THE RCB STARS AND THEIR CIRCUMSTELLAR MATERIAL

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SUMMARY. RCB stars are surrounded by circumstellar dust and gas moving radially outwards at ~200 km/sec. The circumstellar shell is made up of discrete puffs of matter, a typical puff occupying an area ~0.03 of a complete shell. On the average puffs are ejected about once every 40 days (comparable with the known pulsation periods of RCB stars). The reddening law of the dust indicates that it is composed of small carbon particles (radii ~100A). The flux from the shell at L typically varies by 1 to 3 mags over periods of 1000-2000 days. The average mass loss rate is $\sim 10^{-6} M_{\odot}/yr$.

1. INTRODUCTION AND MODEL

The RCB stars are a particularly spectacular subgroup of the hydrogen deficient stars. They are all carbon rich objects and their most striking property - the deep minimum that they undergo at random times - has been attributed for over 50 years to obscuration by soot. Despite this long time there remains very considerable uncertainty as to the place of these stars in stellar evolution and in the physical processes - including particle formation - taking place in their extended atmospheres.

The only viable model that has been proposed for the deep minima of RCB stars involves the ejection by the star of puffs of soot in random directions. Occasionally one puff is ejected in the line of sight causing obscuration. The main pieces of evidence that force one to such a model are as follows (cf. Feast 1975 and (especially) 1979 and references there).

(1) During a "typical" decline the normal absorption spectrum of the star is replaced by a "chromospheric" emission spectrum which changes with time in a manner analogous to the changes in the solar chromosphere with height above the limb (as at an eclipse). The spectroscopic changes (e.g. Alexander et al. 1972) are difficult to explain unless we are witnessing a real eclipse, first of the main body of the star and then of more and more of the chromosphere.

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(2) On the rapid decline, one sees absorption components of the D lines and of H and K displaced by about -200 km/sec. Evidently matter is moving rapidly away from the star. It is reasonable to suppose (e.g. Hartmann and Apruzese 1976) that soot, formed above the stellar surface, is being blown away from the star by radiation pressure and is dragging gas with it. It is this expanding puff of soot which, if in our line of sight, causes the eclipse phenomena.

The forms of the light curves of RCB stars are quite diverse from one deep minimum to another. However they frequently consist of a very rapid initial drop (time scale $\sim$<5 days for RY Sgr in 1967), a slower fall (time scale $\sim$20 days) and then a very gradual return to maximum. The total drop in visual light is often $\sim$8 magnitudes and the time to recover from minimum perhaps 500-1000 days. The deep minimum of RY Sgr in 1967-1969 which remains the event with the most extensive spectroscopic and photometric coverage, was of this type and for definiteness I shall take it as "typical". The initial drop seems to coincide with the fading of the continuum and may be identified as the time taken for the cloud to expand to cover the main body of the star. Coupled with the measured ejection velocity of $\sim$200 km/sec we find that we can make a crude model in which matter is ejected radially from a limited area near the stellar surface. In our "typical" case the semi-angle of the cone of matter so formed (measured at the centre of the star) is about 20°. That is, the cloud occupies about 1/30 the area of a complete shell. The slower decline follows as the extensive chromosphere is covered.

(3) When RCB stars are very faint their spectra are found to contain broad emission lines - the D lines, H and K and 3888 HeI. Structure in these lines has been reported by a number of workers (Alexander et al. 1972, Feast 1979, Herbig unpublished, Spite & Spite 1979). The half width of these lines is roughly constant from star to star and minimum to minimum and is about the same as the expansion velocity of the cloud in the line of sight - though with the structure in the lines, these statements are difficult to quantify. The simplest interpretation of these broad lines is that, with the star obscured, we are seeing the integrated emission from gas being carried away from the star by puffs of dust moving in all directions (radially outwards from the star). A detailed study of the structure of these lines and its variation with time would obviously be very valuable since it would give us information on the structure of the expanding material. Two points are clear from the limited data we already have. Firstly, the broad lines are roughly centred on the stellar velocity. Thus there must be a roughly symmetrical group of puffs around an RCB at any one time - or at least at any one minimum. The puff causing the eclipse is simply one of a group - not of course all necessarily ejected simultaneously. Secondly the presence of structure in the lines and the variation from time to time of the central wavelengths - indicating varying structure - shows that the number of puffs at any one time is relatively small. One might hope in future studies to be able to estimate the number of discrete puffs emitting at a given time. This is of obvious importance for estimating the total mass loss rate. The relative intensities of the various components in a line might also help in estimating the range in the masses of individual puffs.

Studies of 10830 HeI are also of importance in this connection. On the rise of RCrB itself back to normal in January 1978, Querci & Querci (1978) found the line to have a P Cygni profile. Presumably this was the combined effect of emission from the various puffs and absorption from the one in the line of sight (the absorption component had a velocity of -240 km/sec). Similar P Cygni profiles in the D lines and H and K were found earlier at a minimum of RY Sgr (Alexander et al. 1972). Some months after the Querci work, in July 1978 when RCrB had already been back at maximum several months, Zirin (1982) found no normal 10830A (which one would have expected to be strong since HeI 5876 is seen in absorption). However he reported a "huge absorption" at 10822A. It seems reasonable to interpret this as 10830A displaced by -220 km/sec. Presumably the P Cygni profile is now such as to just fill the photospheric 10830A line. The observation is of importance since it shows we can detect and study the still expanding soot and gas puff well after it has become too thin to appreciably dim the star. At low resolution (Alexander et al. 1972) the shell absorption in the D lines disappeared just prior to maximum light but perhaps these lines too could be followed after maximum at high resolution.

(4) On the rise from minimum (at least in the "typical" case of RY Sgr) the normal stellar spectrum is seen (as at maximum) but the star is faint and reddened. We are seeing the gradual dispersal of the soot cloud and the colour can be used to derive the law of reddening of the shell (Alexander et al. 1972, Feast 1979).

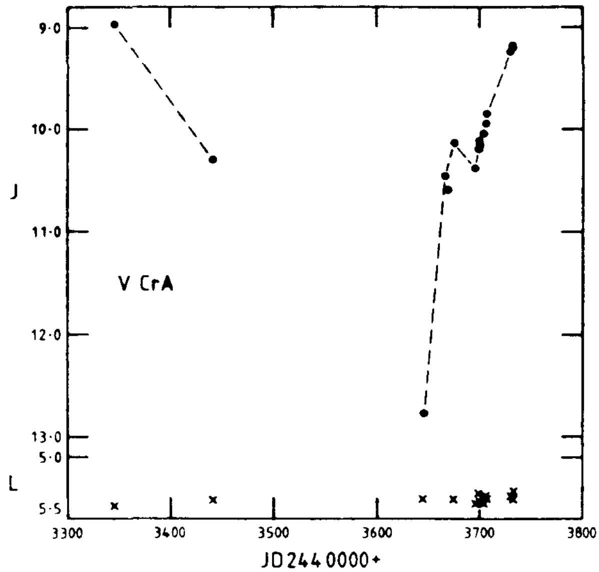

Fig. 1. A minimum of V CrA. The J flux (due to the star) drops by a large amount during minimum whereas the L flux (from the cool circumstellar matter) remains unchanged.

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(5) Infrared excesses are a characteristic of RCB stars (e.g. Feast & Glass 1973, Glass 1978 etc). The exception is XX Cam (Rao et al. 1980), a star for which only a single, relatively shallow (1.7 mag) minimum is known in 80 years; so that its membership of the class is tenuous. The observed excesses correspond roughly to blackbody emission at 700-900K (Feast & Glass 1973, Glass 1978, Kilkenny & Whittet 1984, Walker 1985). It is natural to associate this excess with reradiation from the puffs of soot. The earlier result of Forrest et al. 1972, Glass 1978, Feast 1979 that the excess does not vary significantly (either up or down) when the star goes into deep minimum is fully substantiated by more recent work. One can see this by looking at light curves in J and in L. Rough calculations indicate that the flux at J is almost entirely due to the star whilst the flux at L is from the circumstellar material. Figure 1 shows for instance a minimum in J for VCrA with L remaining constant. The minima in J are of course also seen in V. Similar results apply to several other RCB stars (SAAO observations, to be published).

The results show that the size of the cloud ejected at a minimum cannot be too great otherwise the reradiated flux would increase significantly. Evidently there are enough puffs reradiating at any one time (about 10 or more would be sufficient) so that one new one does not significantly add to the flux.

In all this I am implicitely adopting a model in which the soot is directly heated by the star itself. Evidence that this is indeed so was given some years ago for RY Sgr (Feast et al. 1977). RY Sgr pulsates with a period of 38 days and the variations of the stars luminosity in this period should lead to the flux from circumstellar material showing similar periodicity. The earlier work showed that the flux at L was indeed primarily from the circumstellar dust and that this varied in the 38 day period. Further evidence for this is shown in Figure 2 where it is clear that the flux from the shell (at L) varies in the pulsation period of the star (as seen at J).

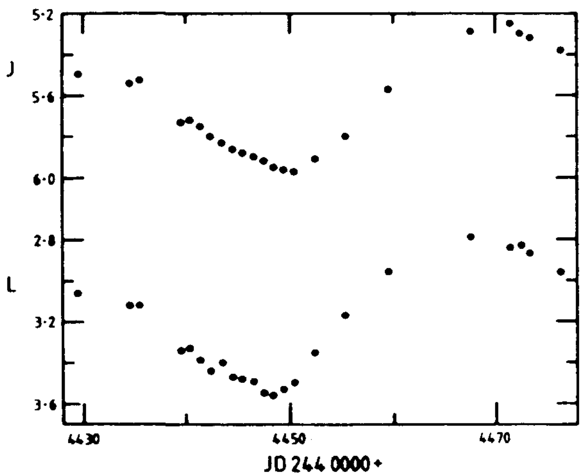

Fig. 2. Observations of RY Sgr showing that both the flux from the star itself (at J) as well as that from the shell (at L) vary in the 38 day pulsation cycle.

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2. THE RCB STARS AS A GROUP

Before discussing the dust shell further it is useful to stress the similarity in the physical characteristics and behaviour of the various RCB stars - at least if one omits the three unusual hot objects MV Sgr, DY Cen and V348 Sgr. This is seen for instance in looking at an infrared two colour diagram. Figure 3 is the composite $(J-H)_O/(H-K)_O$ diagram for 12 RCB stars. All the stars (especially if we omit the crosses) tend to lie along a quite narrow path. This locus is that expected for the combination of a star with emission from a dust shell. Individual stars move along this path as they undergo obscuration phases or when the shell changes luminosity. We have observed several of the stars to track practically the whole length of this path.

These results suggest that the RCB stars have quite a limited range of colour temperatures for both the central stars and for the shells. The open symbols show the position of the non-RCB HdC stars (Catchpole & Feast, unpublished). These are apparently typical of what RCB stars would be if the circumstellar shells were removed.

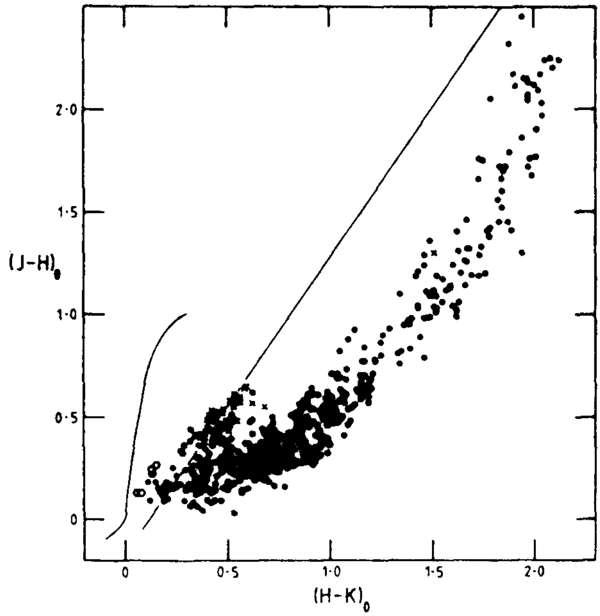

Fig. 3. $(J-H)_O/(H-K)_O$ diagram for 12 RCB stars. Crosses refer to S Aps, open circles to HdC stars. The (straight) blackbody line is shown. The curve is the locus of normal stars.

The position of the HdC stars themselves is of some interest. The deviation of normal stars from the blackbody line in this plot was shown by Catchpole & Glass (1974) to be due to the effects of various sources of continuous opacity - the main one being H^-. Obviously H^- opacity is not expected to be significant in HdC stars so that a position nearer the blackbody line might be anticipated for these stars. It would be useful to have models of HdC stars extending into the infrared with which one could compare the observations. Until we have models we cannot use this sort of diagram to estimate temperatures.

Schonberner (1975) has derived T_{eff} ~7000K for RY Sgr and RCrB. There is a range of C_2 band strengths in RCB stars. S Aps - which is the star shown as crosses in Figure 3 has very strong bands. It is quite likely that this range in bandstrength indicates a range of temperatures amongst these stars - down to say 5000K. However it should be stressed that the existence of such a range of temperatures is by no means certain. Stronger C_2 bands could perhaps indicate higher carbon abundance or the bands might arise in a cool outer shell. The position of S Aps in the $(J-H)_o/(H-K)_o$ diagram could be a temperature effect but could also be due to relatively mild circumstellar extinction. The visual observations of Espin (1890, 1894, 1900) at the end of the last century are perhaps relevant to this problem (cf. Ludendorf 1908, Berman 1935). He found that for a period of a week or so RCrB itself developed strong C_2 bands when the star was at maximum and well away from obscuration minimum. RS Tel has sometimes been mentioned as a very cool (R8) RCB star (Payne-Gaposchkin 1936, 1963). However Bidelman (1953) found C_2 weak and the UBVRI data (Kilkenny & Whittet 1984) do not make the star unusually cool, furthermore the type was given as Ro by Payne (1928). The early spectroscopic observations should be checked to see whether there has really been a large change in C_2 strength.

The range of temperatures covered by the RCB stars is thus uncertain. It is of importance if we want to compare with evolutionary predictions. Furthermore the temperatures are important for the problem of the pulsation of the stars. Saio & Wheeler (1985) were unable to keep the amplitudes finite for temperatures lower than about 7000K.

Are all RCB stars pulsating variables? RY Sgr is, with a mean period of 38.6 days which is decreasing at a rate of about one second per day (Kilkenny 1982) consistent with Schonberner's evolutionary calculations (1977) (cf. also Lloyd Evans 1985). All RCB stars seem to be at least slightly variable near maximum so they could all be pulsating variables but this is not yet certain. A 44-day period for RCrB itself was suggested by Fernie et al. (1972) and extensive radial velocities by Griffin (1985 analysed by Dr L Balona) show a periodicity of ~49 days. A period of ~43 days has been suggested for UW Cen (Bateson 1972, Kilkenny & Flanagan 1983). S Aps has apparently now got a period near 40 days (Kilkenny 1983) though a 120-day periodicity seemed to exist previously. Much more work is needed on this matter but we cannot at present rule out the hypothesis that all RCB stars pulsate with periods near 40 days.

I have stressed the rather narrow range in temperatures both of stars and shells in these stars. This similarity extends to the relative flux of star and shell.

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Values of $(J-L)_0$ (= 2.48 ± 0.12 averaged over 10 RCB stars) are remarkably similar from one star to another. Here L is a mean value for each star and J is the value appropriate to maximum light. This suggests that if the stars have similar luminosities the amount of circumstellar matter is, in the mean, the same for each star within a factor of 3 or less.

3. THE CIRCUMSTELLAR PARTICLES

The size of the soot particles can be estimated from the reddening law. The only really safe way of deriving this law is to follow Alexander et al. (1972) and use only epochs at which the spectrum is observed to be normal. Unfortunately the amount of simultaneous photometry and spectroscopy is limited. However if all RCB stars follow an analogous pattern it is possible to choose phases at which the reddening law can be estimated even without spectroscopic information. Preliminary values have been obtained for 8 RCB stars at UBVRIJ (though not at all wavelengths for all stars) (the data are from the SAAO group (to be published), Kilkenny et al. (1975), Eggen (1985), Böhme (1984). Agreement between different stars is generally good.

Mean values are plotted in Figure 4 together with published ultraviolet results for RY Sgr (Holm et al. 1982). The dotted lines are from recent laboratory work on extinction by amorphous carbon smoke (Borghesi et al. 1985). The mean particle radii of the two samples shown are 40A (upper curve) and 150A (lower curve). One should not be too concerned about the failure to fit in the region of the 2200A graphite bump. Borghesi et al. stressed that the absorption in the ultraviolet is sensitive to the shapes and size distribution of the particles and this appears to be illustrated by theoretical computations for 100A graphite spheres (Draine 1985, Wickramasinghe 1973) which give a huge bump going up to E ~ 15 on the scale of Figure 4.

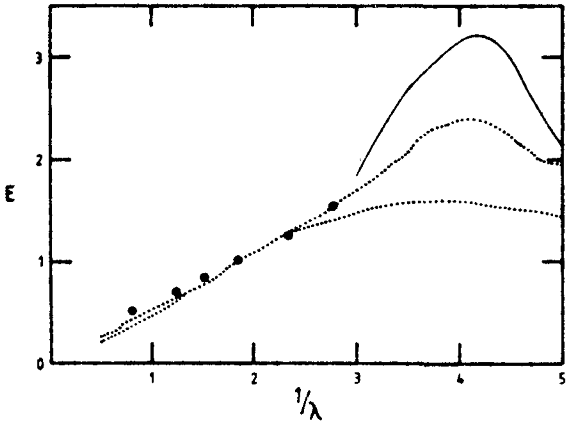

Fig. 4. Extinction for RCB stars as a function of reciprocal wavelength (μm^{-1}). Points are UBVRIJ results. The curve is from IUE data. The dotted curves are laboratory results for amorphous carbon smokes. See text for discussion.

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Thus although the agreement shown is certainly not exact it would appear that the observations can be satisfied by the presence of small carbon particles and in the following I adopt 100A (0.01 µm) as a typical size. We cannot fit the data with the much larger particles (0.1 - 0.2 µm) which observations suggest are around the carbon Mira R For (Feast et al. 1984). Such large particles give essentially neutral extinction shortward of ~1 µm.

On the model I sketched earlier the initial drop of an RCB star is caused by an optically thick (essentially opaque) cloud which is at first smaller than the star. The cloud expands as it moves out, eclipsing more and more of the star. Thus apart from centre to limb effects we would expect the initial drop to be at nearly constant colour. As Alexander et al. showed the chromospheric emission at a later stage, complicates the interpretation of observed colours.

Neutral extinction during the initial phase of a decline of RCrB itself was found by Fernie et al. (1972). UBVRIJHKL observations by R M Catchpole and I M Coulson of RS Tel soon after the start of a recent decline also suggest a very small variation of extinction with wavelength. In view of the complications likely in the real situation these results are probably as good a verification of the model as one could hope for. The alternative of postulating much larger particles on the decline than on the following rise does not seem at all attractive.

Variations in the flux from the dust shell was first reported for RCrB itself (cf. Strecker 1975 and references there). These suggested a periodicity of 1100 days. The few later observations (Ashok et al. 1984 and SAAO unpublished) suggest a more irregular variation but with at least a timescale for change of the order of 1000 days. In the case of RY Sgr the 38 day pulsations introduce considerable scatter. However there is again evidence of a variation in the flux from the shell with a timescale of ~1000 days (cf. Menzies 1985). Extensive observations of 10 RCB stars shows that variations at L of 1 to 3 magnitudes are typical. The times of rise or decline last typically 1000-2000 days (SAAO observations to be published). Menzies (1985) has pointed out that for RY Sgr the last two (or three) obscuration minima have followed maxima in the flux at L. This does not however appear to be a general phenomenon amongst RCB stars.

4. FURTHER CONSIDERATIONS OF MODEL

We can sketch a very crude model which seems to fit the existing data and gives us something to test with future observations.

(1) On the eclipse model for the RY Sgr minimum of 1967, soot is being ejected from near the star at ~200 km/sec in a cone of semi angle~20°. The material begins to become optically thin (i.e. we begin the rise from mimimum) ~200 days after the ejection. These numbers together with a particle size of 0.01µ allow us to estimate that the mass of solid carbon per ejection event is $\sim 10^{-8} M_{\odot}$. If essentially all the ejected carbon is in solid form and if it drags along all the gas out of which it has condensed, then assuming the material has photospheric composition the total mass ejected per event is $\sim 10^{-7} M_{\odot}$.

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(2) RCB obscuration minima seen to occur at random. The three stars which have been studied statistically (Sterne 1935, Howarth 1976, 1977) are RCrB, SU Tau and S Aps. In these three cases the average time bvetween fades (initial drops from maxima) are remarkably similar, 1026 ± 156 days, 1143 ± 220 days, 1249 ± 184 days (Mean = 1139 days). In the case of the first two stars the mean time between minima is roughly half these values, presumably due to new minima occurring before total recovery. An important point that can be inferred from those numbers is that because there is nothing preferred about our line of sight, ejection events must be occurring very frequently. If we take our figures for the 1967 ejection event in RY Sgr as typical then one puff of soot covers ~1/30 of the stellar surface. This suggests that averaged over the star (and taking the frequency of fades as above) the average time between ejections is 1139/30 = 38 days. If we took the time between minima we would get double the frequency. Evidently the model predicts that one or two puffs are, on the average, ejected per pulsation cycle of the star. These figures make plausible the idea that ejection is somehow connected with pulsation - a possibility also suggested by the fact that drops of RY Sgr tend to occur within a narrow range of pulsation phases (Pugach 1977).

One ejection event every 30 days leads to a total mass loss of $\sim 10^{-6} M_{\odot}$ per year. A relatively modest amount.

It is obviously possible to estimate the expected infrared emission from a circumstellar model of this kind. Dr P Whitelock has calculated a preliminary model which suggests that the observed mean flux at L can be maintained by an ejection rate of one puff every 30-40 days. Thus the preliminary indications are that the model will account both for the deep minima and the infrared excess.

(3) If the rise from minimum starts ~200 days after the first drop then our idealized model predicts that the rate of thinning of the cloud will be such that we shall reach ~1.5 mag below maximum ~400 days after the first drop and that we shall be near maximum again 800-1000 days after the first drop. These numbers were roughly correct for the 1967 minimum of RY Sgr.

(4) Since the flux at L shows slow increases or decreases lasting 1000-2000 days, there must be a variation of the mean mass ejection rate on this time scale. It would be important to check whether the pulsation amplitude changes with L flux (Is greater pulsational amplitude associated with greater mass loss?) On our model we would expect to see obscuration events more frequently at times of higher mass loss.

(5) The crude model we have considered predicts too high a colour temperature at K-L for the integrated flux from the dust, ~1000K as against ~800K observed. This is almost certainly due to the oversimplifications adopted. The model predicts that the colour temperature should fall with increasing wavelength - the larger wavelength radiation coming on the average, from further from the star.

A model of the type we have discussed can probably be made to work. However amongst the questions that still need answering are the following:

1. At what height above the photosphere does soot form?
2. Why is soot formation limited to patches (cf. Wdowiak 1975)?
3. Why does the amount of dust formed vary over periods of ~1000 days?
4. Is it true that all RCB stars pulsate? What are their periods if so.

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REFERENCES

Alexander, J.B., Andrews, P.J., Catchpole, R.M., Feast, M.W., Lloyd Evans, T., Menzies, J.W., Wisse, P.N.J. & Wisse, M., 1972. Mon. Not. R. astr. Soc., 158, 305.
Ashok, N.M., Chandrasekhar, T. & Bhatty, H.C., 1984. Inf. Bull. Var. Stars, 2510.
Bateson, F.M., 1972. Inf. Bull. Var. Stars, 661.
Berman, L., 1935. Astrophys. J., 81, 369.
Bidelman, W.P., 1953. Astrophys., J. 117, 25.
Böhme, D., 1984. Inf. Bull. Var. Stars, 2646.
Borghesi, A., Bussoletti, E. & Colangeli, L., 1985. Astr. Astrophys., 142, 225.
Catchpole, R.M. & Glass, I.S., 1974. Mon. Not. R. astr. Soc., 169, 69p.
Draine, B.T., 1985. Astrophys. J. Suppl., 57, 587.
Eggen, O.J., 1985. Preprint.
Espin, T.E., 1890. Mon. Not. R. astr. Soc., 51, 11.
Espin, T.E., 1900. Astr. Nachr., 152, 139.
Espin, T.E., 1894. Astr. Nachr., 134, 127.
Feast, M.W. & Glass, I.S., 1973. Mon. Not. R. astr. Soc., 161, 293.
Feast, M.W., 1975. Variable Stars and Stellar Evolution, IAU Symp. 67, p. 129, eds. Sherwood, V.E. and Plaut, L., Reidel, Dordrecht.
Feast, M.W., 1979. Changing Trends in Variable Star Research, IAU Coll. 46, p. 246, eds. Bateson, F.M., University of Waikato, New Zealand.
Feast, M.W., Catchpole, R.M., Lloyd Evans, T., Robertson, B.S.C., Dean, J.F. & Bywater, R.A., 1977. Mon. Not. R. astr. Soc., 178, 415.
Feast, M.W., Whitelock, P.A., Catchpole, R.M., Roberts, G. & Overbeek, M.D., 1984. Mon. Not. R. astr. Soc., 211, 331.
Fernie, J.D., Sherwood, V. & Du Puy, D.L., 1972. Astrophys. J., 172, 383.

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Forrest, W.J., Gillett, F.C. & Stein, W.A., 1972. Astrophys. J., 178, L129.
Glass, I.S., 1978. Mon. Not. R. astr. Soc., 185, 23.
Griffin, R., 1985. Private communication.
Hartmann, L. & Apruzese, J.P., 1976. Astrophys. J., 203, 610.
Holm, A.V., Wu, C.C. & Doherty, L.R., 1982. Publs. astr. Soc. Pacif., 94, 548.
Howarth, I.D., 1976. Publ. Var. Star Sec. R. astr. Soc. N.Z., No. 4, 4.
Howarth, I.D., 1977. Acta. Astron., 27, 65.
Kilkenny, D. & Flanagan, C., 1983. Mon. Not. R. astr. Soc., 203, 19.
Kilkenny, D., 1982. Mon. Not. R. astr. Soc., 200, 1019.
Kilkenny, D., 1983. Mon. Not. R. astr. Soc., 205, 907.
Kilkenny, D. & Whittet, D.C.B., 1984. Mon. Not. R. astr. Soc., 208, 25.
Kilkenny, D., Coulson, I.M., Laing, J.D., Spencer Jones, J. & Engelbrecht, C., 1985. Sth. Afr. astr. Obs. Circ., No. 9, 87.
Lloyd Evans, T., 1985. Mon. Not. R. astr. Soc. In press.
Ludendorff, H., 1908. Publ. Astrophys. Obs. Potsdam, 19, No. 57.
Menzies, J.W., 1986. This meeting.
Payne, C.H., 1928. Harvard Bull., 861, 11.
Payne-Gaposchkin, C., 1936. Harvard Bull., 903, 35.
Payne-Gaposchkin, C., 1963. Astrophys. J., 138, 320.
Pugach, A.F., 1977. Inf. Bull. Var. Stars, 1277.
Querci, M. & Querci, F., 1978. Astr. Astrophys., 70, L45.
Rao, N.K., Ashok, N.M. & Kulkarni, P.V., 1980. J. Astrophys. Astr., 1, 71.
Saio, H. & Wheeler, J.C., 1985. Astrophys. J., 295, 38.
Schönberner, D., 1975. Astron. Astrophys., 44, 383.
Schönberner, D., 1977. Astr. Astrophys., 57, 437.
Spite, F. & Spite, M., 1979. Astr. Astrophys., 80, 61.
Sterne, T.E., 1935. Harvard Bull. 896, 17.
Strecker, D.W., 1975. Astron. J., 80, 451.
Walker, H., 1985. In press.
Wdowiak, T.J., 1975. Astrophys. J., 198, L139.
Wickramasinghe, N.C., 1973. Light Scattering Functions for Small Particles with Application in Astronomy, Adam Hilger, London.
Zirin, H., 1982. Astrophys. J., 260, 655.

DISCUSSION

LAWSON: One point I would like to make. There is some evidence that XX Cam has a period of about 42 days. The amplitude of the periodic variations of the most of the R CrB stars is 0.1 or 0.2 magnitude. So detecting the pulsations in these stars is hard. The pulsations of RY Sgr are easier to analyse because the amplitude is about 0.5 magnitude.

FEAST: The pulsation problem is very difficult. I work in an institute where one member of the staff probably favours periodicities for a number of these stars and some body else claims that the evidence for periodicities is very unconvincing. So I think in the case of something like UW Cen you do see these cycles. They are isolated. The problem is that for the majority of these stars the visual observations that have been made are just not good enough. What one really has to have is a very large body of high accuracy photoelectric data.

N.K.RAO: Regarding the broad line spectrum in R CrB, the Na D lines also show P-Cygni profiles with the absorption going below the continuum and with a shift of around 300 km s^{-1}.

FEAST: I mentioned the 10830 feature probably seen in absorption from the matter coming towards you, when the star goes back to maximum. This is important, for you can study the matter even at maximum light. I think you have the same thing in the D lines too.

N.K.RAO: Yes. I saw an absorption component in λ 3889 He I also very close to the rise. During the minimum, the He I line λ 3889 is strong in emission; λ 7065 and λ 6678 also are strong in emission, but surprisingly, λ 5876 is not seen in emission. These lines are collisionally excited. They reflect the optical depth effects. Such anaomalies in He I lines are seen in V 348 Sgr.

FEAST: I don't think they are collisionally excited. I think they are radiatively excited.

N.K.RAO: If you are driving the gas along with dust wouldn't you expect to see strong absorption bands characteristic of this cool gas associated with the dust?

FEAST: I think one of the problems is, if the material were optically thick at an early stage, you hope to see strong C_2 bands. But I think you can get around this by saying that in the initial stages of the expansion the material is in fact not optically thick enough to be seen at all and you have to say by the time it does become optically thin, the carbon has already gone into particles.

N.K.RAO: At no stage do we see the presence of cool gas condensing into particles. We do not see an intermediate phase for the presence of cool gas.

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FEAST: The main condensation phase you don't really see because, it is essentially optically thick at that stage. There may be phases, in rare cases, in which you do see some kind of condensation. There is a remarkable observation which has neve been properly explained. Visual observations made by a very experienced observer,Espin, at the end of the last century showed that R CrB itself showed extremely strong carbon bands when it was near maximum light. That has never been seen by anybody alse.

RANGARAJAN: Do you think there are differences between the dust and gas temperatures in the shell?

FEAST: That is not entirely clear to me.

BHATT: Is there any CO emission from the dust shell? What is the dust to gas ratio?

FEAST: CO emission has not been detected. The dust to gas ratio is perhaps a factor 1/10.

LAMBERT: We have two IR spectra for R CrB, one at maximum and one at minimum. The spectra are continuous in that range, CO is not seen in absorption.

WING: I wonder what picture you have in mind as to the size of the region producing the chromospheric emission. We are used to thinking of chromospheres as thin shells just outside the photosphere as in the case of the sun, but IUE studies of chromospheric densities indicate that giant and supergiant stars have very extensive chromospheres occupying perhaps ten times the volume of the star. In this case we should be imagining the soot particles forming under the region we are calling the chromosphere.

FEAST: Well, I think that it introduces all kinds of difficulties. The problem with the early model was that you have a spherical shell of carbon forming near the star and so the chromosphere is seen. I do not think detailed spectroscopic data will fit that, and I don't think the IR will fit that either. I think you have to have a proper sort of limited sized cloud causing a real eclipse. Now where that starts, near the star or far away, I think is a very uncertain question. The rough estimates of size of the chromosphere from the eclipse curve show it to be vey extensive. In this case it was only called chromosphere for want of a better word. The conditions are roughly chromospheric so to speak. It does not have to be the same as in ordinary stars. For example if the material is ejected from outside the chromosphere, then you have the problem of how the ejected material is replaced. Conceivably that is replaced by rather slowly ejected material through the chromospheric region. In fact chromospheric lines, I seem to remember, are displaced slightly by one km s^{-1} or so; is that not so, Dr. Rao?

N.K.RAO: Yes about 3 km s^{-1} in R CrB.

FEAST: Which would agree to a gentle outflow through the region that we call chromospheric.

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N.K.RAO: May I add something to that. The chromosphere of R CrB seems to be something more like that of a normal F type supergiant because the IUE spectra show for R CrB the MgII core emission width etc. similarly as for γ Cyg (Rao, Bappu MNRAS, 1981). In addition it shows the CII line of λ 1335 very strongly in emission, even though the continuum does not appear or is extremely weak below λ 1800. I understand it indicates a temperature of about 2 x 10^4 K; hence there is need for energy input to increase the temperature. There are other emissions poking through the strong resonance lines of Fe II, Mn II etc. even at maximum light which again show similarities to normal giant or supergiant chromospheres.

VARDYA: I was wondering whether you observe any SiC feature at 11.3 microns in R CrB stars as we see in cool carbon stars in the IRAS data?

FEAST: I believe not.

N.K.RAO: Yes, agreed. Do you think this identification with amorphous carbon is established, particularly with the difficulties of chromospheric emission line interference during a minimum.

FEAST: If you want to be absolutely certain you must have simultaneous spectroscopy to see the spectrum of the star. In most cases I have shown that this is not the case.

GURM: In a pulsating star, depending upon certain conditions, a particular mode of radial oscillations becomes unstable and leads to supersonic velocities, thus puffing off some material. The pulsatons will slow down and build up again. This will introduce sort of cycles which seem to be present in the observational data. Are there any quantitative studies?

FEAST: It does seem that the mass loss rate is variable in a time scale of some thousands of days but the basic mechanism responsible for this time scale is not understood.

GURM: Do these stars have magnetic fields? If so, the presence of magnetic fields could lead to a sun like phenomenon of coronal holes. Signatures of the coronal holes in case of the sun are represented by the He I 10830 line. It is this line which has an anomalous behaviour in R CrB stars. Has anything been attempted in this direction?

FEAST: I don't think anything is known about magnetic fields in these stars.

WALKER: R. Wolstencroft and I have looked at RY Sgr with a spectropolarimeter and found intrinsic polarisation in the starlight. There is a feature in the curve which may correlate with a CN band head at about 3880 Å. The polarisation in the blue is very different from interstellar, but the data is of low signal to noise ratio. We have not yet worked out what this is trying to tell us about magnetic fields.

FEAST: These results could be related to a magnetic field; on the other hand they may be telling one something about the structure of the atmosphere which is not necessarily spherically symmetrical (at least as far as the distribution of molecules is concerned).

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WALKER: I am worried about some sort of small particles, which may be of spherical graphite. But there are no spherical graphite grains as graphite forms thin long flakes.

FEAST: I agree entirely that the λ 2200 hump is very sensitive to the shapes of the particles.

WALKER: What is the most significant fact for the particle size?

FEAST: I don't know. I think it is important to know the sizes of the particles because you have a problem when you are trying to form the particles very quickly and if you are told that the particles are of 1000 Å in size. You have a much more serious problem than for the size of 100 Å.

GARRISON: That leads to a question I have. It was not clear to me whether one wants to exclude the 1000 Å particles or whether one has in addition the 100 Å particles.

FEAST: One cannot say anything significant at present about the range of particle size. However, the dominant particles cannot be in the range of 1000-2000 Å since these particles produce neutral extinction shortward of the visible. A range of sizes around 100 Å seems to be demanded by the observations.

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