1988ApJ...325L...9S

THE ASTROPHYSICAL JOURNAL, 325:L9–L12, 1988 February 1
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R CORONAE BOREALIS DUST EJECTIONS: A PREFERRED PLANE?

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Received 1987 October 19; accepted 1987 November 9

ABSTRACT

We present spectropolarimetric observations of R Coronae Borealis obtained during the brightness minimum of 1986. When combined with previous polarization observations of brightness minima, the distribution of observations in the Q-U plane suggests that ejections of dust clouds occur in a preferred plane about the star, in contrast to the standard model for the R CrB–type stars which holds that clouds are ejected from all parts of the stellar surface. The possibility of an ejection mechanism connected with nonradial pulsations is discussed as the most likely explanation of the preferred plane.

Subject headings: polarization — stars: circumstellar shells — stars: R Coronae Borealis — stars: variables

I. INTRODUCTION

R Coronae Borealis (R CrB) is the prototype of a small class of variable stars which show declines in brightness ranging from small dips to dramatic fadings of 7 mag or more at irregular intervals. The large declines in brightness have long been attributed to obscuration by clouds of dust grains condensing out of gas ejected from the star along the line of sight (Loreta 1934; O'Keefe 1939). Visible photometry and spectroscopy (Payne-Gaposchkin 1963; Alexander *et al.* 1972) and infrared photometry (Feast *et al.* 1977; Schaefer 1986) support the cloud model. Hecht *et al.* (1984) fit extinction curves to observations of the stars R CrB and RY Sgr made with the *International Ultraviolet Explorer* (*IUE*) using a distribution in radii from 50 to 600 Å of glassy or amorphous carbon particles. Other explanations of the brightness variations, including orbiting dust clouds and a binary companion (Wing *et al.* 1972, and Humphreys and Ney 1974, respectively), do not fare as well when confronted with the observations of R CrB, and RY Sgr, the other well-studied member of the class (Feast 1975, 1986). For example, both of these alternative models cannot reproduce the observed color changes during minima. The cause of the dust ejection is still unknown, although the idea that clouds are formed in connection with radial pulsations gains some support from the observations of semiregular low-amplitude variations in the visual magnitude of R CrB by Fernie (1982) and Fernie, Percy, and Richer (1986).

Polarimetry can be used as a tool to investigate the nature of brightness variations in R CrB. Light from R CrB is polarized when it scatters off dust surrounding the star. This polarized component becomes relatively more important when direct unpolarized starlight is obscured by dust along the line of sight. Very few polarization observations exist for these stars. Coyne and Shawl (1973) found large polarization variations associated with a brightness minimum in 1972. During a decline of 7 mag, the polarization rose from 0.29% to 3.29% in the B band over 3 weeks.

Serkowski and Kruszewski (1969) monitored the variations in polarization during a small minimum in 1968. Such small dips (0.5–1.0 mag) in the brightness of R CrB are often observed. These could be attributed to dust clouds partially obscuring the star or to larger-than-normal pulsations. To investigate the long-term relationship of polarization and brightness variations, a program to monitor R CrB has been started at Pine Bluff Observatory.

II. THE DATA

a) New Observations

The new data presented here were obtained with the spectropolarimeter and the 36 inch (0.9 m) telescope at Pine Bluff Observatory. The detector is a Reticon dual photodiode array behind a Varo microchannel plate intensifier. The dual array, along with a dual slit and decker, allows simultaneous signal and sky observations. Wavelength coverage extends from 4800 Å to 7200 Å, using the 400 lines mm^{-1} grating, with polarimetric resolution varying from about 75 Å at 5000 Å to 180 Å at 7200 Å. Polarimetric and spectroscopic information are obtained simultaneously using a Lyot analyzer which modulates the spectrum in wavelength with a pattern whose amplitude is proportional to the polarization. The spectropolarimeter is described in detail in Lupie and Nordsieck (1987). Observations of unpolarized standard stars showed the instrumental polarization value to be constant during the two observing seasons so that correction was easily made. The position angle in the equatorial system is calibrated by observing polarization standard stars at regular intervals.

The data reduction process leading from counts per pixel to flux per unit wavelength is described in Tobin (1979), Percival (1979), and Anderson, Oliversen, and Nordsieck (1980). The observations result in two modified spectra which show opposite senses of the polarization modulation function. Combining these spectra gives the true spectrum, while differencing them gives the polarization function. Fourier analysis of this function yields a variety of fits for the Stokes parameters $Q(\lambda)$, $U(\lambda)$, and $V(\lambda)$. Errors are calculated by differencing the data and the fit at each pixel and finding the weighted average over the chosen number of wavelength intervals of the fit. Typically, the errors are consistent with those expected from photon-counting statistics. A comparison of the polarization values to the errors shows that our results are at the 10 σ level. The results of two observing seasons (1986–1987) are shown in Figure 1 for a bandpass ($\lambda_{\rm eff} = 4817$ Å, $\Delta\lambda = 650$ Å) similar to the Johnson B band. This bandpass was chosen for easy comparison to similar bandpasses in the other two data sets. As can be seen in Figure 1, the typical errors (1 σ) in Q and U for one

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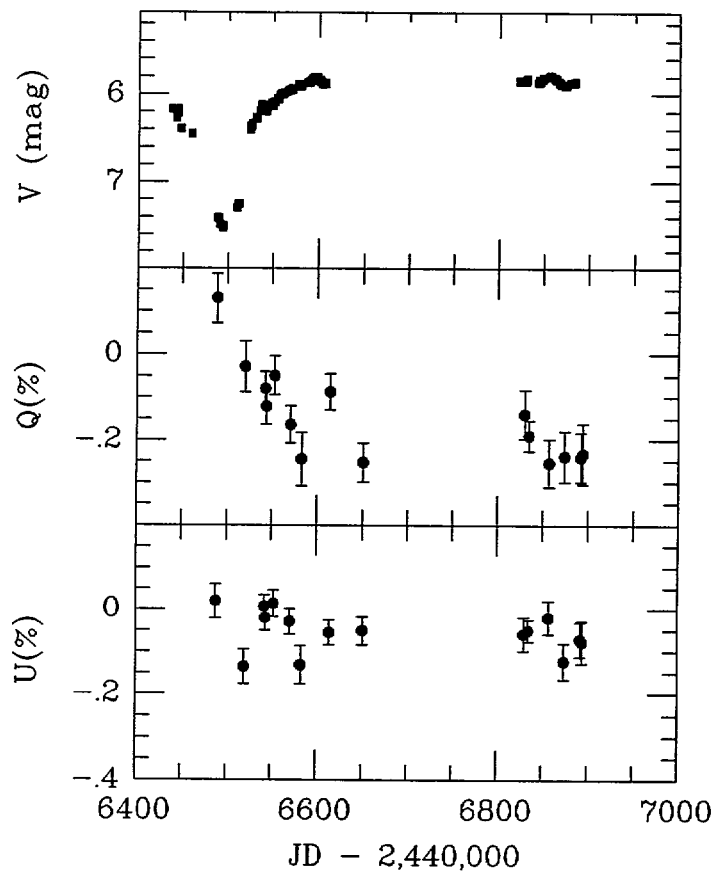

FIG. 1.—Polarization observations of R CrB from Pine Bluff Observatory in 1986–1987. Top panel contains visual magnitudes from Fernie (1987); middle panel, Q values in percent; and the bottom panel, U values in percent. The error bars on the Q and U points correspond to 1 σ.

observation are 0.03%–0.04%. Visual magnitudes are from Fernie (1987).

b) Previous Observations

Serkowski and Kruszewski (1968) obtained polarization data for R CrB from 1968 January to March during a decline of about 0.5 mag. We use their Johnson B band observations which show polarization variations of about 0.15% and have typical errors of 0.03% in the polarization values. Coyne and Shawl (1973) observed R CrB from 1972 late March to mid-May during a drop of 7 mag in the visual brightness. We use their B band observations which show polarization observations of over 3% and have typical errors of 0.13%. Both the new and the previous data sets contain a small amount of interstellar polarization which is a significant fraction of the 1968 and 1986–1987 data. This interstellar component may include a contribution from dust associated with R CrB but lying at large (up to 8 pc) distances from the star (Gillett *et al.* 1986). This dust probably contributes little or nothing to the interstellar polarization and, since it will be constant anyway, will be removed as part of the interstellar polarization component. To estimate this component, the data taken in 1987, a period in which no brightness fluctuations were observed, have been averaged. This component, $Q = -0.21\%$, $U = -0.07\%$, was subtracted from all the data sets. All three corrected data sets are plotted for comparison in the Q-U plane in Figure 2. Each of the three sets of data is associated with a decline in brightness of R CrB. The 1968 data are taken during a dip of 0.5 mag, the 1972 data during a major fading of 7 mag, and the new data cover a brightness dip of 1.2 mag which occurred from 1986 January to March. All show significant polarization variations associated with the declines in brightness.

III. ANALYSIS

a) Position Angle Variations

Although more data are clearly needed, the behavior of the polarization variations in the Q-U diagram, seen in Figure 2, implies that there is a preferred direction to the variations in all three events. If true, then the dust is not ejected randomly from all parts of the star but rather in some preferred plane. As noted in Lupie and Nordsieck (1987), an axisymmetric distribution of scatterers around a star will produce a Q-U diagram with the data points lying along a line when the number of scatterers changes with time. To test the validity of the preferred direction hypothesis, we have applied two statistical tests to the three data sets.

First, we performed a linear correlation test on all three data sets. The null hypothesis that there is zero correlation between Q and U was disproved at the 99% significance level. Further, the Spearman Rank-Order correlation test, which is a more general test since it does not assume any knowledge of the probability distribution function of the input data, gives the correlation coefficient $r = 0.78$ at a 99% confidence level. We also performed these tests on the three data sets separately with the expected result that the 1972 data contribute more to the high degree of correlation than the other data sets. We conclude that the distribution over time of Q, U values during

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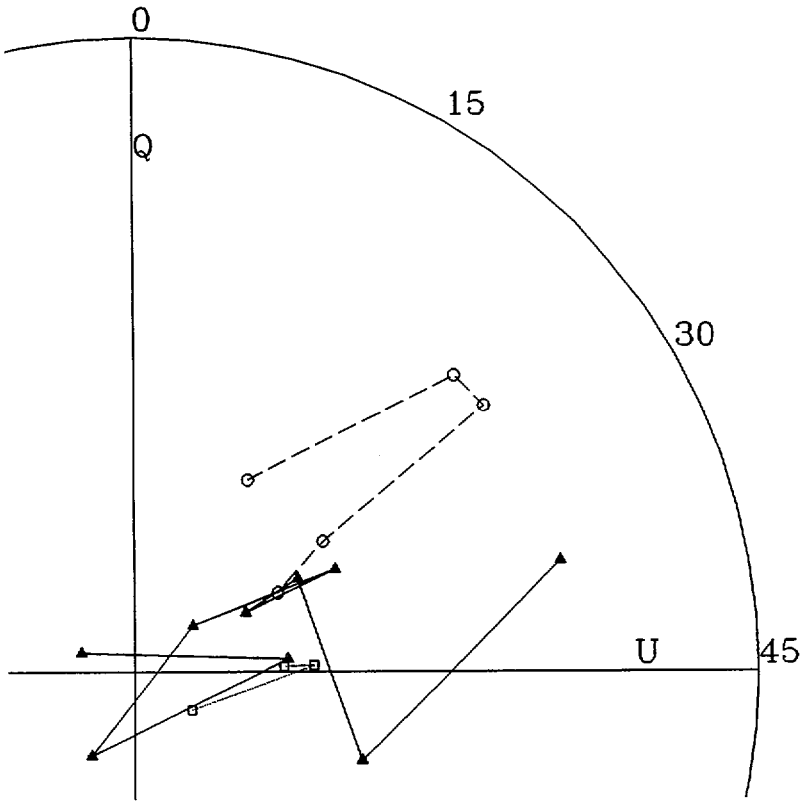

FIG. 2.—*Q-U* polar diagram of the three data sets. The Serkowski and Kruszewski (1968) data are plotted as open squares; the Coyne and Shawl (1972) data, as open circles; and the new data of 1986–1987, as filled triangles. The position angle is plotted around the edge of the circle, which has a radius equal to 0.5%. Note that the magnitudes of the Coyne and Shawl data points have been divided by 10, and the axes are plotted to correspond to a similar plot in Coyne and Shawl (1973).

minima are linearly correlated, indicative of an axisymmetric rather than a spherically symmetric ejection model.

b) Model

To test whether random spherically symmetric ejections can produce *Q*, *U* variations similar to those observed, we have constructed a simple model of the R CrB system, assuming the standard characteristics for cloud size, composition, and ejection velocity given in Feast (1986). The model calculates the expected polarization from a star surrounded by a group of 10–15 clouds, assuming a Rayleigh scattering phase function, following the methods developed by Brown and Maclean (1977) and Cassinelli, Nordsieck, and Murison (1987). Each cloud is formed at a distance of approximately 2 R_*, where it is assumed that all the grains condense out of the ejected gas at a given size (Feast 1986). The optical depth in a cloud depends on the way the grain number density changes with time. The functional relationship between the density and time is derived from the mean cloud mass, grain size, and mass density, and by assuming that a cloud expands to fill a cone with semi-angle 20° as it moves away from the star at a velocity of 200 km s^{-1}. The model scatters starlight off dust grains in the clouds to an optical depth of 1. As the cloud moves away from the star, the number density decreases and the starlight penetrates further into the cloud, which becomes optically thin about 35 days after ejection. For the spherically symmetric case, clouds are ejected at random angles once every 40 days. Because the outer clouds contribute an extremely small amount of scattered flux, the total expected polarization results from the sum of individual *Q* and *U* values for only the nearest 10 clouds. Brightness minima occur whenever a cloud is ejected within a cone of semi-angle 30° centered on the star pointed toward the observer. This condition restricts the output of the model to only the events where all or part of the stellar disk is obscured by the most recently ejected cloud, as is the case in all three sets of data considered here.

The predicted amount of polarization as a fraction of the total flux from the system does not exactly match observations, because the model does not correctly account for the obscuration of the direct, unpolarized starlight in the calculation of the polarization of the system. However, the *relative* positions of the points in the *Q-U* plane are correct. Linear correlation tests of three randomly chosen data sets produced by the model give a correlation coefficient $r = 0.01$ at a 1% confidence level. Thus, the spherically symmetric ejection model predicts that tracks in the *Q-U* plane will not define a single line for different brightness minima, in contrast to the observations shown in Figure 2 of three separate minima.

IV. DISCUSSION

We now discuss a number of possible explanations of the preferred-plane ejection mechanism. Rapid rotation could induce a deformation about the equator of the star which might lead to a higher probability of forming dust in the cooler regions of the extended atmosphere. A similar mechanism has met with some success in the modeling of the winds of Be stars, which are observed to have large values of $v \sin i$ (Poe 1987). However, R CrB has $v \sin i = 18$ km s^{-1} (Uesugi and Fukuda 1970), so the rotationally induced ejection mechanism is very unlikely.

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The binary system model of Humphreys and Ney (1974) offers another explanation of the preferred-plane ejection mechanism. This model is based on an observed periodicity of about 3.5 yr in 3.5 μm data and posits that the visual light variations are due to dust clouds ejected from a cool companion, not from the primary supergiant of the R CrB system. To explain the brightness minima, their model supposes that the supergiant is occulted as it moves through the shell of ejected dust clouds surrounding the companion. If the clouds in the shell were forced into the orbital plane by gravitational interaction with the supergiant, then the passage of the supergiant through the plane of the clouds would produce the observed polarization. But given that no spectroscopic or photometric observations of the system have turned up any evidence of a close companion, the likelihood of this explanation seems remote also.

A related idea comes from Iben and Tutukov (1985) who theorize that the R CrB class originated from the merger of two close, evolved dwarfs. The smaller He dwarf would overflow its Roche lobe so severely as to form a disk about the CO dwarf. Over time the disk would be accreted in the merger model. Some support for this idea is found in its predictions of the abundances of C, N, and O relative to Fe, which match the estimates derived by Cottrell and Lambert (1982), and in the number of extreme He supergiants in the Galaxy, which is correctly predicted to be 1300 ± 700. If we happen to be observing the system during the latter part of the merger sequence then we might see a preferred plane for cloud ejections in the same plane as the nearly accreted disk.

Other stellar evolution studies (Iben *et al.* 1983), which attempt to describe the R CrB stars as the central stars of planetary nebulae just after the final helium pulse, point to another way of explaining the preferred plane of ejections. Such central stars sometimes become magnetic white dwarfs. The beginnings of a magnetic field at the R CrB stage could be responsible for the selective formation of dust, or for biasing polarization observations of such dust because of alignment of the dust grains by the field. But, given the very small fields typical of supergiants, this mechanism is also unlikely.

The last idea we consider is that of pulsations. The existence of pulsations in R CrB and RY Sgr appears to be well established (Feast 1975; Fernie, Percy, and Richer 1986) but the connection with dust cloud ejection is tenuous. Pugach (1977) and Goncharova, Kovalchuk, and Pugach (1983) find that fadings of R CrB tend to begin in a restricted range of phase from statistical studies of observed fadings. But Percy, Carriere, and Fabro (1987) find no significant connection between the times of the onset of fadings and the pulsational period of R CrB. Holm and Doherty (1987) use a combination of variations in photospheric temperature due to pulsations and in dust obscuration to fit the *IUE* spectrum of R CrB during a small dip in 1982. They find that, if the amount of obscuring dust varies with the drop in temperature but with a lag in time, their model gives the observed wavelength dependence of the amplitudes and phase shifts of the light curves. Thus, the idea of pulsations being the cause of the temperature variation is consistent with the observed radial velocities.

The problem, of course, is that their model assumes radial pulsation whereas a preferred ejection plane is associated with nonradial pulsation. For example, the mode described by the spherical harmonic parameters $l = 1$ and $m = 0$ would produce a bulge around the equator once every pulsation period. The outer atmosphere above such a bulge would be cooler than other parts of the atmosphere, so that dust would be more likely to form in the plane defined by the bulge. Being formed at a larger than average height above the surface of the star where the gravity is lower, such dust would then be more easily driven from the star by radiation pressure. Jeffrey *et al.* (1985) show spectroscopic and photometric evidence of nonradial pulsations in the g-mode for the extreme helium star BD $-9°4395$, which is very similar to R CrB. Calculations of such pulsations have not yet been undertaken for R CrB. Such a mechanism appears to be the most likely candidate for explaining the preferred ejection plane. To test this idea we need to modify our model so that it takes into account nonradial pulsation modes and axisymmetric ejections. Most importantly, polarimetric observations of R CrB and other members of this class must be made during every decline in brightness to see if the observed pattern of Q-U variations continues. Such data will then provide the means for testing the predictions of a nonradial pulsation model.

The authors acknowledge support from the contract NAS5-26777 for the Wisconsin Ultraviolet Photo-Polarimeter Experiment to the University of Wisconsin, J. D. Fernie for providing unpublished photometry of R CrB during the 1986–1987 period, and several helpful conversations with A. D. Code.

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