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SPECTROPHOTOMETRY OF R CORONAE BOREALIS DURING THE MINIMUM OF 1974

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ABSTRACT

Spectrophotometric observations of R Coronae Borealis were obtained as the star returned to normal brightness during the minimum of 1974. Absolute flux distributions and extinction optical thicknesses were determined for those nights on which observations were made. The optical thicknesses were found to be consistent with extinction by spherical graphite particles having radii of about 0.07 μ. No trend toward either an increase or a decrease in particle size was detected. A close fit to the rising branch of the visual light curve of R CrB was obtained using a simple model in which the return to maximum brightness of R CrB is caused by the radiation pressure dispersal of a cloud of graphite particles.

Subject headings: spectrophotometry — stars: circumstellar shells — stars: individual — stars: R Coronae Borealis

I. INTRODUCTION

The model for the light variations of R Coronae Borealis originally proposed by Loreta (1934) and extended by O'Keefe (1939), in which the sudden and deep decreases in brightness are caused by the condensation of graphite particles, has been considerably strengthened in recent years by measurements of the infrared radiation of R CrB and the polarization of its light. The infrared excess reported by Stein *et al.* (1969) and Forrest, Gillett, and Stein (1971, 1972) is a clear indication of the presence of circumstellar particles while the polarization measurements of Coyne and Shawl (1973), made during the minimum of 1972, are consistent with the polarization which could be produced by graphite particles with sizes between 0.05 and 0.10 μ. A further test of the particle model would be to determine whether the flux distribution of R CrB during the time of reduced brightness is just the flux distribution at maximum brightness extinguished by a cloud of small graphite particles. In order to carry out such a test, we have made spectrophotometric observations of R CrB as it returned to normal brightness during the minimum of 1974.

II. OBSERVATIONS

The observing program began shortly after R CrB reached minimum brightness and included observations made in 1974 between March 13 and October 10 and on 1975 May 15. The observations were made using the University of Iowa 61 cm telescope and a photoelectric spectrophotometer which has been described by Neff and Clements (1972, 1973). The instrumental profile was triangular with a full-width at half-maximum response of 62 Å, and measurements were made at 62 Å intervals in the region between 3351 and 5768 Å. A number of standard stars were measured nightly for use in computing atmospheric extinction, while α Lyr was scanned each night to determine instrumental sensitivity and to serve as the basis for the calculation of the absolute flux distribution of R CrB.

III. DISCUSSION

The absolute flux distribution of R CrB was determined for each night by multiplying the relative flux distribution by a scale factor which was found from observations of α Lyr and the absolute flux distribution of α Lyr adopted by Neff *et al.* (1975). The resulting absolute flux distributions of R CrB are shown in Figure 1. It is clear that R CrB became progressively bluer as it returned to normal brightness. Uncertainties in the absolute flux of α Lyr, the relative fluxes of R CrB and α Lyr, and the scale factors combine to produce probable errors in the absolute fluxes of R CrB which are typically about 12 percent. Under the assumption that the flux distribution of R CrB during the period of reduced brightness is just the flux distribution at maximum brightness extinguished by a cloud of small particles, we have calculated, for each night, the optical thickness required at each wavelength to produce the observed flux distribution from the flux distribution at maximum light. We have assumed that the flux distribution obtained on 1975 May 15 may be used for the flux distribution at maximum light. We found that the optical thickness generally increased linearly with wavenumber, so we have therefore normalized the optical thicknesses to the value of 5458 Å and calculated linear least squares fits to the optical thickness–wavenumber relationship for each night. The slopes of the least squares fits are given, along with their standard deviations and the correlation coefficients of the fits, in Table 1. Although the slope of the optical thickness–wavenumber relationship became increasingly difficult to determine

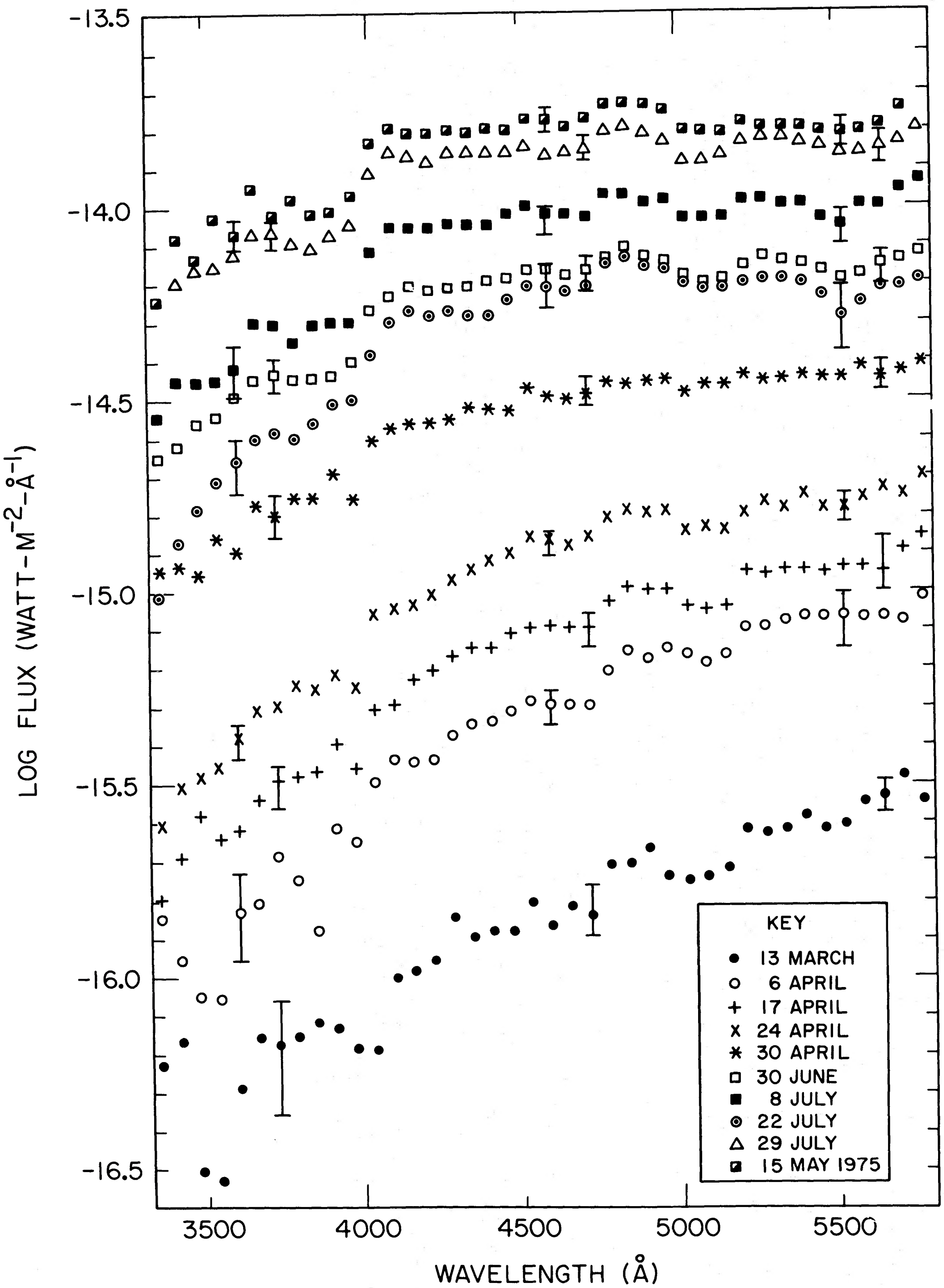

FIG. 1.—Absolute flux distribution of R CrB in watts m^{-2} Å^{-1} versus wavelength in angstroms for indicated nights. March 20 and October 10 were omitted for clarity. The typical error bars shown are ±1 standard deviation.

TABLE 1

RESULTS DETERMINED FROM THE OBSERVATIONS

Date (1974)	Slope (microns)	Standard Deviation of Slope	Correlation Coefficient	Particle Size (microns)	Column Density (particles m^{-2})
March 13..........	0.229	0.026	0.825	0.075	9.7×10^{13}
March 20..........	0.292	0.015	0.958	0.073	9.2×10^{13}
April 6............	0.471	0.020	0.971	0.069	7.2×10^{13}
April 17...........	0.366	0.014	0.978	0.072	6.2×10^{13}
April 24...........	0.384	0.012	0.983	0.071	5.1×10^{13}
April 30...........	0.254	0.023	0.892	0.074	3.3×10^{13}
June 30............	0.223	0.022	0.881	0.075	1.9×10^{13}
July 8.............	0.442	0.066	0.772	0.070	1.2×10^{13}
July 22............	0.328	0.040	0.838	0.072	2.1×10^{13}
July 29............	1.310	0.357	0.570	0.033 0.055	0.4×10^{13}
October 10.........	17.461	15.587	0.211	...	...

as R CrB brightened and optical thickness decreased, the large values of the correlation coefficients show that a linear relationship between optical thickness and wavenumber is a reasonable one.

In order to compare the results of our measurements to the extinction produced by small graphite particles, we have computed the extinction efficiency factors for graphite spheres having sizes between 0.001 and 3.0 μ for six wavelengths in the region corresponding to our observations. Except for particle sizes between 0.08 and 0.09 μ the dependence of extinction efficiency factor on wavenumber was linear, so we have normalized the extinction efficiency factors to the value at 5458 Å and calculated the least squares slope of the extinction efficiency factor–wavenumber relationship. This slope is shown versus particle size in Figure 2. The slopes of the measured optical thickness–wavenumber relationships have been used with Figure 2 to determine the particle sizes for the various nights. The particle sizes found in this way, except for the ambiguity on the night of July 29, lie between 0.069 and 0.075 μ and thus fall within the range of particle sizes found by Coyne and Shawl (1973) from their polarimetric study of R CrB during the 1972 minimum. Unlike Coyne and Shawl, we found no indication of a significant change in particle size during the course of these observations. However, the polarimetry of Coyne and Shawl was carried out before the time of minimum brightness as well as afterward, whereas our observations were entirely confined to the rising branch of the light curve. The particle size and column density of 0.072 μ size particles required to produce the observed extinction are given, for each night, in Table 1.

Since our spectrophotometry is consistent with the extinction of the normal spectrum of R CrB by a cloud of small graphite spheres, and since we found no evidence for changing particle size as R CrB returned to normal brightness, we have attempted to match the rising branch of the 1974 light curve of R CrB using a simple model in which a cloud of graphite spheres having radii of 0.07 μ is dispersed by radiation pressure. In order to use the Planck mean radiation pressure efficiency factors calculated for graphite by Gilman (1974), we have assumed that the normal spectrum of R CrB can be characterized as blackbody radiation of the same temperature as that of R CrB (about 6000 K). By further assuming that the graphite particles are fully grown by the time of minimum brightness and are moving freely away from R CrB at that time, we can calculate model light curves which depend on the optical thickness of particles at the time of minimum brightness and the distance and velocity of the particle cloud at that time. We find that the choice of initial velocity is relatively unimportant in determining the shape of the resulting light curve and that for an initial optical thickness of 4.6 (at visual wavelengths) and an initial cloud distance of 100 stellar radii we can obtain a good match to the rising branch of the visual light curve of R CrB as measured by the AAVSO. The computed light curve, as well as a visual light curve kindly provided by the AAVSO (Mattei 1974) and our measured magnitudes 5556 Å, are shown in Figure 3. We find that if the initial cloud distance is chosen to be much smaller than 100 stellar radii, the calculated light curve rises too steeply because the particles are too rapidly dispersed. Correspondingly, the calculated light curve does not rise rapidly enough if an initial cloud distance much larger than 100 stellar radii is chosen.

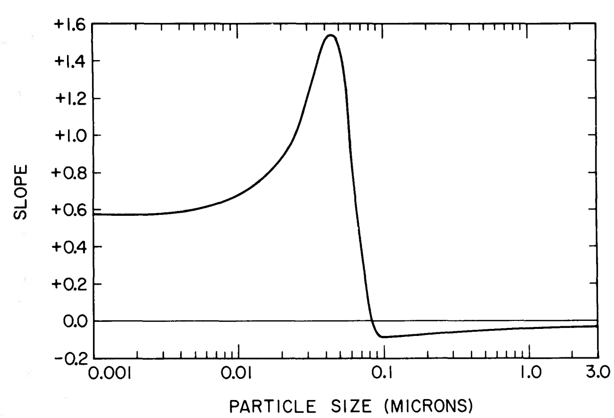

FIG. 2.—Slope of normalized extinction efficiency factor–wavenumber relationships in microns versus particle size in microns for graphite.

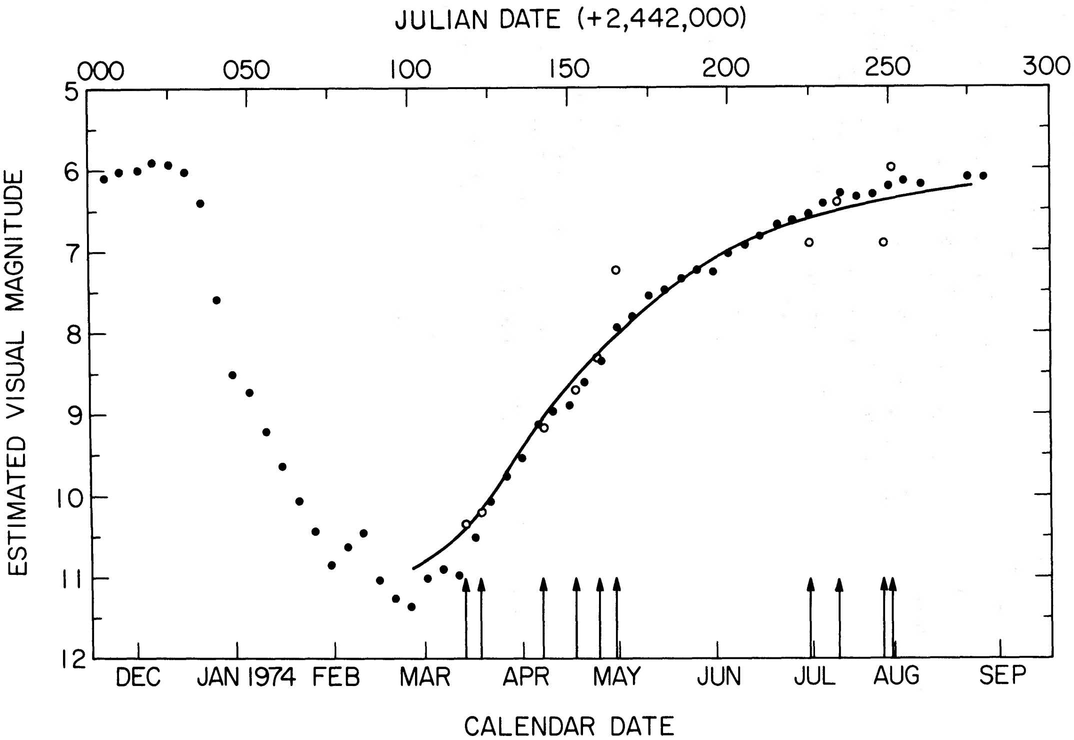

FIG. 3.—Light curve for R CrB, Julian date 2,442,000 to 2,442,300. *Filled circles*, 5-day means of visual estimates provided by the AAVSO. *Open circles*, photoelectric magnitudes at 5556 Å obtained on dates of observations indicated by arrows. The smooth curve is the result of the radiation pressure dispersal model described in the text.

IV. CONCLUSION

Our spectrophotometric measurements of R CrB are consistent with a model in which the reduced brightness of R CrB is caused by the condensation and dispersal of a cloud of small graphite particles. Observations of the kind reported here should be made during the descending branch of a future minimum of R CrB in order to determine whether the decline to minimum brightness can be modeled by the growth and motion of small graphite particles. Failure to detect any change in the radius of the particles during the decline to minimum brightness would be a serious obstacle for the particle model of the variations of R CrB.

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