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Probing circumstellar dust formation through high resolution spectroscopy

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Abstract. The existence of cool regions where dust can condense is explored in RCB stars at minimum.

Keywords : RCB stars; dust condensation; C_2 molecule

1. Introduction

The ubiquitous presence of dust is seen almost everywhere ranging from high redshift quasars to brown dwarfs. Although dust is thought to be formed in the circumstellar environment of Asymptotic Giant Branch stars, R Cor Bor stars, WR stars, novae, supernovae etc., the physical process of gas condensing into grains in such environments (some times very harsh) is still not well understood. The best way to study dust formation would be to compare (observe) the behaviour of the same star during the process of dust formation and out of it (i.e normal state). In principle, the change of physical parameters of the star and its environment in between the two states should give clues to the process of grain condensation. The RCB stars do offer such a possibility. These are carbon rich, helium rich, hydrogen poor F-G supergiants which suddenly undergo large light drops ranging from 2 to 8 magnitudes at irregular intervals of time and are very unpredictable. At maximum light they do show small amplitude quasiperiodic variations in light (and radial velocity) in the period range of 30 to 100 days. Only one star, RY Sgr, shows a more regular variation of 38.5 day period. RCBs are the first objects in which dust production and subsequent dispersal has been invoked to explain the behaviour of the light curve (Loreta 1934, O'Keefe 1939). The discovery of infrared excesses in these stars confirmed the presence of dust at a characteristic black body temperature of 600 to 900 K (Stein et al., 1969, Feast et al., 1997). Typically, about a third of the stellar flux

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comes out as excess in the infrared. It soon became clear that dust is not distributed in a spherically asymmetric shell but in the form of clouds (Forrest et al., 1972). It has even been suggested from polarization studies that the clouds of dust are distributed in a preferred plane (Clayton et al., 1997, Rao and Raveendran 1993). The recent 2.2 and 4.05 μ images of RY Sgr with high angular resolution do show clearly that dust is distributed as clouds (de Laverny and Mekarnia 2004) that are located about 700 to 1400 R_*. Several basic questions that arise in this regard are : 1) What is the nature (composition) of the dust grains? 2) Where does the dust form in the environment of such hot stars? 3) What triggers dust formation in a star that remains normal for a long time and suddenly gets into a frenzy of dust making?

Although it was realised quite early that the dust contains carbon atoms, what sort of carbon grains exist was not clear. The search for spectroscopic signatures of the minerals was not very successful in the early ground based infrared spectra which were smooth and featureless and led to the suggestion of graphite grains (Forrest 1974). The UV extinction curves obtained during some shallow minima of R CrB and RY Sgr suggested amorphous or glassy carbon (Hecht 1991; Holm et al., 1967). Only after our Infrared Space Observatory (ISO) spectra in the 3 to 25 μ region of R Cr B, RY Sgr and V854 Cen became available, emission features that could be attributed to amorphous carbon in the case of R CrB and RY Sgr and hydrogenated amorphous carbon grains (at or $>$ 800 K) in the case of V854 Cen were detected (Lambert et al., 2001).

2. Dust condensation

The question as to where does the dust condensation occur remains a mystery. Whether it occurs in or close to the stellar atmosphere or in the far reaches of the dust clouds located at a few hundred stellar radii (aided by stellar wind) is not clear. Woitke et al., (1997) proposed pulsation related, shock-induced dust formation in the atmospheres of these stars. On occasion when the pulsation amplitude exceeds a critical value (30 to 50 km s^{-1}) an atmospheric shock is generated. Dust condensation is expected to occur behind the shock front where the recombined gas could reach temperatures as low as 1000 - 1500 K ($<$ 2000 K) and particle densities of 10^9 to 10^{10} cm^{-3}. These are the issues which we aimed to study by obtaining high resolution spectroscopic observations during the light minima of RCB stars. In particular we wanted to probe the evidence and the kinematics of the cool gas from which the grain condensation is to occur.

Goeres (1996), Woitke et al., (1997) and Cherchneff et al., (2000) modeled the chemistry that is expected from hydrogen-deficient, carbon rich (helium rich) gas appropriate for the composition of RCBs during the grain condensation phase. Nucleation could occur in the temperature range of 1000 to 1500 K and particle density greater than of 10^8 to 10^9 cm^{-3}. Although the monoatomic carbon gas builds up to grains containing more than 60 to 100 carbon atoms during this process, the dominant species that forms the main link is the C_2 molecule.

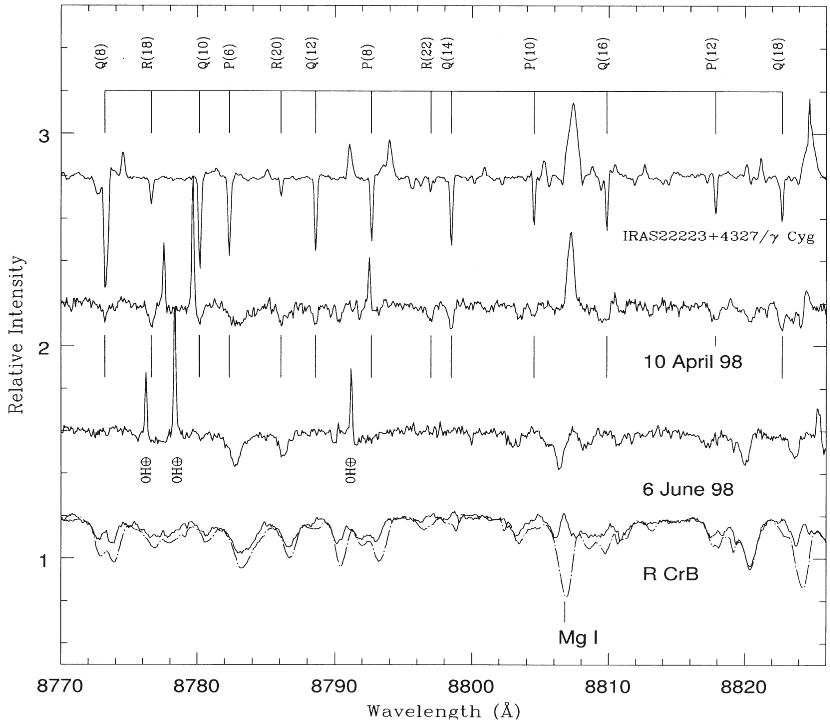

Figure 1. Spectra from 8770-8826Åof V854Cen and IRAS 2223+4327. Locations of C_2 Phillips 2-0 lines are indicated at the top of the figure and below the 1998 April 10 spectrum of V854 Cen.

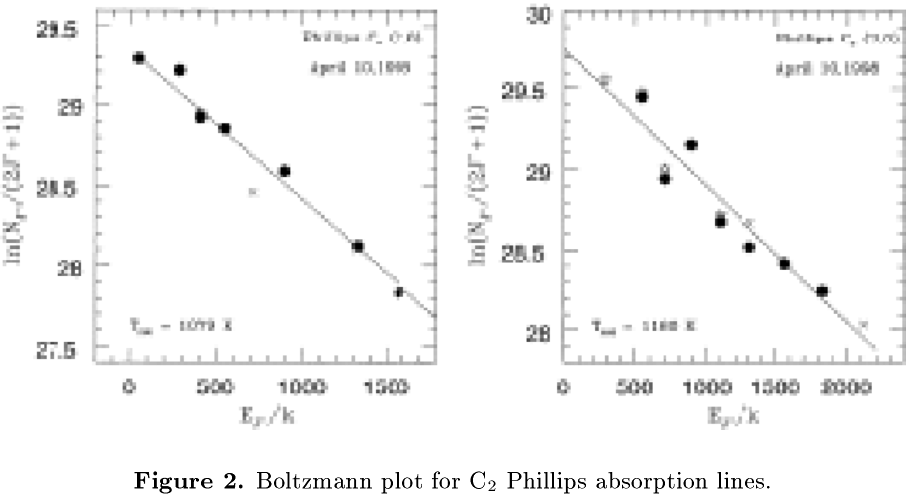

Figure 2. Boltzmann plot for C_2 Phillips absorption lines.

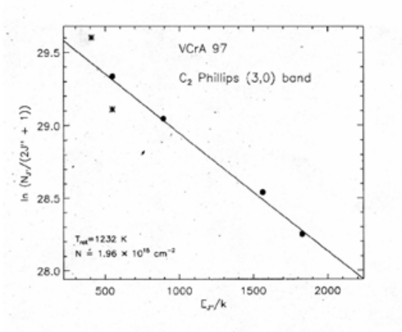

Figure 3. Boltzmann plot for C_2 Phillips lines for V CrA.

The ground electronic state of C_2 molecule is $X^1\Sigma_g^+$. Phillips system connects the ground state to the next higher singlet state $A^1\Pi_u$. The rotational lines of Phillips system of C_2 are the ones that are expected to occur in the cold gas in the optical region as such became targets of an observational search.

3. Observations

High resolution spectroscopic observations have been mostly conducted with Coude Echelle spectrometer of 2.7 meter McDonald Observatory (Tull et al., 1995). The spectral resolution achieved is about 60000 for most spectra and covers the spectral region 3700Å to 10000Å with gaps.

So far we could obtain observations of three stars, V854 Cen, V CrA and finally R CrB during three minima (mainly light recovery phase). In contrast we could observe the Phillips system lines in U Aqr, a cooler RCB star, at normal light maximum (that suggest a rotational temperature of 2230 K for the C_2 gas). V854 Cen was observed in 1998 minimum, V CrA in 1997 minimum and R CrB during the 2003 minimum.

4. C_2 Phillips system lines at minimum light

The observations of V854 Cen covered the Phillips (2-0) and (3-0) bands. Weak absorption lines due to several rotational transitions of these two system were present on the early decline of the light minimum but disappeared at a later time (after two months) on the recovery branch of the light curve (Rao and Lambert 2000) (see Figure 1.). The rotational temperatures obtained from the analysis of the equivalent widths of these lines are 1079 K and 1180 K for 2-0, and 3-0 systems respectively (Figure 2). The radial velocity of these lines is close to the systemic velocity but has mild expansion of about 5 km s^{-1} . For the first time we could see the presence of cool gas with temperatures close to the expected

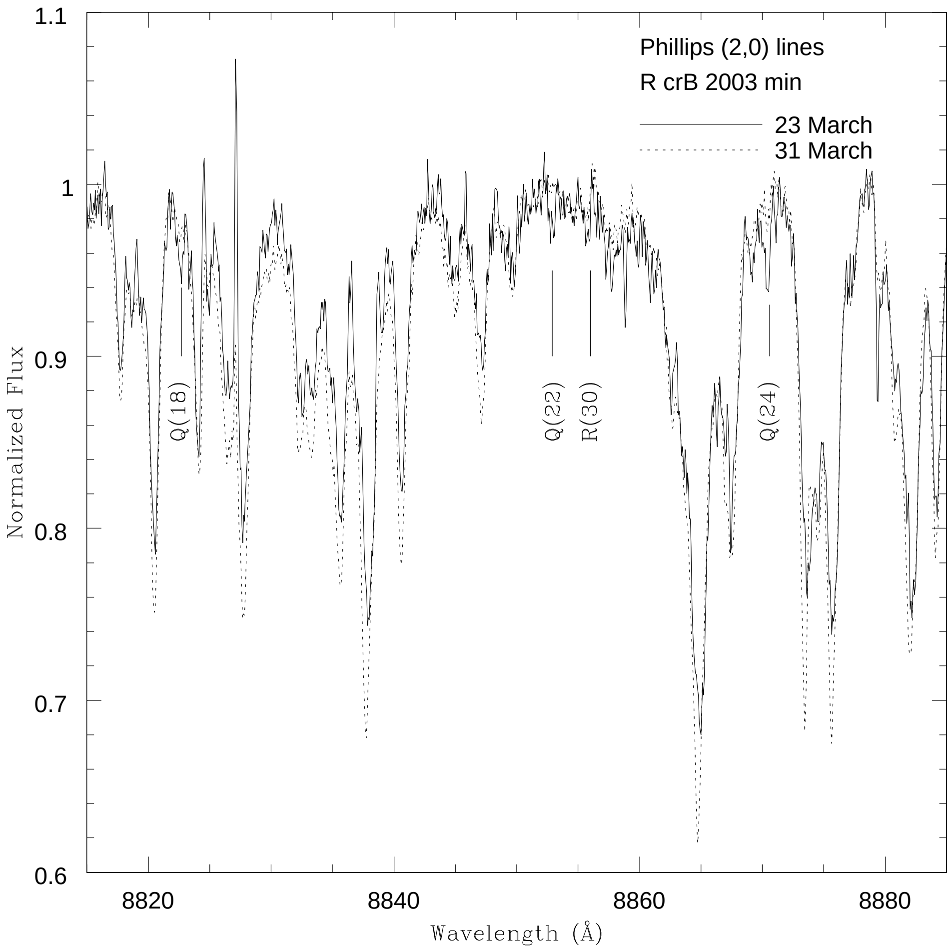

Figure 4. Spectrum of R CrB in Phillips band region.

condensation temperatures and probably located not too far from the photosphere (outer atmosphere). The interesting thing is these lines are transient suggesting that after the dust condensation episode is over the cool gas does not exist.

The question is how general is this phenomenon? Does this occur in every RCB star at every minimum? We could observe similar Phillips (3-0) band rotational lines in V CrA during the recovery phase in 1997 suggesting a gas temperature of 1230 ± 30 K. The same lines were not present at maximum light (Figure 3). And again the gas has a radial velocity close to the systemic velocity but has a mild expansion of about 5 km s^{-1}

(Rao and Lambert 2005). However, the coverage of 1995-96 of deep light minimum of R CrB (Rao et al., 1999) did not show the presence of Phillips band lines. The spectroscopic coverage on the recovery light was very sparse but adequate during decline - still we could not detect them even in the decline phase. Either the column density was not adequate or the gas was not directly in the line of sight. There could be several reasons. We got lucky in 2003. The recovery spectra of the 2003 minimum of R CrB (V $\sim$ 10.3) do show the presence of the Phillips (2 - 0) band lines in absorption (Figure 4) with a rotational temperature of 1377 K. Again this gas has a mild expansion velocity of 13 km s^{-1} relative to the stellar velocity (Rao, Lambert and Shetrone 2005). The same lines were absent in the spectrum obtained about 8 days later emphasizing the transient nature of these feature as seen in the other two stars. Either the column density of the cool gas became too small for detection or it is no more in the line of sight.

The above observations present convincing evidence for the existence of physical environment for dust condensation to occur in the atmospheres of these relatively hot stars. High resolution spectroscopy does reveal many more aspects regarding the outer atmospheres and dust dispersal around these stars. In this brief account we tried to illustrate one of the crucial aspect of dust condensation. Further studies are in progress regarding the trigger of dust formation. Is pulsation the main cause? There are stars like V854 Cen which do not show the presence of significant stellar pulsations. There might be more than one cause for the initiation of dust nucleation, an area to be explored.

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