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EXOSAT OBSERVATIONS OF THE SUSPECTED FLARE STAR BD +48°1958A

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ABSTRACT

We present the first X-ray observations of the BY Dra type of variable BD +48°1958A using the low-energy (LE) and the medium-energy (ME) detectors of the *EXOSAT* observatory. The star is detected in both the LE and the ME detectors, and we find some evidence for a long-duration (>2 hr) X-ray flare. We have carried out a combined spectral fit to the LE and ME data and derived an X-ray plasma temperature of 1.6 ± 0.4 keV during the quiescent state and a temperature of 5.0 ± 1.4 keV during the flare, using the plasma emission models given by Raymond and Smith. The X-ray luminosity in the 0.1–4.0 keV energy band is 2.7×10^{29} ergs s^{-1} during the quiescent state, and a nearly 20% increase in the X-ray flux is detected during the flare. The X-ray luminosity and the temperature are typical of a dMe type flare star. We suggest that (*a*) BY Dra type of variability is conducive to flare activity and (*b*) the study of X-ray emission from BY Dra type of variables is an important tool for understanding the flare activity among them.

Subject headings: stars: flare — stars: individual (BD +48°1958A) — stars: X-rays

I. INTRODUCTION

The visual pair BD +48°1958A, B (=ADS 8242 A, B = McC 283; separation 1".8) consists of two dwarfs, both of spectral type near M0. The distance to the star is estimated to be 22.7 pc from the photometric parallax (Eggen 1968). The brighter component, BD +48°1958A (=DF UMa), is a single-line spectroscopic binary with an orbital period of 1.03 days (Bopp and Fekel 1974). It shows several characteristics typical of a dMe flare star, such as BY Draconis type photometric variability (Bopp and Espenak 1977), strong Ca II H and K emission, and variable Hα emission (Bopp 1974). The possibility that it is a flare star was first suggested by Mumford (1956), who found that its color was too blue for its spectral type. Bopp and Fekel (1974) obtained a distinctly double Hα line in one (out of about 30) spectrograms from BD +48°1958A, with a velocity separation of about 130 km s^{-1}, which was interpreted as a flare on the normally unseen secondary. Several hours of photometric observation, however, failed to detect any optical flare from this source (Bopp 1974).

BD +48°1958A is the only single-line spectroscopic binary of dwarf M type known so far. Normally, all late-type (dK and dM) spectroscopic binaries are BY Dra types of variables (Bopp and Fekel 1977), and most of the BY Dra types of variables are flare stars (Pettersen 1983). There is little direct evidence for flare activity in BD +48°1958A, except perhaps from its unseen companion as pointed out above. On the other hand, coronal X-ray emission is a good diagnostic of flare activity, the X-ray luminosity being well correlated with the bolometric luminosity (Agrawal, Rao, and Sreekantan 1986; Pallavicini, Tagliaferri, and Stella 1990). Hence, it is very interesting to examine the coronal X-ray emission of BD +48°1958A. The star was observed using the *EXOSAT* (*European X-Ray Astronomy Satellite*) Observatory in 1985. We have obtained and analyzed the X-ray data from the *EXOSAT* archives. Here we present the details of the observations and the results of our analysis.

II. OBSERVATIONS

The X-ray observations were performed on 1985 December 16, using both the medium-energy (ME) detectors and the low-energy (LE) telescope having a channel multiplier array (CMA) as the detector. The ME detectors are sensitive to X-rays in the energy range of 1–10 keV, whereas the LE + CMA combination detects softer X-rays in the energy range of 0.1–2.0 keV. The details of the instruments used are given by Turner, Smith, and Zimmermann (1981) for the ME detectors and by de Korte *et al.* (1981) for the LE + CMA. The particulars of the observations are given in Table 1. The observations lasted for 6 hr, starting from 3 hr UT on 1985 December 16, which covers the binary phase 0.75–1.00 of BD +48°1958A. The LE data were obtained with three filters: namely, Lexan 3000 (LX3), aluminum/parylene (Al/P), and boron (BOR) (see White and Peacock 1988 for filter efficiencies). The ME data analyzed were acquired from seven of the eight argon-filled detectors, as detector 3 was off throughout the observations. These observations were carried out by first pointing the first three detectors (viz., detectors 1, 2, and 4, collectively known as the half 1 detectors) at the source while the other four detectors (viz, 5, 6, 7, and 8, collectively known as the half 2 detectors) monitored the background. The roles of the two halves were exchanged later on, and the observations continued.

III. ANALYSIS AND RESULTS

The data reduction and analysis were performed using the XANADU (X-Ray Analysis and Data Utilization) software package.

a) *The LE Data*

We detected only one X-ray source within 1° of the center of the LE field of view. The X-ray image position is within 8" of the optical position of the source (Caillault, Drake, and Florkowski 1988), which is consistent with the source location accuracy with *EXOSAT* (see Gronenschild 1985). The background-subtracted count rates corrected for vignetting, telemetry dead time, and the sum-signal distribution are shown in Table 1. The background was obtained from a region adjacent to the position of the source.

The background-subtracted count rates are shown in Figure 1, with 1000 s time resolution for the LX3 and the Al/P filters,

TABLE 1

LOG OF *EXOSAT* OBSERVATIONS ON 1985 DECEMBER 16 AND THE COUNT RATES

Detector Combination	Start time (UT)	End time (UT)	Exposure Time (s)	Count Rate[a] (10^{-4} cm^{-2} s^{-1})
CMA + LX3	$3^h15^m48^s$	$4^h14^m51^s$	3102.5	3.62 ± 0.44
CMA + Al/P	4 18 36	6 11 55	5214.5	1.35 ± 0.25
CMA + boron	6 24 10	8 59 39	8971.5	0.38 ± 0.16
ME(half 1)[b]	2 54 58	6 15 08	10891.7	3.40 ± 0.67
ME(half 2)	6 40 00	8 53 00	7206.6	0.87 ± 0.53

[a] Between 1.5 and 6 keV for the ME detectors.
[b] Detector 3 was not active.

and for the complete duration of the BOR filter data. The flarelike appearance of the light curve is due to the different filters used at different times. Individually, there is no evidence of variability in the count rates obtained from each filter. The average count rates obtained in each filter are mutually consistent with a constant source hypothesis for a wide variety of temperatures (see Pallavicini *et al.* 1988 for the variations of count rate ratios with temperature). There is, however, an indication of a decrease in the count rate as observed from the Al/P filter. The data from 1.5×10^4 to 2×10^4 s show a marginal decrease. A constant source hypothesis gives a χ^2 of 4.9 for five data points, and it decreases to 1.03 if a linear term is added. This decrease in the χ^2 is significant at a confidence level of 95% using the F-statistic. Hence there is marginal evidence for a flarelike behavior, which is further strengthened by the ME data (see below).

b) *The ME Data*

For the analysis of the ME data we have used the background obtained from the same detectors while offset from the source. The count rates obtained are listed in Table 1. As can be seen from this table, the count rates obtained from half 1 are a factor of 4 higher than that obtained from the half 2 detectors. The background-subtracted ME light curve is shown in

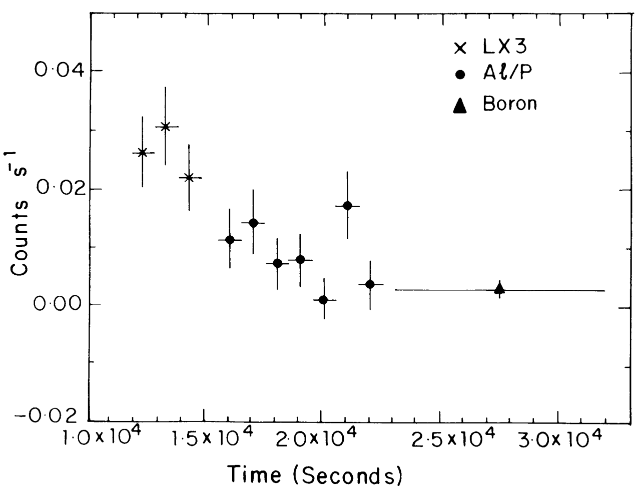

FIG. 1.—Background-subtracted soft X-ray light curve of BD +48°1958A, obtained with the LE using LX3 (*crosses*), Al/P (*filled circles*), and BOR (*triangles*) filters. The apparent decrease in the count rate is an artifact of different filter efficiencies. The bin size for the LX3 and Al/P data is 1000 s.

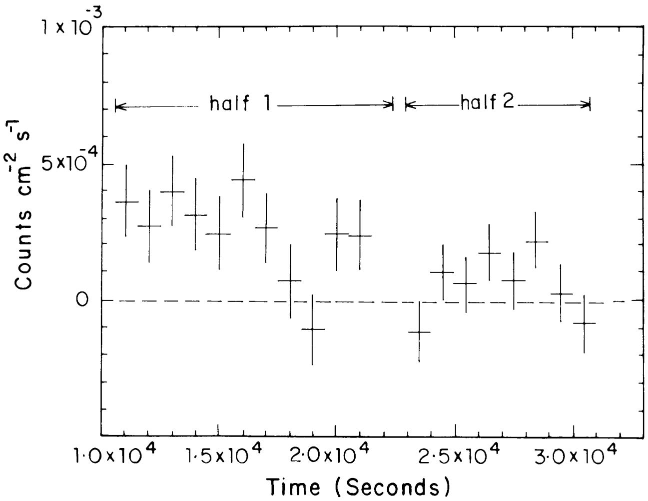

FIG. 2.—1.6–6.0 keV light curve of BD +48°1958A obtained from the ME detectors after background subtraction. The durations of observations with the ME half 1 and the half 2 detectors are indicated.

Figure 2. The counts remained at a high level for about 6000 s, and decreased in about 4000 s and showed another increase. The reality of the count rate decrease is verified by the F-statistic. The hypothesis of a constant source gives a χ^2 of 13.4 (for 11 degrees of freedom), and, by neglecting the two data points which show a marked count rate decrease, the χ^2 decreases by 10.9, which has a significance level of greater than 99%. Alternately, the decreasing part of the light curve (1.55×10^4–1.95×10^4 s) has a χ^2 value of 9.5 (4 dof) for constant source hypothesis, and decreases by 9 if a linear term is added (where the confidence level is greater than 99%). There is a data gap of 1500 s duration, when the detectors were switched off for a brief period. The count rates were a factor of 4 lower during the 7000 s of observation afterward. We would like to point out that the durations of the high and low count rates were obtained with two different sets of detectors, and such decrease could also be due to inaccurate background subtraction. We rule out this possibility, however, because our examination of individual detectors shows that the count rate difference is seen in each of them. Further, the decrease in the ME count rate is contemporaneous with a similar trend seen marginally with the LE detectors using the Al/P filter.

We have cross-correlated the simultaneously obtained ME and LE (with the Al/P filter) count rates and found a positive correlation with a coefficient of 0.23 for 68 data points (confidence level 94%). No significant correlation (significance of correlation ~20%) is found between the LE and the background counts obtained contemporaneously with the half 2 detectors. It therefore appears that the X-ray emission from this star is variable. In this context, the observed characteristic seems to resemble long duration multipeaked flares (unresolved here due to low count rate) seen in other flare stars. For example, the flare star YZ CMi showed a multipeaked broad enhancement of about 4000 s duration in the LE light curve (Fig. 6 in Pallavicini, Tagliaferri, and Stella 1990). The count rate decreased in about 2000 s and showed another increase, a behavior quite similar to that seen for BD +48°1958A (Fig. 2). Henceforth, we would refer to the high count rate data as belonging to a "flare," and the rest of the data would be treated as a quiescent state data.

c) *Spectral Analysis*

The pulse-height information obtained from the LE and the ME detectors can be used to provide a spectral estimation. The background information for the ME data is obtained from the same detectors, using the "swap" technique (Smith 1984). The subtracted counts were further corrected by using the accumulated "difference" spectra—the difference in the background spectra acquired while in the offset position and aligned position, resulting due to changed environment and shielding. The difference spectra used were provided in the ME calibration file and obtained close to the actual observation time of the source. We have used the Raymond-Smith plasma-emission models (Raymond and Smith 1977; Raymond 1986) to estimate the spectral parameters of the X-ray emission from BD +48°1958A. Addition of an absorbing interstellar column density always gave zero absorption, and, therefore, it was neglected while fitting the data. The spectral modeling was attempted separately for the ME half 1 with the LE LX3 and the Al/P filters (taken as the flare spectra) and the ME half 2 with the LE BOR filter (taken as the quiescent state spectra). A best-fit temperature (kT) of 5.0 ± 1.4 keV (90% confidence limits 3.2–8.7 keV) is obtained for the flare spectra ($\chi^2 = 12.9$ for 29 degrees of freedom). The observed pulse height spectrum (during the flare) is shown along with the best-fit model (drawn as a histogram) in Figure 3. For the quiescent state spectrum, the best-fit temperature is 1.6 ± 0.4 keV (90% confidence limits 1.0–3.2 keV). The observed pulse height data is shown in Figure 4 along with the best-fit model ($\chi^2 = 18.2$ for 19 dof).

The adopted method of applying the difference corrections to the half ME arrays does not always yield a reliable background-subtracted spectra (see Yaqoob, Warwick, and Pounds 1989); therefore, we also obtained the spectral data from those ME detectors that were in the "corner" configuration (viz., detectors 1, 4, 5, and 8) and immune to such corrections. The analysis of the spectral data thus obtained gave estimates of the spectral parameters that were identical to the ones quoted above, but with higher error limits.

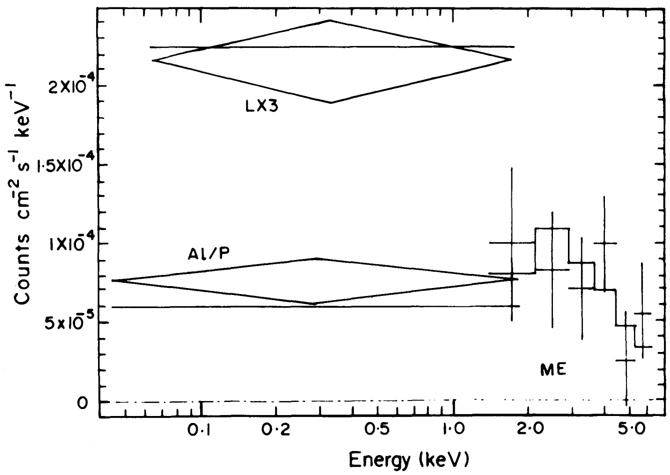

FIG. 3.—Observed count rate spectrum of BD +48°1958A obtained using the LE (LX3 filter and Al/P filter) and the ME half 1 detectors of the *EXOSAT* observatory, during the "flare" observation (see text). The best-fit spectrum using the Raymond-Smith plasma emission model ($kT = 5$ keV) is shown as a histogram. The zero level is shown as a dash-dotted line.

IV. DISCUSSION

The quiescent state X-ray luminosity (L_x) of the triple system BD +48°1958A, B, as estimated from the spectral fit to the data and using a distance of 22.7 pc, is 2.7×10^{29} ergs s^{-1} in the 0.1–4.0 keV band. Using the cooling curves given by Raymond, Cox, and Smith (1976), the emission measure is calculated to be 1.4×10^{52} cm^{-3}. The visual companion BD +48°1958B is a "nonemission" type dM0 star (Bopp and Fekel 1974) and should contribute ~10% to the X-ray luminosity (Agrawal, Rao, and Sreekantan 1986). The unseen spectroscopic companion of BD +48°1958A is estimated to be 2–3 mag fainter (Bopp and Fekel 1974) and hence will contribute ~10% to the X-ray luminosity if it is an "emission-type" star and ~1% if it is a "nonemission" type. Hence we can attribute the bulk of the observed X-ray flux to BD +48°1958A.

The bolometric luminosity (L_{bol}) of BD +48°1958A is 3.0×10^{32} ergs s^{-1} (the bolometric correction is calculated using the method given by Pettersen 1983). This gives an L_x/L_{bol} value of $10^{-3.1}$. The values of L_x and L_{bol} agree (within 0.2 dex) with the general trend in these two parameters for a population of flare stars studied by Agrawal, Rao, and Sreekantan (1986) and Pallavicini, Tagliaferri, and Stella (1990). The quiescent state coronal X-ray temperature (1.6 keV) obtained for BD +48°1958A agrees with the high-temperature solution obtained for the flare stars by Pallavicini *et al.* (1988) and also with the coronal temperature (1.4 to 1.8 keV) measured for the rapidly rotating K dwarf AB Dor (Collier-Cameron *et al.* 1988) and rapidly rotating M dwarf Gl 890 (Rao and Singh 1990).

We follow the method suggested by Pallavicini, Tagliaferri, and Stella (1990) to determine the parameters of the "flare" detected during our observations, which is most likely due to the more active component of the system BD +48°1958A. The average excess flare luminosity is 5.8×10^{28} ergs s^{-1}, and the total flare energy is 5.8×10^{32} ergs. The emission measure during the flare is about 3×10^{51} cm^{-3}. Assuming that the decreasing trend seen in the LE and the ME light curves is of the order of the flare decay time, we obtain the electron density as 2×10^{11} cm^{-3}, by equating the flare decay time to the radiative cooling time. The flare loop length is calculated to be 2×10^{10} cm by assuming that the observed emission measure

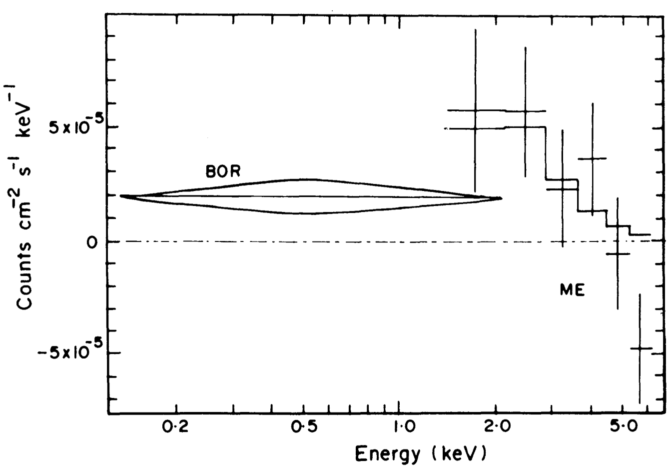

FIG. 4.—Quiescent state count rate spectrum of BD +48°1958A as observed with the LE (BOR filter) and the ME half 2 detectors. The best-fit temperature is 1.6 keV (line style as in Fig. 3).

originates from a single loop. The calculated loop length is about half the stellar radius and about a quarter of the interbinary separation (see Pallavicini, Tagliaferri, and Stella 1990 for the assumptions involved in the above calculations). These values are similar to those derived by Pallavicini, Tagliaferri, and Stella (1990), for several X-ray flare observations from flare stars.

There are 11 confirmed M type BY Dra variables, of which 10 are flare stars. On the other hand, only five K type BY Dra variables are known to be flare stars (Pettersen 1983). It is known that intrinsically brighter stars have lower flare frequency (Kunkel 1975), and therefore we think that the nondetection of flaring activity in all the BY Dra type variables is only an observational selection effect. We suggest that all BY Dra type of variables are flare stars and long duration observations are needed to detect flaring activity in stars of spectral type earlier than M. For example, for BD +48°1958A the estimated flare frequency is about once in 48 hr (using the formulation of Kunkel 1975).

Finally, we wish to point out that both flaring and spot activity are manifestations of emerging magnetic fields from stellar convection zones due to dynamo effects. The coronal X-ray emission is a measure of the magnetic activity, and hence, sensitive X-ray observations can be very useful in identifying a flare star. First, the quiescent state X-ray luminosities of flare stars are well correlated with (*a*) their bolometric luminosity (Agrawal Rao, and Sreekantan 1986; Pallavicini, Tagliaferri, and Stella 1990) and (*b*) with the average flare energy emitted in the *U* band (Doyle and Butler 1985). Second, it is observationally easier to detect a flare in the X-ray band for intrinsically brighter stars. For example, several X-ray flares are detected in the RS CVn binaries (Agrawal, Rao, and Reigler 1986)—another class of active stars with spot activity like in the flare stars, but intrinsically brighter than them, whereas optical flares have been extremely hard to observe from these stars. Study of the X-ray emission of the BY Dra variables as a class is, therefore, not only interesting in itself but can also be an important tool to discern their membership in the flare star category, as has been borne out by the observations presented here.

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