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THE R CORONAE BOREALIS STARS

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Abstract

A review of our current state of knowledge of the R CrB stars is given.

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1. Introduction

The R CrB stars are old disk population stars, meaning that they are distributed in the disk (as distinct from the halo) of our galaxy, but a disk that is not as flattened as that formed by young stars like B-stars. This suggests that the R CrB stars are evolved stars, older than the sun, but not as old as such objects as RR Lyrae variables.

They are a subgroup of the hydrogen deficient carbon stars, wherein hydrogen, normally by far the dominant element in a stellar atmosphere, is reduced to negligible proportions, with helium taking its place as the overwhelmingly abundant element. Elements heavier than sulfur are present in relative abundances much like those in the sun; carbon, on the other hand, is an outstanding anomaly, being many times more abundant than it is in the sun. The details of these abundances are discussed by Cottrell and Lambert (1982).

The most distinguishing feature of R CrB stars is their habit of plunging into sudden, steep declines of light, sometimes fading by eight magnitudes in a few weeks. This behavior, while apparently unpredictable, greatly enhances the chances of discovering these stars.

Discoveries of R CrB stars in the Magellanic Clouds, as well as studies of their spectra, indicate that these stars have quite high luminosities ($M_V \sim -5$ or even brighter). This too enhances their chances of discovery, and it is therefore significant that only two to three dozen of them are in fact known. Evidently rather special conditions are necessary for a star to become an R CrB star and/or this stage of evolution is one which passes very quickly, so that in our snapshot view of the universe we catch only a few stars at this stage.

Finally, although no known R CrB star occurs in a binary system suitable for determining its mass, indirect evidence based mainly on the star's spectral energy distribution suggests that these stars have masses similar to that of the sun, despite being 10,000 times more luminous. They also (at least the majority) have surface temperatures not much different from the sun (7000 K as compared to 6000 K).

2. Evolution

All of this observational evidence makes for a quite consistent theory of the evolution of R CrB stars. Being so luminous yet of modest temperature means they are yellow supergiant stars that, because of their quite low mass, must be well-advanced in evolution. Such big stars with such low mass must have only a weak surface gravity, so that they are very liable to lose matter to their surroundings. And in fact such circumstellar matter is known to exist because it radiates even more strongly than the star in the far infrared (Kilkenny and White 1984).

Stars with these properties are the so-called post-asymptotic-giant branch (AGB) stars. They have already been cool red giants, where their helium cores were suddenly switched on to nuclear burning. The suddenness of this phenomenon, as well as of subsequent helium burning in a shell around the core, has led to the term 'helium flash'. Such flashing may lead to the shucking of the star's original hydrogen-rich envelope, and further flashes may pump up the star's underlying helium layers with deeper carbon-rich material.

Some quantitative details are still missing, but this picture indicates the R CrB stars to be old stars entering their final stages of evolution, rapidly contracting and heating to become at least akin to the central stars of planetary nebulae and eventually white dwarfs.

Recent work relating to the fact that some R CrB stars show low-amplitude pulsational behavior has provided observational tests of this. There are two aspects. One is to ask whether the theoretical models of the stars predict periods and amplitudes of pulsation in agreement with observation; the other is to note that a pulsating star that is rapidly contracting should pulsate faster as time goes by, and is this in fact so?

The question of whether or not current theory predicts the correct periods and amplitudes of R CrB stars is a moot one. Trimble (1972), Wood (1976), and King (1980) found that while they could predict periods close to the actual ones, the amplitudes were violently unstable and the models tended to 'blow themselves apart'. Better stability was obtained if it was assumed that the star pulsates in a higher harmonic, but then the periods were far too short. King found it possible to stabilize the amplitude in the fundamental mode if a larger mass were invoked, but even so the amplitude was some 2 mag instead of the observed values of a few tenths of a magnitude. More recently Saio and Wheeler (1985) have claimed that these problems can be resolved by adopting slightly higher temperatures for the theoretical models, but this remains to be checked by others.

The suggestion that the R CrB stars might show marked period changes due to rapid evolution goes back at least as far as Warner (1967), but it is only recently that this has been examined in any detail (Kilkenny 1982; Kilkenny and Flanagan 1983).

The method of approach for finding period changes is well-known. In brief, if a star pulsates with a constant period it will obey a relation of the form

$$JD(max) = JDo + P \cdot E \tag{1}$$

where E is the count of cycles. If, however, the period is itself a linear function of time (represented by E),

$$P = Po + k \cdot E \qquad (2)$$

then substitution of equation (2) into equation (1) tells us that the observed times (O) of maximum light will be a quadratic function of E:

$$JD(max) = JDo + Po \cdot E + k \cdot E^2 \qquad (3)$$

Usually, predicted times of maximum are computed (C) on the basis of equation (1), and the difference O-C formed. A plot of O-C against E will then show a parabola if a smooth, linear period change is present, from which the value of k can be determined.

This observationally determined value of k can then be compared to the value found from theoretical models which describe how the radius of the star (on which the period is critically dependent) changes with time as the star evolves.

Kilkenny (1982) applied this to the well-observed southern R CrB star, RY Sgr, using for theoretical models those of Schonberner (1977). The result was most satisfactory: the observed value of k (= -0.00051 days) was neatly accounted for by a theoretical model of one solar mass at an effective temperature of 6900 K. Some variation in these parameters was permitted; e.g. a model of 0.7 solar masses and about 6600 K would do as well, but the essential point was that theory and observation were in good broad agreement.

However, subsequent work (Kilkenny and Flanagan 1983) met with setbacks. A study of S Aps yielded an observational k value of -0.184 day, which is far beyond the realm of predicted values. Further analysis of the S Aps data (Kilkenny 1983) suggested that the star had rather abruptly changed its period from 120 days to 38 days around 1971, and so the matter of interpretation is left unclear. What is clear, though, is that S Aps, like other R CrB stars, needs continued precise observations on a regular basis if we are to arrive at a correct understanding of its nature.

The same is to be said of UW Cen, for which Kilkenny and Flanagan found k = +0.0030 days. Not only is the numerical value of this much larger than expected, but the plus sign implies evolution in the opposite direction to that expected.

In summary, then, while there is no reason to think that our broad qualitative understanding of the evolutionary status of R CrB stars is wrong, there are clearly matters of detail which will have to be addressed.

3. The Deep Declines

Nothing about the R CrB stars has proved more enigmatic than the sudden, unexpected deep declines in brightness into which they plunge. Despite nearly two hundred years of data for R CrB itself, no way has been found for predicting when a deep minimum will occur. There is a characteristic time of about 1100 days between fades but with a large dispersion (Howarth 1977).

An intriguing question has recently arisen as to whether these deep declines are related to the low-amplitude pulsation. Goncharova, Koval'chuk, and Pugach (1983) analysed the available pulsational data for R CrB, and found three significant periods at about 54, 40, and 27 days. They then found from an examination of the dates of onset of deep declines that these occurred at multiples of the 40-day period. This, however, was not substantiated in an independent analysis made by Percy et al. (1986), and a more recent paper (Goncharova 1985) has relaxed the claim to allow the other two periods to be involved too. It is the view of some of us that as yet there is insufficient precise photometry of R CrB near maximum light to be sure of any period analysis. In any case, of course, the question of what is the physical trigger for the deep decline remains.

What else happens besides the loss of light during a deep decline? One thing is a definite reddening of the starlight (Fernie, Percy, and Richer 1986). At first glance this might seem to imply a cooling of the star, but that this isn't so is shown by the star's spectral type, which essentially does not change. An alternative, then, is to suppose that the star becomes veiled, and -- given the high abundance of carbon -- an attractive possibility is that this veiling is by some form of soot.

Support for this view comes from a study of the spectrum during deep decline. While the actual pattern of lines hardly changes, the lines themselves reverse from dark lines to bright lines in a way very reminiscent of the sun's spectrum at a total solar eclipse when the moon hides the sun's bright photosphere (surface) and we see the spectrum of the solar chromosphere (atmosphere). In the R CrB stars something (the soot) intervenes to hide the star's surface, allowing the chromospheric spectrum to appear.

This basic idea is at least fifty years old and has been developed into a variety of models. In one (Payne-Gaposchkin 1963) the soot forms between the photosphere and the chromosphere, but the difficulty of condensing the soot so close to the hot surface has not been overcome satisfactorily. In another (Wing et al. 1972) the soot is in the form of clouds orbiting the star, but the asymmetry of the minima (steep decline but slow recovery) is then difficult to account for. The most likely model is similar to the original so-called Loreta-O'Keefe one. The star emits compact, dense puffs of material which condense at some considerable distance from the star, expanding to hide the bright disk and so reveal the chromosphere, but then continuing to expand across the chromosphere as well until eventually the soot is so thinned out that the bright disk begins to shine through once again. The soot finally gathers in the circumstellar shells around the star, so tenuous as to have negligible effect on the visible light, but readily revealed by infrared observations.

Feast (1986, preprint) has had considerable success in developing this model in a semi-quantitative way. Putting together various observational data he shows that each puff would comprise about a hundred millionth of a solar mass of material, and that it would initially cover 1/30 of the stellar surface. If these puffs are emitted in random directions, but we only detect those emitted near our line of sight, then to account for the characteristic 1100 day interval between declines, there must be a puff emitted about every 40 days -- which returns us to the Goncharova hypothesis of the connection with the pulsational cycle!

4. Other Recent Developments

With the advent of observations from above the earth's atmosphere a considerable new set of data has become available for the R CrB stars. These data have given much new information about the nature of the 'soot' grains. Ground-based data alone make it difficult to say whether or not these grains differ significantly in their extinction properties from ordinary interstellar matter. But now, with observations ranging from the far ultraviolet to the far infrared (Holm et al. 1982; Hecht et al. 1984; Evans et al. 1986) we begin to see distinct differences from normal interstellar matter, and discussions of grain sizes and the actual form of the carbon are underway.

A study of IRAS data (Schaefer 1985) in the extreme infrared has revealed a connection between some R CrB stars and planetary nebulae, thus strengthening our evolutionary view of these old stars.

5. Concluding Remarks

With the exception of Mira stars, one would be hard-pressed to think of any field of variable stars where amateur astronomers have made so rich a contribution as in the R CrB arena. Their observations have been and continue to be invaluable. If we are ever, for instance, to test the Goncharova hypothesis convincingly we must have more data on the epochs of deep declines and increasingly accurate photometry of these stars near maximum light. Inevitably that job will be done mainly by amateurs as it always has in the past.

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