Photometry of R Coronae Borealis

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Photoelectric photometry of R CrB was obtained during the years 1966—71. During this time the star emerged from a prolonged minimum, showing a change in colour indices which was very like those of the supergiant sequence between G 8 and F 8 if allowance is made for an ultraviolet excess and some interstellar reddening. Superimposed on this rise towards maximum was a sharp minimum, during which the V magnitude was observed to decline through more than 3 magnitudes without any corresponding reddening in the colour indices. Throughout the emergence from the extended minimum the star showed irregular fluctuations of up to 0.2 mag. on a timescale of weeks.

Detailed observations near maximum light showed that R CrB exhibits a sinusoidal variability of period about 44^d and amplitude about 0.15 mag. The light-curve is somewhat irregular and suggests RV Tauri-like behaviour. The B-V colour-curve seems irregular with an amplitude of about 0.04 mag., while the radial velocity at maximum is also slightly variable by 4 or 5 km/sec.

Assuming the star to be pulsating at maximum, the 44^d period may be combined with SEARLE's spectroscopic determination of its surface gravity to indicate a mass of about 2 $M_\odot$ and a radius of about 100 $R_\odot$.

[The complete details of this work will appear shortly in the Astrophysical Journal.]

Discussion to the paper of FERNIE

SCHUMANN: What is the precision of your estimates of the U-B colour indices in your first slide? There are 2 points $0^m\!\!.1$ higher than the constant level during the light minimum.

FERNIE: In those earlier observations taken without use of a comparison star, the general precision of U-B is about $\pm 0^m\!\!.03$.

LLOYD EVANS: RY Sgr shows complicated colour and spectral changes during a deep minimum; emission lines and reddening by the ejected cloud effect the colours. Observations near maximum show a 39 day pulsation (semi-regular), visual amplitude $= 0^m\!\!.4$, with colour and velocity changes similar to those in a W Vir star.

Models for R Coronae Borealis Stars

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If we believe in the spectral analysis of the atmospheres of R CrB stars these objects should have a pure helium envelope slightly enriched in carbon (SEARLE 1961, DANZIGER 1965). However, they cannot be homogeneous helium stars since in that case they should be on the helium main sequence in the Hertzsprung-Russell-diagram, whereas they are found in the region of late supergiants. Their internal chemical structure must therefore be more complicated than that of a homogeneous helium star. From the viewpoint of stellar evolution the next degree of complexity would be to have a carbon-oxygen core.

Therefore, we have constructed models with a helium rich envelope and a carbon-oxygen core, the latter consisting of a mixture of roughly 50% carbon and 50% oxygen. For the energy equation we used the simple form

$$\frac{dL_r}{dM_r} = \varepsilon$$

where L_r and M_r have the usual meaning, while ε is the net energy production by nuclear reactions including neutrino losses (based on the rates given by BEAUDET, PETROSIAN and SALPETER 1967). Models which undergo rapid changes, such as contraction phases or cooling, cannot be described by such a simple method. However, since R CrB stars seem to be in a relatively slow phase of evolution, i. e. living on nuclear reactions, our simplification appears to be reasonable. Supergiants are not expected to be observed in rapid phases of evolution, such as the pre-main sequence contraction. For reasons of simplicity we have assumed that the transition in chemical composition from envelope to core is discontinuous at $M_r = M_{core}$.

All models of the type described above form a two parametric set $\{M, q_0\ (= M_{core}/M)\}$. A general description of the properties of these models has been given by us recently (BIERMANN and KIPPENHAHN 1971).

We restrict ourselves here to the models which might be candidates for R CrB stars. In Fig. 1 an HR-diagram is given indicating the R CrB stars' region. Models of two kinds lie in this region, first, models with a degenerate core and a helium burning shell, and second, models with a carbon burning core and a helium burning shell that provides most of the star's luminosity, except for q_0 close to unity.

Since for the first type of model, i. e. a degenerate core, a helium burning shell and a helium envelope, the luminosity depends only on the core mass (see also UUS 1970) we can directly deduce the range of core masses from the range of luminosities. The core masses are found to be in the interval

$$0.6 \leqslant M_c/M_\odot \leqslant 0.74$$

with corresponding values of q_0 of:

$$0.3 \leqslant \quad q_0 \quad < 1.0 \ .$$

From this we readily conclude that the total masses of R CrB stars are in the range of

$$0.6 \leqslant M/M_\odot \leqslant 2.5 \ .$$

This is a larger mass range than that given by PACZYNSKI (1971) who has constructed similar models. The difference is probably due to the different kind of approach PACZYNSKI used: He calculated the real evolution of helium stars whereas we calculated stationary models for a very large range of possible parameter values. However, since the R CrB stars are believed (WARNER, 1967) to be old Pop I or Pop II stars, the above range can be limited to below 2.0 $M_\odot$ because old stars of higher mass would be past red giants phases by now.

It is also possible that the R CrB stars have carbon burning cores since at least some models of this type lie in the right region of the HR-diagram. We would in that case expect a core mass of 0.95 $M_\odot$ and total masses in the range of 1.0 to 3.6 $M_\odot$. From this range again stars with masses above 2.0 $M_\odot$ can be excluded because of age.

Comparing the two types of models, the first one is favored by us (the one with a degenerate core), since many models of this type widely different parameters (q_0, M) are found in the R CrB region of the HR-diagram. On the other hand, it is difficult to see how only the lower limit of core masses for carbon burning cores (i. e. 0.95 $M_\odot$) should be realized among the R CrB stars.

Finally, in Tables 1 and 2 we give details for models of 1.2225 $M_\odot$ and 0.6860 $M_\odot$, respectively, both models having a degenerate core. Using these data we can discuss the 40 day periodic pulsation of RY Sgr and R CrB that occurs during maximum light.

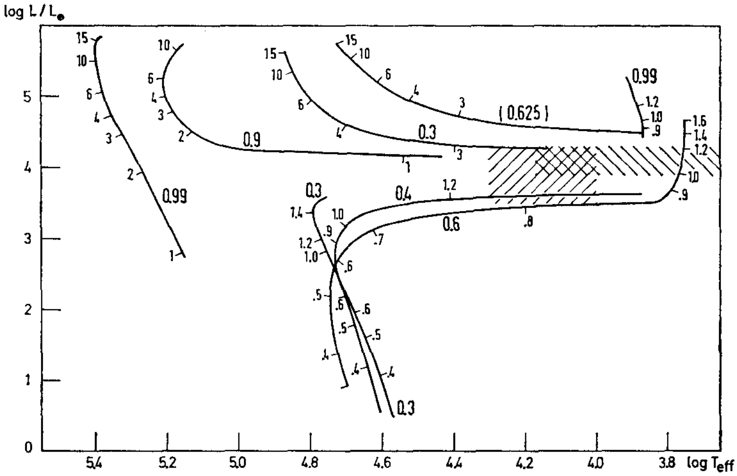

Fig. 1: The two-parametric set of models in the HR-diagram. The parameters along each solid line give the mass in solar units, the solid lines are characterized by their q_0-value. The two hatched areas give the regions in which helium stars (left rectangle) and R CrB stars (right rectangle) are observed.

Since these models have extended outer convection zones they are not expected, at first sight, to have the same type of pulsational instability as Cepheids have. However, the pulsational instability mechanism of the Cepheids might operate in the envelopes of R CrB stars if the convection is sufficiently ineffective. This would ensure a radiative temperature stratification — the prerequisite for the $\varkappa$ mechanism of the Cepheids (BAKER and KIPPENHAHN 1962). Thus there are two general mechanisms possible for the explanation of the pulsation:

The $\varkappa$ mechanism: Since the convection zone in the outer region is not adiabatic the radiative energy transport might still be important. It can then be modulated because of the variations in opacity during the contraction and expansion phases. This mechanism can keep a pulsation going.

The Mira mechanism: The R CrB stars have a convective envelope which makes the Mira stars their counterparts among the hydrogen rich stars. Supposing that the interaction between convection and pulsation is the cause of the Mira variability it is suggestive to conclude that the same mechanism works for the R CrB stars.

A choice between these two mechanisms can only be made on the basis of a theory for pulsating convection zones. Using such a theory further conclusions could then be drawn regarding the interior structure of the R CrB stars.

In conclusion, a numerical model for the R CrB stars emerges, consisting of a degenerate carbon-oxygen core and a helium burning shell with a helium envelope.

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References:

BAKER, N., KIPPENHAHN, R., 1962, Z. f. A. 54, 114.
BEAUDET, G., PETROSIAN, V., and SALPETER, E. E., 1967, Ap. J. 150, 979.
BIERMANN, P., and KIPPENHAHN, R., 1971, Astron. & Astroph. 14, 32.
DANZIGER, I. J., 1965, M. N. R. A. S. 130, 199.
PACZYNSKI, B., 1971, Acta Astron. 21, 1.
SEARLE, L., 1961, Ap. J. 133, 531.
UUS, U., 1970, Nautchnije Informazii 17, 25.
WARNER, B., 1967, M. N. R. A. S. 137, 119.

Table 1: Details of a model of 1.2225 solar masses with $q_0 = 0.5$, $\log T_{eff} = 3.773$ and $\log L/L_\odot = 3.954$. Helium is completely ionized in this model below the region with $\log P = 6.18$.

a) gives the pressure P, temperature T, central distance r, density ϱ and $\nabla = \mathrm{dlnT/dlnP}$ for comparison with $\nabla_{ad} = (\mathrm{dlnT/dlnP})_{ad}$ in the outer layers.

b) gives $q = M_r/M$, P, T, r, the luminosity L_r (in units of its surface value L) and ϱ in the interior.

In convective regions log T is printed in italics. Negative values of L_r are due to neutrino losses in the core.

log P	logT	log r	log ϱ	∇	∇_{ad}
3.812	3.772	12.799	−7.287	0.275	0.399
3.892	*3.799*	"	−7.234	0.408	"
4.132	*4.014*	12.797	−7.210	1.281	0.341
4.212	*4.153*	"	−7.297	1.099	0.098
4.262	*4.192*	12.796	−7.321	0.580	0.078
4.362	*4.236*	12.794	−7.333	0.352	0.074
4.562	*4.300*	12.789	−7.307	0.351	0.092
4.842	*4.523*	12.779	−7.322	0.735	0.221
5.082	*4.602*	12.764	−7.203	0.198	0.098
5.402	*4.656*	12.739	−6.982	0.153	"
6.042	*4.768*	12.678	−6.514	0.237	0.179

q	log P	log T	log r	L_r/L	log ϱ
0.970	6.101	*4.789*	12.671	1.000	−6.476
0.920	6.799	*5.008*	12.577	"	−6.014
0.798	7.694	*5.315*	12.385	"	−5.456
0.682	8.485	*5.567*	12.144	"	−4.945
0.608	9.290	*5.806*	11.856	"	−4.415
0.579	9.947	*5.994*	11.613	"	−3.975
0.564	10.550	*6.162*	11.396	"	−3.568
0.559	10.908	*6.259*	11.269	"	−3.323
0.558	10.963	6.274	11.250	"	−3.284
0.553	11.516	6.411	11.068	"	−2.867
0.547	12.357	6.623	10.811	"	−2.240
0.542	13.479	6.882	10.521	"	−1.338
0.536	14.574	7.140	10.258	"	−0.481
0.530	15.547	7.376	10.027	"	0.267
0.523	16.663	7.649	9.761	"	1.115
0.515	17.703	7.901	9.512	"	1.913
0.5000	19.371	8.283	9.116	−0.0014	3.344
0.4998	19.387	"	9.113	"	3.362
0.494	19.878	8.282	9.040	"	3.891
0.472	20.660	8.280	8.944	−0.0013	4.645
0.404	21.532	8.257	8.831	−0.0011	5.365
0.254	22.267	8.133	8.683	−0.0005	5.887
0.113	22.692	7.922	8.514	−0.0001	6.172
0.009	23.012	7.826	8.109	0.0	6.384
0.0	23.073	7.815	$-\infty$	0.0	6.424

Table 2: Details of a model of 0.6860 solar masses with $q_0 = 0.9$, $\log T_{\mathrm{eff}} = 3.783$ and $\log L/L_\odot = 3.968$. Helium is completely ionized below the region with $\log P = 5.76$. Otherwise see the legend of Table 1.

log P	log T	log r	log ϱ	∇	∇_{ad}
3.676	3.783	12.784	−7.435	0.288	0.399
3.756	3.813	„	−7.384	0.469	„
3.996	4.070	12.781	−7.406	2.094	0.214
4.046	4.166	12.780	−7.495	1.040	0.083
4.096	4.205	12.779	−7.535	0.592	0.073
4.196	4.253	12.775	−7.578	0.438	0.076
4.376	4.409	12.766	−7.672	2.150	0.321
4.456	4.530	12.759	−7.756	0.708	0.151
4.536	4.568	12.750	−7.751	0.344	0.107
4.676	4.608	12.731	−7.703	0.252	0.102
5.036	4.723	12.670	−7.561	0.491	0.238
5.756	5.004	12.453	−7.305	0.299	0.262

q	log P	log T	log r	L_r/L	log ϱ
0.982	5.856	5.031	12.422	1.000	−7.240
0.978	6.420	5.178	12.221	„	−6.845
0.9745	7.690	5.506	11.804	„	−5.952
0.9738	8.108	5.614	11.674	„	−5.657
0.972	9.424	5.917	11.346	„	−4.536
0.970	10.306	6.119	11.155	„	−3.807
0.969	11.016	6.295	11.001	„	−3.271
0.966	11.837	6.499	10.819	„	−2.649
0.963	12.808	6.723	10.598	„	−1.866
0.959	13.646	6.925	10.418	„	−1.216
0.955	14.373	7.094	10.261	„	−0.641
0.949	15.249	7.307	10.067	„	0.031
0.941	16.109	7.517	9.872	„	0.686
0.931	17.036	7.742	9.657	„	1.398
0.919	18.017	7.979	9.427	„	2.149
0.903	19.125	8.244	9.165	0.971	3.004
0.900	19.336	8.282	9.116	0.200	3.189
0.8992	19.356	„	9.112	−0.0013	3.326
0.8987	19.386	„	9.107	„	3.361
0.890	19.809	„	9.044	„	3.820
0.847	20.726	8.279	8.933	„	4.705
0.705	21.650	8.249	8.812	−0.0011	5.452
0.561	22.077	8.190	8.732	−0.0007	5.756
0.416	22.375	8.090	8.654	−0.0004	5.961
0.249	22.651	7.944	8.547	−0.0001	6.145
0.103	22.876	7.861	8.392	0.0	6.294
0.008	23.063	7.819	7.990	„	6.417
0.000	23.098	7.813	$-\infty$	0.0	6.441

Discussion to the paper of BIERMANN and KIPPENHAHN

FERNIE: My remark is that I would be relieved if R CrB behaves more like a Mira star, because then I wouldn't worry about the low radial velocity amplitude.

My question is: I understand that Miss TRIMBLE's results indicated a large amplitude of pulsation. Do you know whether she still believes this?

KIPPENHAHN: To your remark: If the R CrB pulsation resembles more that of Mira pulsation one might expect the ratio of radial velocity amplitude to photometric amplitude to be smaller, but on the other hand the colour variation unfortunately should be rather big. I think even if one believes that the mechanism which is driving the pulsation is similar to that working in Mira stars, one should not expect that the fully developed pulsation should resemble that of a Mira star.

To your question: I have no information about Miss TRIMBLE's work of pulsation of R CrB models. But computing the pulsations of our R CrB models would mean to make assumptions on the interaction between pulsation and convection. One has not yet succeeded in doing this for Mira stars properly.

Some Properties of Magnetic Variables

Karl D. RAKOŠ (Vienna)

It is certain, that the mechanism causing variations of the magnetic field and spectral lines in Ap stars must also cause variations in their luminosities. The light curves are synchronous with the magnetic variations and usually the maximum of the positive magnetic field strength coincides with the minimum of the light curve. In the past the oblique rotator theory was not able to explain easily such brightness change. There is no simple reason to suppose, that the brightness of the surface of a star would increase or decrease at one magnetic pole only. Since that time a few stars were found with some indications for secondary minima and maxima in the light curves, but the first established double wave in a light curve was recently found by H. M. MAITZEN and K. D. RAKOŠ in HD 125 248 (1970), see Figure 1. It is a very exciting result, only the light curve in yellow light shows two maxima and two minima. The light curves in blue and ultraviolet are very smooth and show no evidence for secondary waves.

The photoelectric observations of α Andromedae made by the author at Lowell Observatory show also very nicely double waves in all three colors, see Figure 2. The period of the light curve derived from these observations lies near one day.

$$P = 0\overset{\mathrm{d}}{.}9636$$

It is in good agreement with the line width in the spectrum of this star. Very remarkable is the difference between primary and secondary minimum for different colors. The secondary minimum and maximum for ultra-violet and blue can be found only from a very long set of good observations.

HD 125 248 and α Andromedae show very instructivly how effective the secondary wave can be hidden in the light curve of magnetic stars.

Figure 3 shows the smooth light curves in UBV for HD 224 801 (K. D. RAKOŠ, 1963). The secondary wave can be recognized easily.

The observations of HD 71 866 (K. D. RAKOŠ, 1962) also show the secondary minimum and maximum in yellow. The U and B light curves show no evidence for secondary waves, very similar as HD 125 248, see Figure 4.