed at around 20$R_\star$ in the line of sight and was then moved away under radiation pressure obscuring the star for a while (see Clayton (1996) for more information). Payne-Gaposchkin (1963) proposed a different model, in which the puff is formed much closer to the star (2$R_\star$), in the upper atmosphere of the star, and very rapidly blown out of the atmosphere, obscuring the star only when ejection is in the line of sight.

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2. Observations

Mattei (1995) reported that R CrB had started to fade in October 1995, and Efimov and Rosenbush (1996) reported a deep minimum at the end of January 1996, when the visual magnitude was now 13.50 (V at maximum light is usually around 6). ISO observed R CrB on 10 February 1996. Full descriptions of ISO (Kessler et al, 1996) and ISOPHOT (Lemke et al, 1996) are given elsewhere. Photometry was performed using PHT-C in staring mode. Multi-aperture photometry, using PHT-P, at 60μm was also performed. PHT-S, the low resolution spectrometer, was used to take a spectrum covering both 2.5μm to 5μm and 5.8μm to 11.6μm (resolving power between 60 and 130 for both channels). The data were reduced from the ERD level using the ISOPHOT Interactive Analysis Package, PIA version 4.9.2. Corrections were made for the nonlinearity of the integration ramps, the removal of glitches (from high energy particle hits on the detectors) both within the integration ramps and in the ramp slopes. The dark current was subtracted, and data affected by detector drifts were removed. The glitches in the ramp slopes were rejected at the 2σ level in the PHT-C and PHT-P observations, and they were calibrated using the fine calibration source (FCS1).

3. Results

Figure 1 shows the multi-aperture photometry for R CrB (as filled circles). If the dust shell around the star is unresolved, the flux density (in Jy) will remain constant with increasing aperture, if it is resolved the flux density will increase with increasing aperture as more of the dust shell is included. The diffraction limited aperture at 60μm is 52$''$. Figure 1 gives (as open circles) multi-aperture photometry of NGC 6543, a planetary nebula unresolved at 60μm, to show the results of the technique on a point source. The fluxes of NGC 6543 have been scaled to allow them to be plotted on the same figure as R CrB.

A separate measurement of the background at 60μm, near to R CrB, was taken to subtract from the multi-aperture data. The error in measuring the flux densities is shown in Fig. 1, calculated using the first and third quartiles of the data for source and background (which are then combined to give the error shown). The uncertainty in the preliminary flux calibration is around 30%. The data, when compared to NGC 6543, suggest the inner dust shell may be resolved, but that the data need further investigation. The measurement error in the background and the measurement error on-source are about the same. The Airy disc at 60μm is 50$''$ and the size of the dust disc could be much larger than this (possibly as large as 90$''$, including the instrumental profile), although still very much smaller than the 14$'$ – 20$'$ fossil dust shell.

Figure 2 shows the ISOPHOT multi-filter (filled circles) and spectroscopic data (thick line). The measurement errors (see table 1) are plotted for the ISO data, but they are generally less than the size of the symbol used. These are compared to the visible magnitude at maximum (open triangle), and at minimum (filled triangles) from Efimov and Rosenbush (1996). IRAS data (Walker, 1986) are also shown (as open circles). Also plotted are two blackbody energy distributions, both at 650K, scaled to match flux densities at the IRAS 60μm point and the ISO 60μm point.

Fig. 1. Multi-aperture photometry of R CrB at 60μm. R CrB is shown by filled circles, NGC 6543 (a point source at 60μm) by open circles. The error bars represent the measurement error

Table 1. ISOPHOT photometry of R CrB

Wavelength (μm)	Flux density (Jy)	Error in measurement
60.8	5.98	± 0.15
80.1	3.46	± 0.13
103.5	1.62	± 0.12
119.0	2.38	± 0.19
161.0	1.75	± 0.15
204.8	1.48	± 0.16

The table lists the median values derived for the photometric data, with the measurement error (derived from the estimates of first and third quartiles). Due to the glitches in the data, the mean values were judged inappropriate. The main sources of uncertainty in the results arise from the still preliminary calibration (estimated to be a 30% uncertainty) and from the astronomical background removal.

There is a discontinuity between the measurement at 103.5μm (with the C-100 detector) and at 119.0μm (with the C-200 detector). This could be due to the difference in size of detector and the influence of background emission,

Fig. 2. The energy distribution of R CrB from 0.36μm to 240μm. Filled triangles represent optical data from Efimov and Rosenbush (1996); the open triangle represents the normal V magnitude of R CrB; filled circles are PHT-C data; open circles are IRAS data from Walker (1986); the thick line shows the PHT-S data; the two curves represent 650K blackbody curves scaled to the ISO 60μm point and the IRAS 60μm point

and/or calibration differences. The C-100 measurements are taken from the value derived for the pixel in the middle of the array (since R CrB was well centred), for C-200, the mean of the four median values was used. The slope of the photometry from C-100 agrees well with the IRAS data, and the 60μm/80μm ratio gives a similar dust temperature of around 650K. The energy distribution for the 650K blackbody peaks around 8μm, which is consistent with the PHT-S data. This shows that these data relate solely to the dust shell around R CrB, and no significant emission from the star is observed. The C-200 data have a much shallower slope, suggesting a much cooler temperature (perhaps as low as 30K, the temperature of the fossil shell), which suggests the fossil shell is dominating the emission measured by the C-200 array. The IRAS data were taken when R CrB was undergoing a fading episode, but this decline did not affect the IRAS data significantly, since data were taken at different times during the mission.

The PHT-S spectrum (shown by the thick line in Fig. 2) is calibrated using the most recent standard calibration files for dark current and instrumental response function. A short dark measurement is made immediately before the spectrum is taken, to check that no memory effects, from previous observations, impact the measured spectral shape. None were seen for R CrB. The "emission feature" around 2.8μm is due to instrumental effects, and is seen in a wide variety of PHT-S spectra. However, the shape of the R CrB feature is broader than for other objects, so there may be additionally some intrinsic emission.

4. Discussion

Walker (1985) used a 650K blackbody to fit the IRAS data, which appears appropriate for some of the ISOPHOT data here. This suggests that the dust reaches an equilibrium temperature very quickly after expulsion from the immediate vicinity of the star, presumably at a higher temperature. However, a dust shell in thermal equilibrium at 650K would be too close to the star to be resolved by ISOPHOT. The flux density at 60μm is different by a factor of 2 between the IRAS value and the

ISOPHOT value, yet the 100μm values are very similar. It is too early in the ISO mission to be certain whether the difference in the scaling of the model is significant, as the calibration is still preliminary. The astronomical background needs investigation (particularly the effect of the fossil shell emission), this will be done later in the ISO mission.

Walker (1986) also showed an IRAS (IRAS, 1986) Low Resolution Spectrum (LRS) of the R CrB, and commented that the spectrum showed the smooth decline to be expected of carbon dust. There was no evidence of silicate dust emission or of emission from silicon carbide dust. The PHT-S longer wavelength spectrum (from 5.8μm to 11.6μm) confirms this and the smooth decline, but only in the LRS range, i.e. longward of 8μm. There is no evidence of the 11.3μm PAH feature (Polycylic Aromatic Hydrocarbons) or the C_{60} feature at 8.6μm (Clayton et al, 1995). Buss et al (1993) found a weak feature in their spectrum of R CrB around 6.3μm, redder than the usual C–C stretch feature from PAHs (around 6.2μm). Duley (1993) noted that graphite has a first-order Raman spectrum peak near 6.3μm. There is no evidence of any feature in the PHT-S spectrum which could be attributed to hydrogenated carbon molecules. Buss et al (1993) subtracted a 700K blackbody from their data and noted a broad plateau between 7 and 9 μm. This may be present in the PHT-S data. The Swan and Phillips bands, due to molecular carbon, are known to affect the energy distribution of R CrB in the visible red, and the blue edge of the PHT-S spectrum has probably been influenced by the edge of next (redder) set of C_2 bands, the Ballik-Ramsay bands.

The distance of R CrB is very uncertain, since it is at high galactic latitude, with values given between 1 and 2 kpc. (Schönberner, 1975) derives a luminosity for R CrB of $10^4 L_\odot$. If the luminosity of the inner dust shell were comparable, this would lead to a radius for the 650K blackbody of 5.5×10^{14} cm, whereas a size of 75$''$, resolvable by ISOPHOT at 60μm, would require a shell nearer 10^{18} cm at 1 – 2 kpc. The peak of the energy distribution is sharper than would be expected from a blackbody distribution. A single temperature blackbody may not be an appropriate assumption. It is also unlikely that R CrB has a smooth dust shell, since it arises from random puffs of carbon, so geometric effects should be included in the model. The broader wavelength coverage from ISOPHOT implies a more sophisticated model than a single temperature blackbody is now required.

5. Summary

The ISOPHOT observations show that at long infrared wavelengths, the temperature of the warm dust shell is unaffected by the creation of a new puff of carbon ejected from R CrB. The spectrum shows no evidence of hydrogenated carbon molecules, so C_2 and graphite remain the likely components of the dust, but other materials cannot be excluded.

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