

EXOSAT observations of variable coronal X-ray emission from the young K dwarf AB Doradus (=HD 36705)

A. Collier Cameron,^{1,2} D. K. Bedford,³
S. M. Rucinski,⁴ O. Vilhu⁵ and N. E. White⁶

¹ *Astronomy Centre, University of Sussex, Falmer, Brighton BN1 9QH*

² *Institute of Astronomy, Madingley Road, Cambridge CB3 0HA*

³ *Department of Space Research, University of Birmingham, PO Box 363, Birmingham B15 2TT*

⁴ *David Dunlap Observatory, Box 360, Richmond Hill, Ontario, Canada L4C 4Y6*

⁵ *Observatory and Astrophysics Laboratory, University of Helsinki, SF-00130 Helsinki 13, Finland*

⁶ *EXOSAT Observatory, ESTEC, 2200 AG Noordwijk, The Netherlands*

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Summary. We present the results of a search for rotationally-modulated X-ray emission from the young K0 dwarf AB Doradus, using the low- and medium-energy detectors on board the *EXOSAT* spacecraft. Two sets of observations were obtained, each covering all or nearly all of the 0.514 day rotation period of the star, in 1984 December and 1986 January. A single large stellar X-ray flare occurred during each observation. The long rise-times (~ 6000 s) observed for both these flares suggest that they occurred in loop structures with lengths of several stellar radii. During quiescence, the amplitude of variability seen at low energies (0.05–2.0 keV) was significantly greater than that in the 2.0–5.0 keV band. The 1.0–10.0 keV pulse-height spectra obtained with the medium-energy experiment are well-fitted by thermal bremsstrahlung at $\sim 1.9 \times 10^7$ K, with possible excess emission at lower energies. The data are consistent with a model in which a range of coronal loop temperatures are present, the cooler loops tending to be confined closer to the stellar surface and thus being subject to rotational self-eclipse, while the hotter loops extend at least one stellar radius above the photosphere. The emission measure observed during quiescence was $(1.5 \pm 0.3) \times 10^{53} \text{ cm}^{-3}$ for an assumed distance of 20 pc. If the emitting region is to be confined within a pressure scale height or so above the photosphere, and if the pressure in the transition region at the base of each loop is to be no greater than 10–20 dyn cm⁻², a high volume filling factor and hence some global ordering of the field configuration is likely.

1 Introduction

The X-ray emission observed from many stars with spectral types later than early F is thought to originate in plasma at temperatures between 10^6 and a few times 10^7 K, confined in closed magnetic loop structures similar to those observed in the solar corona. The quiescent coronal X-ray temperatures and luminosities of late-type stars increase dramatically with increasing rotation rate, and hence presumably with increasing dynamo-generated magnetic flux at the stellar surface (Walter & Bowyer 1981; Pallavicini *et al.* 1981). Some information on the structure of a stellar corona can be gleaned from X-ray spectroscopy. The spectra of late-type stellar coronal X-ray sources are usually well-fitted by thermal emission models. It has been found that a single plasma temperature rarely gives a satisfactory fit to the observed 0.5–10 keV spectra of active late-type stars obtained with the *Einstein* and *EXOSAT* observatories, but double or multiple temperature components with temperatures ranging from solar values of a few times 10^6 up to a few times 10^7 K give greatly improved fits. These in turn allow loop dimensions to be estimated for assumed mean densities and volume filling factors (Swank *et al.* 1981).

A more detailed picture of the relationships between loop sizes, temperatures and densities can be obtained using time-resolved X-ray spectroscopy during the eclipse of a discrete emitting component in the stellar corona. Previous attempts at mapping the radial structures of stellar coronae in this way have been restricted to the eclipsing binary systems AR Lac (Swank & White 1980; Walter, Gibson & Basri 1983; White *et al.* 1987b), Algol (White *et al.* 1986) and ER Vul (White *et al.* 1987a). The evidence for eclipses of the 10^7 K X-ray emission in these studies is marginal, and generally indicates that the coronal scale heights in the active, cool subgiants in these binaries are at least equal to the stellar radius. However, stronger eclipse effects and rotational modulation have been observed at X-ray energies lower than 1 keV in AR Lac (White *et al.* 1987b), indicating that the 10^6 K component may be confined in more compact structures with scale heights of order $0.1 R_\odot$.

The southern K0 dwarf AB Doradus (=HD 36705) is one of the most rapidly rotating late-type stars known. Its proximity to the Sun, its known X-ray emission and its short rotation period make it an ideal candidate for the study of spatial inhomogeneities in the lower part of the corona of a single dwarf star. As the star rotates, discrete X-ray emitting structures located at low latitudes and less than a stellar radius or so above the photosphere will undergo rotational self-eclipse. This star is therefore of particular interest in establishing the effects of increased rotation and dynamo-generated surface magnetic flux on the distribution of loop-sizes, temperatures and plasma densities in active lower main-sequence stars.

AB Dor was first noted as a strong late-type Ca II emitter by Bidelman & MacConnell (1973) and by Houk & Cowley (1975). Pakull (1981) identified it as the probable optical counterpart of the flaring X-ray source 1E 052840–6529.5, discovered in the course of an *Einstein* survey of the LMC region in 1979. In an optical follow-up study, Pakull discovered the star to have RSCVn-like photometric variability with an amplitude of up to 0.12 mag in *V* and a rotation period of 0.51423 day. In a spectroscopic study of the same star, Collier (1982) measured an equatorial rotation speed $V \sin i = 75 \pm 5 \text{ km s}^{-1}$ but found no evidence for radial velocity variations and so identified it tentatively as a new member of the FK Com class of highly active, rapidly rotating giants. However, the discovery by Rucinski (1982) of a strong lithium absorption feature suggested that the star might be a young, rapidly rotating K0–K2 dwarf.

Although no direct parallax measurement has yet been made for this star, Innis, Thompson & Coates (1986) obtained a dynamical parallax by identifying it as a probable member of the Pleiades moving group. In this case, the proper motion and radial velocity give a distance in the range 27 ± 7 pc. A main sequence fit to the 13th mag dMe visual companion Rossiter 137B, which has a common proper motion with AB Dor and an angular separation of 9 arcsec, yields a

distance of 20 ± 5 pc. Both distances are consistent with a distance estimate of 20–30 pc obtained by Rucinski (1985) based upon the strength of the interstellar Mg II *h* and *k* absorption observed in this star with the *IUE* satellite.

The apparent magnitude ($V=6.95$) and colour ($V-R_{\text{Cousins}}=0.495$) yield an angular diameter of 0.52 mas via the colour-surface brightness relations of Barnes, Evans & Moffet (1978). The distance estimate of Innis *et al.* then gives a radius of $1.3 \pm 0.3 R_{\odot}$ for AB Dor. A set of H α spectra with resolution $R \approx 40000$ was published recently by Robinson & Collier Cameron (1986, hereinafter referred to as RC). These spectra, obtained simultaneously with the 1984 December *EXOSAT* observation described in the present paper, yielded an improved value for $V \sin i$ of $85 \pm 5 \text{ km s}^{-1}$, which when combined with the rotation period gives a lower limit on the radius, $R \sin i = 0.90 R_{\odot}$ and hence an axial inclination in the range $34^{\circ} < i < 64^{\circ}$. The results of RC, which show corotating circumstellar hydrogen clouds transiting the stellar disc, suggest that an inclination in the higher part of this range is the more likely. Similar results have been published recently by Vilhu, Gustafsson & Edvardsson (1987), based on detailed high-resolution spectroscopy of this star.

For the remainder of this paper we therefore adopt a radius of $1.0 R_{\odot}$ and a distance of 20 pc as the combination which gives the best agreement with all the observational constraints above. Membership of the Pleiades moving group would indicate an age of a few times 10^7 years, consistent with the young age implied by the high lithium abundance and by the radius, which is some 10–20 per cent greater than that expected for a zero-age main-sequence K0 dwarf with the same *UBVRI* colours as AB Dor. AB Dor therefore appears to be similar in nature to the rapidly rotating K dwarfs discovered in the Pleiades cluster by van Leeuwen & Alphenaar (1982) and Stauffer *et al.* (1984).

2 Observations

The *EXOSAT* observations reported here were made on 1984 December 11 to 12 and 1986 January 21. The first observation consisted of five contiguous 10^4 s units of observing time, covering just over a full rotation cycle from 1984 December 11 11:30 to December 12 01:20 UT. The second observation lasted for 3.5 units, slightly less than a full rotation, from 1986 January 21 04:08 to 13:46 UT.

During most of the first observation and all of the second, a Lexan filter of thickness $0.3 \mu\text{m}$ (hereinafter referred to as Lexan 3000) was used on the low-energy imaging elescope (LEIT, de Korte *et al.* 1981), giving an effective bandpass from 0.05 to 2.0 keV with peak transmission at ~ 0.1 keV. The ultraviolet contribution to the signal through the sideband of the Lexan 3000 filter is expected to be negligible for K0 dwarf at the distance of AB Dor. Rucinski's (1985) *IUE* spectra confirm that there is no anomalous ultraviolet excess from this star other than the usual chromospheric and transition region line emission spectrum found in active late-type stars.

Observations were also made with the medium-energy (ME, Turner, Smith & Zimmermann 1981) experiment, which consisted of an array of eight proportional counters of which four were kept on-source at any one time while the other four were used to monitor the particle background; the two halves of the array were placed on-source alternately, with about 10^4 s between array swaps, to optimize background subtraction.

3 Data analysis

3.1 BROAD-BAND VARIABILITY

The LEIT count rates, averaged in 300 s bins with background subtracted, are shown in Figs 1(a) and 2(a) for the 1984 December and 1986 January observations respectively. The corresponding

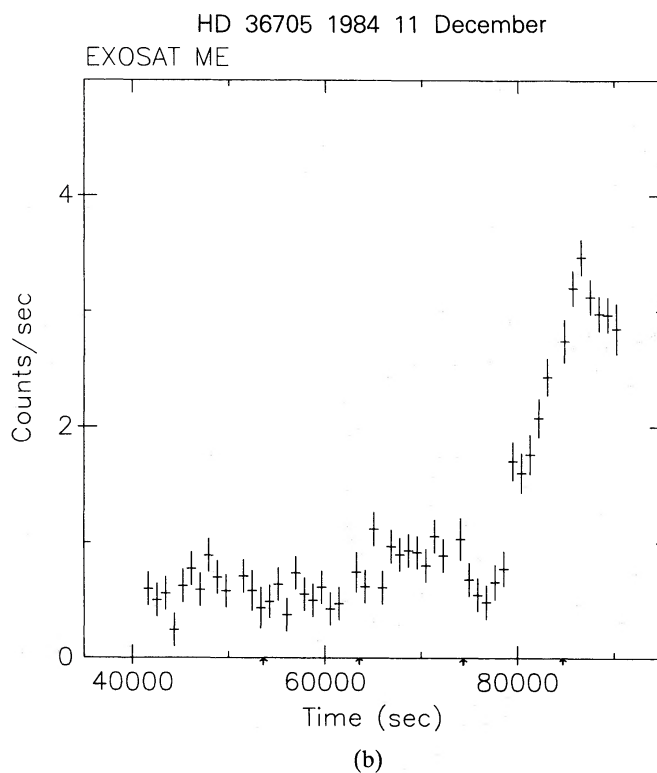
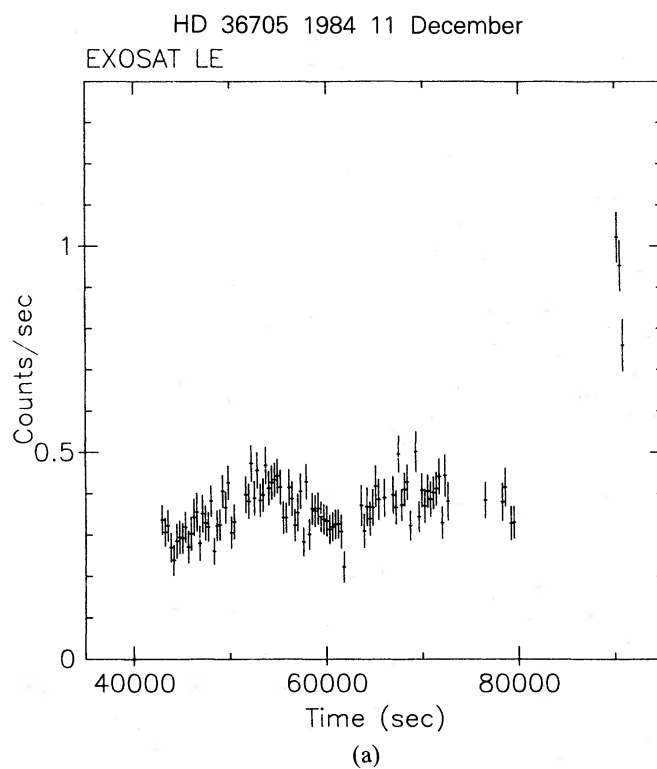


Figure 1. Background-subtracted count rates in (a) LEIT with Lexan 3000 filter, and (b) ME, plotted against UT in s from 1984 December 11.0. The energy range for the LEIT data is from 0.05 to 2.0 keV, with peak transmission at ~ 0.1 keV, while the ME data are summed over channel energies from 2 to 6 keV. The LEIT and ME data are grouped in 300 and 900 s bins respectively. Arrows denote times of ME array swaps.

HD 36705 1986 21 January

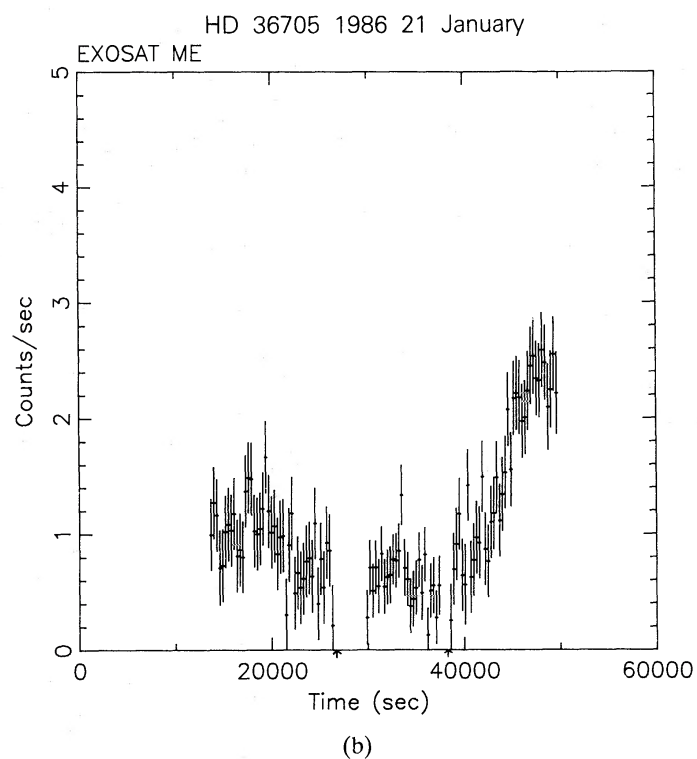
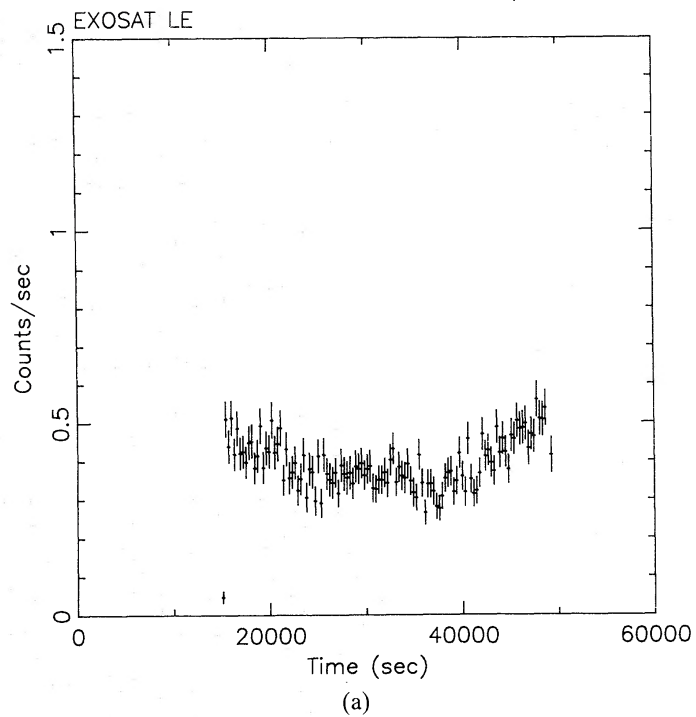


Figure 2. As for Fig. 1, with (a) LEIT and (b) ME count rates grouped in 300 s bins and plotted against UT in s from 1986 January 21.0. The first point in the LEIT data is probably spurious, as it occurs at or slightly before the start of the first LEIT observation.

ME rates, summed over channel energies from 2 to 6 keV for the four on-source detectors, are given in Figs 1(b) and 2(b).

A single stellar X-ray flare occurred during each of the 1984 December and the 1986 January observations. In both cases the flux began to rise steeply some 2–3 hr before the end of the observation, peaking about an hour before the end of the observation. In neither case, however, was the decay of the flare observed. The LEIT data on the early stages of the 1984 December flare were corrupted by a series of bursts of solar activity between 61 000 and 81 000 s UT. The strongest solar events occurred between 73 000 and 77 000 s, during which time LEIT background subtraction could not be carried out reliably. Between 81 000 and 90 000 s, several filter changes were made on the LEIT. Observations through the Lexan 3000 filter were resumed at 90 000 s and were continued for the remaining 20 min of the observation, by which time the stellar flare had peaked.

In the 1984 December observation, the pre-flare LEIT lightcurve shows a slow modulation with an amplitude of about 30 per cent, with minima at 43 000 and 60 000 s, and a maximum at 55 000 s.

The uncertainties in the form of the ME light curve during the same period are greater because of the higher background level in the ME array (the source count rate is some 20 per cent of the background). As described in Section 3.2 below, the background problems were worst in the inner detectors in each array half, necessitating the rejection of data from detectors 2, 3 and 7 for spectral fitting purposes. However, when summed over the 2–6 keV energy range used here, where the source count rate is greatest, the inclusion of the data from the inner detectors gave a slight improvement in the signal-to-noise ratio. The ME light curves shown in Figs 1(b) and 2(b) therefore include the data from all detectors.

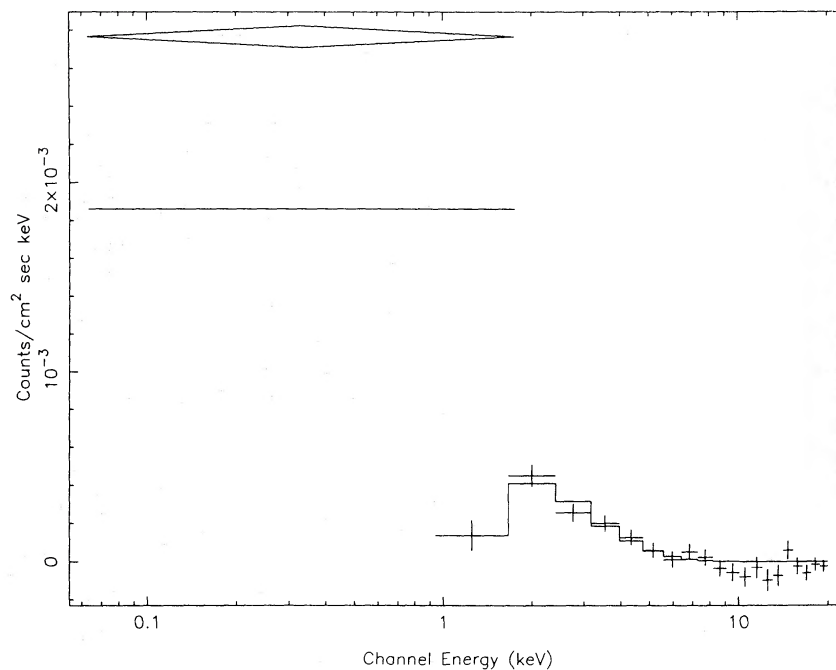
Because of the intermittent bursts of solar activity, the offset ME array half was used for simultaneous background monitoring, with an appropriate correction for the different spectral responses of the on-source and off-source halves of the array. A temporary increase in the ME rate occurred between 65 000 and 75 000 s. As the rise to this ‘plateau’ and the subsequent fall were viewed by the two different halves of the array (the relevant array swaps were made at 62 000 and 73 000 s) this feature does not appear to be an artifact caused by incorrect background subtraction. Although the phase coverage is less complete, a smaller rise is apparent at this time in the LEIT data.

Simultaneous background monitoring was not necessary in the ME during the 1986 January observation, and background subtraction was carried out for each individual detector using the background rate observed in the same detector during those intervals when it was pointed off-source. The 1986 January pre-flare data show a much stronger correlation between the LEIT and ME count rates, both of which decreased steadily from the start of the observation at 15 000 s to the start of the flare at 40 000 s.

3.2 SPECTRAL VARIABILITY

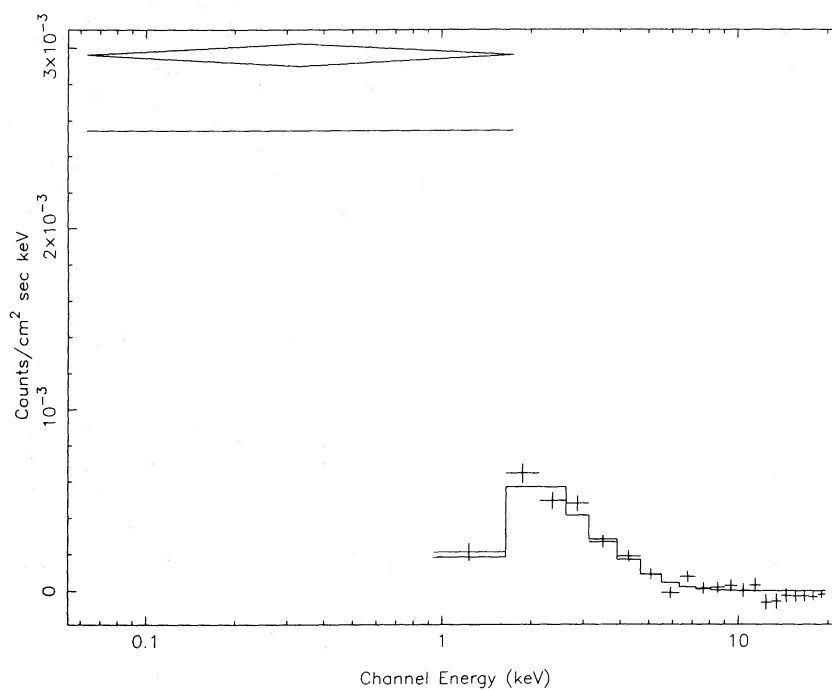
The broad-band flux variations seen in both the LEIT and the ME detectors during the 1984 December and 1986 January observations appear to be partially correlated. There is little evidence that the increase seen in the LEIT between 43 000 and 60 000 s in the 1984 data was present in the ME. Conversely, the rise seen in the ME between 63 000 and 77 000 s in the 1984 data, and the slow decay during the early part of the 1986 January observation, do appear to be present (but with lower amplitude) in the LEIT. Moreover, the 1986 flare appears to have been considerably harder than its 1984 counterpart, as evidenced by the relatively small rise seen in the LEIT emission during the 1986 flare.

AB Dor 1984 Dec 11 53868 – 62956 s UT: Data and folded model



(a)

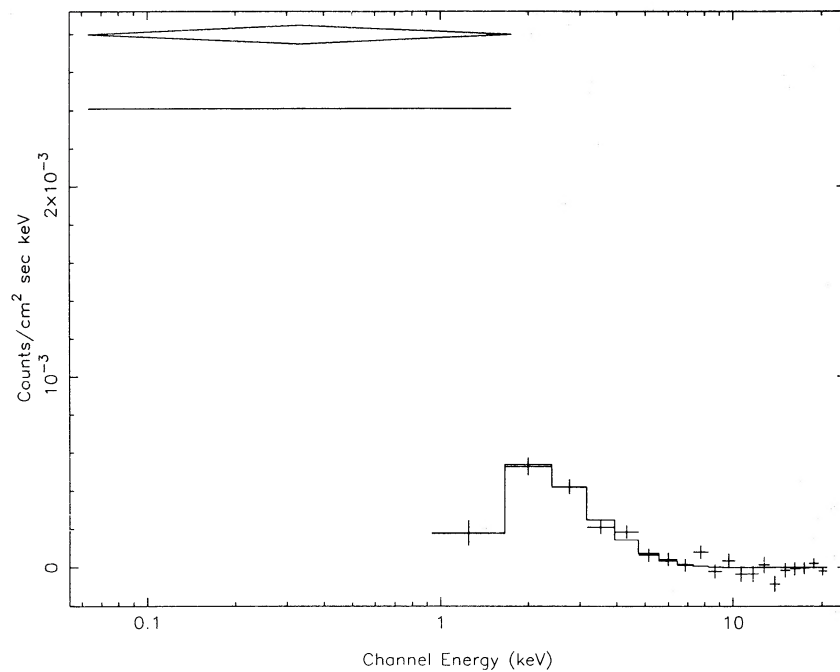
AB Dor 1984 Dec 11 63612 – 73772 s UT: Data and folded model



(b)

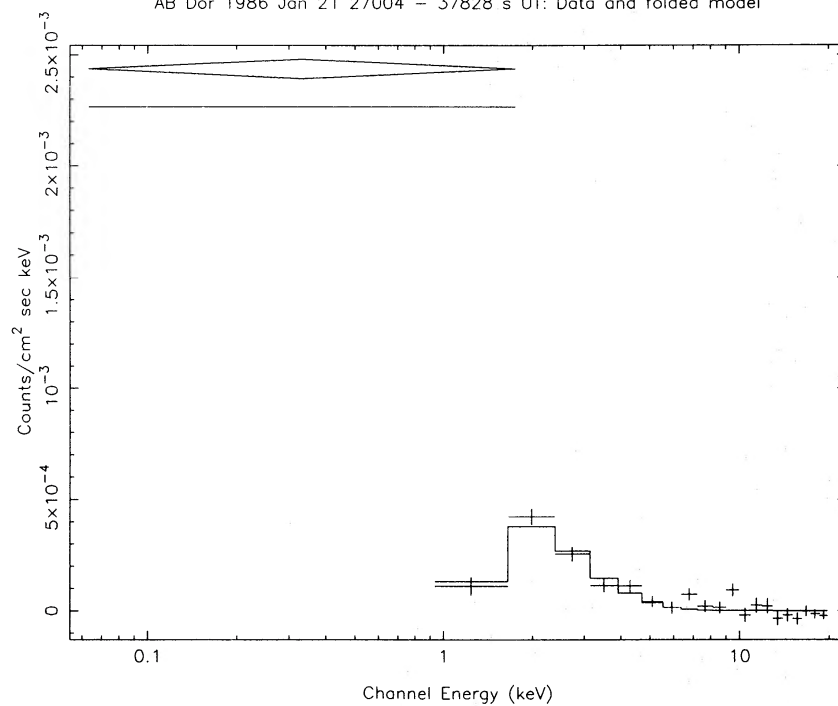
Figure 3. Quiescent ME pulse height spectra and LEIT count rates obtained on 1984 December 11. 1σ error bars are given for ME data, and a 1σ error diamond for the LEIT rate over the same interval. The solid lines correspond to the spectral fits to the ME spectra given in Table 1, and are extrapolated for comparison with the observed LEIT count rate.

AB Dor 1986 Jan 21 13540 – 26420 s UT: Data and folded model



(a)

AB Dor 1986 Jan 21 27004 – 37828 s UT: Data and folded model



(b)

Figure 4. As for Fig. 3, for the quiescent spectra obtained on 1986 January 21.

The LEIT fluxes and the ME pulse-height spectra during the pre-flare periods in both data sets were fitted satisfactorily with single-temperature thermal bremsstrahlung spectra. It was necessary to reject spectral data from three of the four inner detectors on the ME (numbers 2, 3 and 7) which registered unacceptably high background levels for spectral fitting purposes. The models are shown folded through the responses of both the ME and LEIT in Figs 3 and 4. Initially, the temperature, emission measure and neutral hydrogen column density were left as free parameters. In no case did the fit require a hydrogen column density higher than 10^{18} cm^{-2} , consistent with the amount of interstellar Mg II *h* and *k* absorption observed by Rucinski (1985) with *IUE*. The final spectral fits, details of which are given in Table 1, were carried out for a fixed hydrogen column density $n_{\text{H}} = 10^{18} \text{ cm}^{-2}$.

The first of the 1984 December spectra covers the peak and decay of the LEIT feature described above. The second covers most of the ME 'plateau' feature. The shape of the ME spectrum does not change appreciably between the two spectra, although there is an overall increase by about 30 per cent in the total flux above 1 keV. If all the flux in the LEIT were contributed by this hot component, a similar increase would be expected in the LEIT. Figs 1 and 2 show that this rise at constant temperature in the ME flux was accompanied by a 15–20 per cent

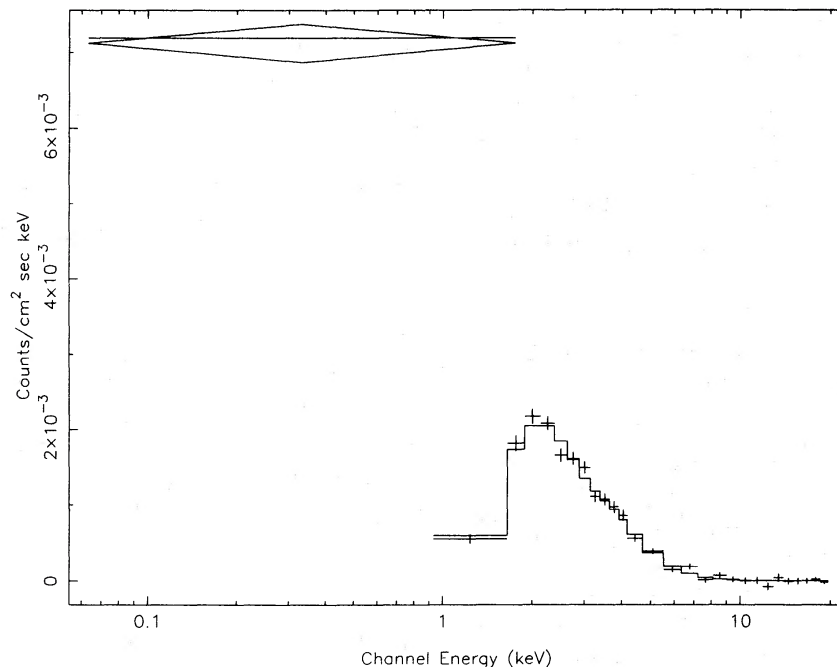
Table 1. Single-component fits to quiescent ME spectra, with LEIT rates. L_x is for the 0.1–10 keV energy range; $d=20 \text{ pc}$ and $n_{\text{H}}=1 \times 10^{18} \text{ cm}^{-2}$ assumed. Tabulated errors are 90 per cent confidence limits.

UT (s)	kT (keV)	$\int n_e^2 dV$ ($\times 10^{53} \text{ cm}^{-3}$)	L_x (erg s^{-1})	LEIT count rates ($\times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$)	
				Observed	Predicted
(1984 Dec 11)					
53868 - 62956	1.68 ± 0.34	1.27 ± 0.54	1.47×10^{30}	4.66 ± 0.10	3.14
63612 - 73772	1.78 ± 0.18	1.87 ± 0.37	2.09×10^{30}	5.00 ± 0.10	4.29
(1986 Jan 21)					
13540 - 26420	1.69 ± 0.21	1.67 ± 0.39	1.92×10^{30}	4.72 ± 0.08	4.06
27004 - 37828	1.38 ± 0.19	1.18 ± 0.35	1.56×10^{30}	4.11 ± 0.07	3.82

rise in the LEIT between 60 000 and 66 000 s, so it is likely that the high-temperature component seen in the ME contributes over half, but not all, the LEIT flux.

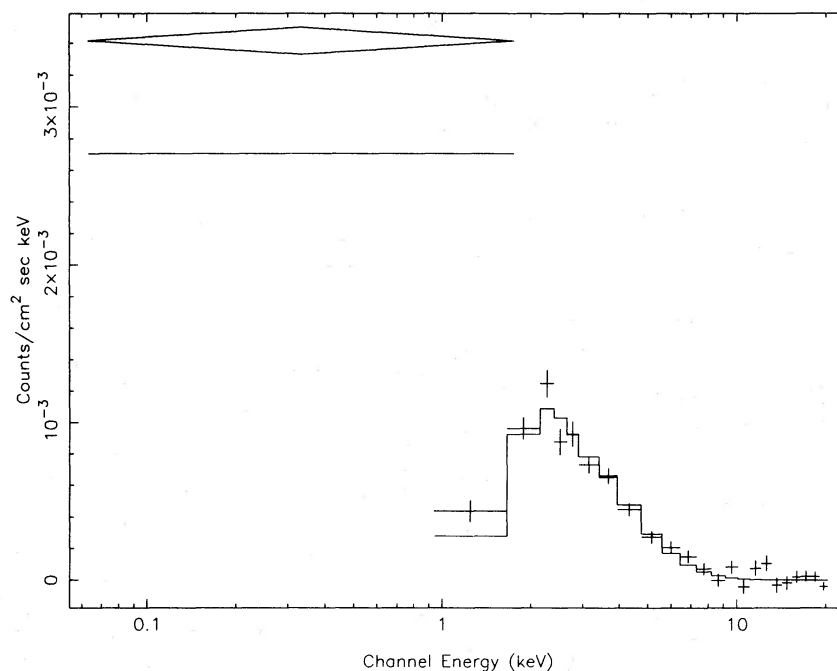
Conversely, the spectral data confirm that the rise seen in the LEIT between 43 000 and 60 000 s had no counterpart in the ME. The *ratio* of the time-averaged LEIT to the 1 to 3 keV ME flux dropped by 20 to 25 per cent between the first and second spectral observations. Material at temperatures of order 10^6 K could provide the remainder of the LEIT flux during the first observation without contributing at all to the ME. The existence of variations which are seen in the LEIT but *not* in the ME constitutes strong evidence for a geometrically or intrinsically variable low-temperature component in the corona of AB Dor. The former explanation is the more attractive, as short-term variability caused by flaring would normally involve temperatures considerably higher than 10^6 K . Moreover, the maximum in the LEIT excess occurred at the same rotation phase as the minimum of the optical lightcurve obtained by T. Lloyd Evans at SAAO contemporaneously with the 1984 December *EXOSAT* data (Collier Cameron *et al.* 1986). Relatively short, cool low-lying loops associated with the active, spotted regions would be expected to produce a soft X-ray excess with a maximum at the rotation phase of maximum starspot visibility, as observed here. Those variations which show up strongly in the broad-band ME data and to a lesser extent in the LEIT must originate in a much hotter component, at temperatures of 10^7 K or more, and could be caused either by low-level flaring or by geometrical self-eclipse.

AB Dor 1984 Dec 11 85402 – 12 4858 s UT: Data and folded model



(a)

AB Dor 1986 Jan 21 45950 – 49044 s UT: Data and folded model



(b)

Figure 5. Similar to Figs 3 and 4, but for the flare spectra obtained on (a) 1984 December 11/12, and (b) 1986 January 21. The single-component fits to the ME data listed in Table 2 are shown here as solid lines, and are extrapolated for comparison with the observed LEIT rates. These fits are for illustrative purposes only: they are not intended to be indicative of the flare plasma properties, because the quiescent spectrum has not been subtracted from the data. Note, however, that the 1986 January flare spectrum is the harder of the two.

The variations seen in the 1986 January observations appear to originate mainly in the hot component of the corona. The first spectrum in Fig. 4 covers the decrease in flux seen in both the LEIT and the ME between 14 000 and 26 000 s, while the second spans the flat minimum between 30 000 and 38 000 s. The second spectrum is significantly softer than the first, and the decrease seen in the LEIT flux in Fig. 2(a) is similar in form to the decrease in the ME flux seen at the same time. The softening of the spectrum during the decrease is very similar to that seen in the last stages of a large flare observed in Algol by White *et al.* (1986), and it is very likely that the decrease represents the final decay of a flare which peaked before the start of the observation.

3.3 FLARES

The late stages of both the 1984 December and the 1986 January X-ray light curves are dominated by large flares. On both occasions, the rise to flare maximum and the maximum itself were observed, but observations ended before the decay phase had progressed far enough for the decay timescale to be measured. The rise times of both flares from onset to maximum were approximately 7000 s, three times longer than (for example) the flare observed in Algol by White *et al.* (1986). The plasma temperatures derived for the two flares differ considerably. The spectra shown in Fig. 5 were obtained near the maxima of the two flares, and from these alone it is clear that the spectrum of the 1986 January flare was the harder of the two. This is borne out by the crude single-component fits to the two flare spectra give in Table 2. The temperature derived for

Table 2. Single-component fits to flare ME spectra including quiescent component, with LEIT rates. L_x is for the 0.1–10 keV energy range; $d=20$ pc and $n_H=1\times10^{18}\text{ cm}^{-2}$ assumed. Tabulated errors are 90 per cent confidence limits.

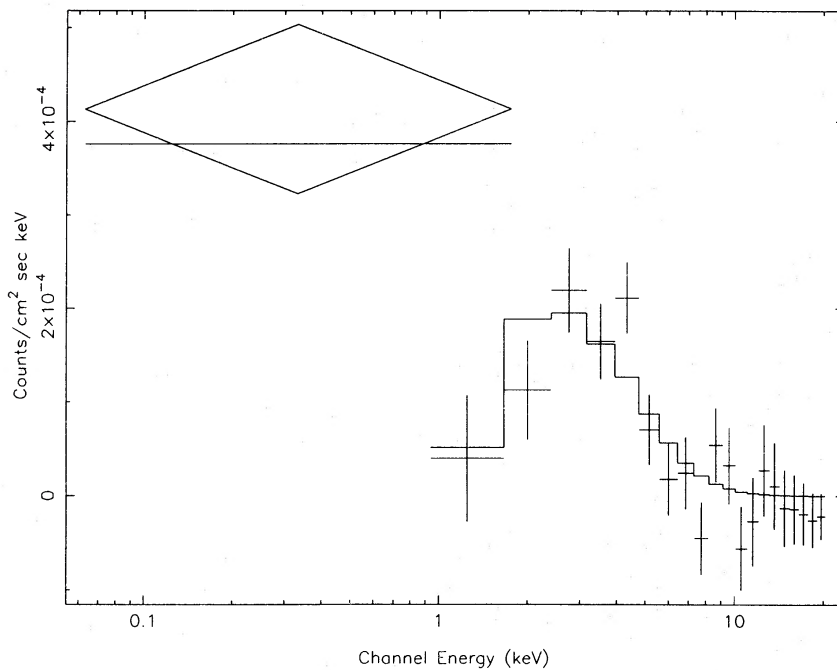
UT (s)	kT (keV)	$\int n_e^2 dV$ ($\times 10^{53} \text{ cm}^{-3}$)	L_x (erg s^{-1})	LEIT count rates ($\times 10^{-3} \text{ cm}^{-2} \text{ s}^{-1}$)	
				Observed	Predicted
(1984 Dec 11)					
85402 - 91258	2.08 ± 0.09	6.35 ± 0.42	6.59×10^{30}	12.01 ± 0.04	12.13
(1986 Jan 21)					
45950 - 49044	3.04 ± 0.26	3.38 ± 0.39	3.21×10^{30}	5.76 ± 0.14	4.56

the earlier flare is less than half the 5.8×10^7 K derived for the 1986 January event, although the emission measure is greater by a factor of nearly two.

Because observations were obtained with both the LEIT and ME throughout the rise of the 1986 January flare, a more detailed study of the spectral evolution of the flare emission was possible. In order to isolate the flare emission from the quiescent hot coronal component, the spectrum during the rise was re-calculated using as ‘background’ the spectrum recorded by the on-source half of the ME array during the quiescent period immediately prior to the onset of the flare. The quiescent hot coronal component was thus subtracted out along with the background. A similar procedure was followed for the LEIT data. The three resulting spectra are shown in Fig. 6, and the parameters of the best-fitting bremsstrahlung models are listed in Table 3. The data during the early part of the rise are noisy, but all three spectra give plasma temperatures in the range 5.8 to 8×10^7 K, with the emission measure increasing during the flare rise.

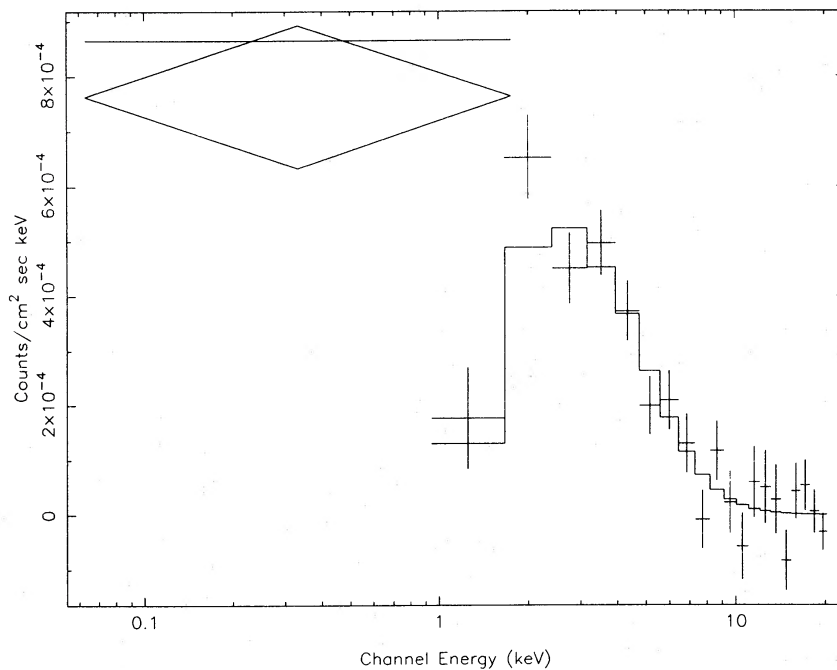
It was not possible to isolate the 1984 December flare spectrum as was done for the 1986 data, because (i) the solar activity during the observation precluded non-simultaneous background subtraction, and (ii) no data were obtained with the LEIT and the Lexan 3000 filter during the flare rise. Qualitatively, the behaviour of the 1984 December flare appears to be similar – that is, an increase in the emission measure at constant temperature – but at a lower temperature of $2\text{--}3 \times 10^7$ K.

AB Dor 1986 Jan 21 41000 – 45950 s UT: Data and folded model



(a)

AB Dor 1986 Jan 21 45950 – 48000 s UT: Data and folded model



(b)

Figure 6. Flare spectra with quiescent component subtracted, taken during (a) early rise, (b) late rise and (c) peak of the 1986 January 21 flare. The solid lines correspond to the thermal models listed in Table 3. Note that the LEIT data were used in addition to the ME spectra to constrain the model fits in contrast to the earlier fits (Figs 2–5 and Tables 1–2) in which only the ME data were used.

AB Dor 1986 Jan 21 48000 – 49050 s UT: Data and folded model

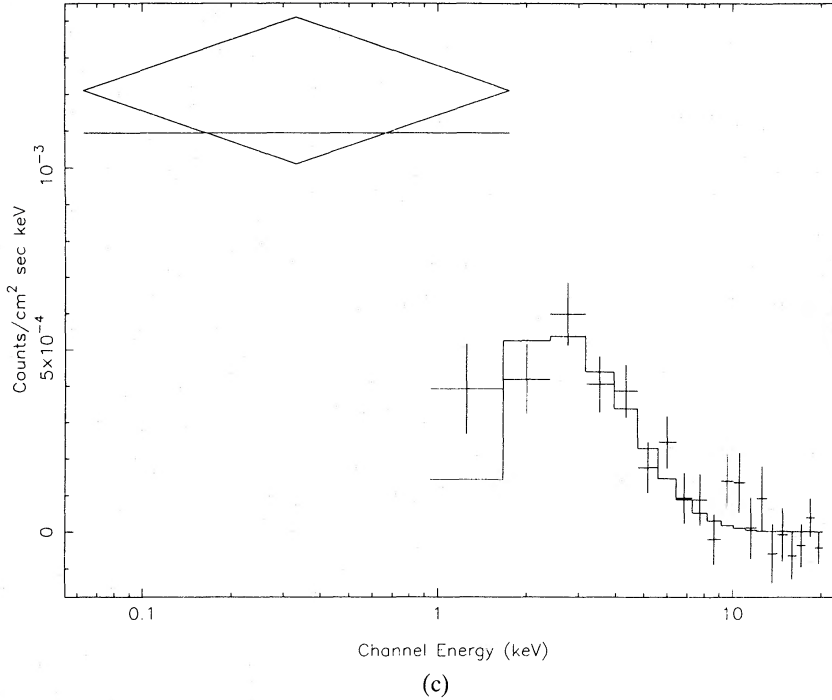


Figure 6–continued

Table 3. Single-component fits to flare ME+LEIT spectra with quiescent spectra subtracted, 1986 January 21. L_x is for the 0.1–10 keV energy range; $d=20$ pc and $n_H=1\times10^{18}\text{ cm}^{-2}$ assumed. Tabulated errors are 90 per cent confidence limits.

UT (s)	kT (keV)	$\int n_e^2 dV$ ($\times 10^{53}\text{ cm}^{-3}$)	L_x (erg s^{-1})
41000–45950	5.43 ± 1.64	0.68 ± 0.19	0.64×10^{30}
45950–48000	7.40 ± 1.62	1.77 ± 0.30	1.73×10^{30}
48000–49050	4.92 ± 1.02	1.87 ± 0.37	1.76×10^{30}

4 Discussion

4.1 DIMENSIONS OF FLARING REGION

The most notable feature of the two flares which we observed in AB Dor with *EXOSAT* was the unusually long rise time from onset to flare maximum. In both cases this rise time was between 5000 and 7000 s, during which time the ME count rate increased more or less linearly with time.

The spectral evolution of the 1986 January flare was consistent with a model in which flare plasma at a temperature of around 5.8×10^7 K gradually fills the flaring region. This behaviour might be expected if the heating source of the flare were located in a large loop structure, and remained active throughout the rise, causing evaporation of chromospheric material into the loop via electron beam heating, as is often considered to be the case in solar flares (Brown, Smith & Spicer 1981; MacNeice *et al.* 1984).

The main difference between the present case and solar flares is that in the AB Dor flares the beam heating phase would have to be maintained for 5000 to 7000 s, a hundred times longer than the impulsive phase (around 60 s) of a large solar flare. For an assumed decay time between 0.5

and 1.0×10^4 s the energy radiated in 0.1–10 keV X-rays was of order 10^{34} erg, two orders of magnitude greater than the corresponding value for a large solar flare with similar plasma temperatures. Thus the heating rate during the rise need not have been any greater than solar values.

Provided the radiative and conductive cooling times were equal to or longer than the rise time, the temperature would remain roughly constant but the emission measure would rise linearly with time as the flare plasma evaporated into the loop. Given the higher ion sound speed in the flare plasma, a shock should form at the leading edge of the rising flare material, propagating along the loop at the ion sound speed $(kT_e/m_p)^{1/2}$ of the flare plasma. For a flare temperature of 5.8×10^7 K, the ion sound speed is 700 km s^{-1} , giving a total length for the flaring region of order $4 \times 10^{11} \text{ cm}$ (about 6 stellar radii) if the flare site was near a loop footpoint, or twice these values if the flare occurred near the loop summit, sending flare material up along the loop from both footpoints.

It is unfortunate that the decay phases of the two main flares were not observed. However, if indeed the flux decrease and spectral softening which occurred at the start of the 1986 January observation represent the decay phase of an earlier, similar flare, the decay timescale appears to be no less than 5000 s and probably nearer to 10^4 s. If the flare plasma cools radiatively, as is normally the case in solar flares, the cooling time is given by

$$\tau_r = \frac{3kT_f}{n_e \Lambda}$$

where T_f is the flare temperature and Λ is the radiative loss function. The estimated cooling time of 10^4 s then gives an upper limit on the electron density $n_e \approx 2 \times 10^{11} \text{ cm}^{-3}$.

If, as seems more likely in view of the long loop length, the flare plasma density is much lower than this, conduction will become the dominant cooling mechanism. The conductive cooling time-scale is

$$\tau_c \approx 1.18 \times 10^{-10} \times \frac{n_e L^2}{T_e^{2.5}}$$

where L is the loop length (Culhane, Vesecky & Phillips 1970). For a cooling time of 10^4 s and a loop length of $4 \times 10^{11} \text{ cm}$, conduction will become the dominant cooling mechanism at electron densities below $1.4 \times 10^{10} \text{ cm}^{-3}$ (or $4 \times 10^9 \text{ cm}^{-3}$ for the longer loop length).

The total observed emission measure at flare maximum for the 1986 January flare was $\int n_e^2 dV = 1.87 \times 10^{53} \text{ cm}^{-3}$. For radiative cooling ($n_e = 2 \times 10^{11} \text{ cm}^{-3}$) and a loop length of $4 \times 10^{11} \text{ cm}$, this would give a flare volume of $4.7 \times 10^{30} \text{ cm}^3$, and hence a cross-sectional radius to length ratio of 0.005. Conductive cooling gives a more plausible loop geometry, with a total flare volume of $9.5 \times 10^{32} \text{ cm}^3$ (for $n_e = 1.4 \times 10^{10} \text{ cm}^{-3}$, $L = 4 \times 10^{11} \text{ cm}$) and hence a radius to length ratio of 0.07. The double-length loop model gives a radius to length ratio of 0.085. Since this ratio varies as the inverse half power of the electron density, its value will increase by a factor of 1.4 if the actual cooling time is as short as 5000 s.

4.2 QUIESCENT LOOP CONFIGURATIONS

The evidence for the existence of relatively short loops at temperatures of order 10^6 K, and their spatial coincidence with the cool starspots in AB Dor has already been discussed in Section 3.2 of this paper. For such loops to be subject to rotational self-eclipse by the limb of the star, their heights can be no more than a few tenths of a stellar radius, so in many respects their properties may not differ greatly from those of the interconnecting loops between solar active regions.

X-ray eclipse observations have shown that the 10^7 K components of the coronae of the cool subgiants in AR Lac (Walter, Gibson & Basri 1983) and Algol (White *et al.* 1986) extend more

than a stellar radius above the photosphere, implying the existence of large, hot closed loop structures which have no solar counterpart.

AB Dor possesses a hot coronal component: the *EXOSAT* ME spectra obtained during the apparently quiescent periods between flares in 1984 December and 1986 January are all well-fitted by a thermal bremsstrahlung spectrum with a temperature of 1.9×10^7 K and emission measure $\int n_e^2 dV = 1.5 \times 10^{53} \text{ cm}^{-3}$. The 0.1–10 keV luminosity of this quiescent hot component is approximately $2.0 \times 10^{30} \text{ ergs}^{-1}$.

The long rise-times of the flares provide evidence that very large magnetic structures must also be present in the corona of AB Dor. Other types of observation also suggest the presence of closed magnetic structures extending several stellar radii above the photosphere in this star, notably the $H\alpha$ observations of Cameron & Robinson (1987, in preparation), which show prominence-like clouds of mainly neutral hydrogen held in forced corotation with the star at distances up to nine stellar radii from the stellar rotation axis, or three times the radius of a synchronous Keplerian orbit. Closed magnetic loops are the most likely confining agent for these clouds.

The thermal properties of such large loops will not be discussed in detail here. However, several points are worth bearing in mind. First, the pressure scale height $2kT/m_p g$ in an isothermal loop at a temperature of 1.9×10^7 K is $\sim 1.4 \times 10^{11}$ cm at the surface of a star with $M = 0.9 M_\odot$, $R = 1.0 R_\odot$. Secondly, this value will increase with distance from the star as the effective value of g decreases. Thirdly, in such a rapidly rotating star centrifugal forces play an important role in determining the hydrostatic equilibrium configuration of loops whose heights are comparable with or greater than the Keplerian corotation radius. Beyond the corotation radius closed loop structures are possible only if the magnetic tension in the loop exceeds the centrifugal force acting on the confined plasma.

The problem is then to fit the observed emission measure into the smallest available volume without requiring unrealistically high pressures. Mestel & Spruit (1987) have made a theoretical study of the extent of the closed-field region for a simple dipole-like field configuration, and find that the field lines should open out between 2.4 and 4.4 stellar radii above the equator in stars with rotation rates comparable with that of AB Dor. The volume enclosed between the photosphere and the outer limiting field line of such a dipole configuration is some 30 times the stellar volume (for a limiting field line with its apex $\sim 3R_*$ above the equator). If we assume that the enclosed region is filled with coronal plasma at uniform density, the observed emission measure gives a mean electron density $n_e \approx 3 \times 10^9 \text{ cm}^{-3}$. The corresponding pressure is 13 dyn cm^{-2} , which is comparable with pressures found in solar active regions. This means that unless the hot X-ray component is formed at pressures very much greater than solar active-region pressures, the quiescent loops must occupy a large fraction of the volume available for the formation of closed magnetic structures. In this case, some global ordering of the field pattern may be required in order to achieve such close packing of the loops.

Because the bulk of the emission will come from the outer parts of the enclosed region, the length of the outermost field line (about $4.5R_*$) and the mean electron density can be used to estimate the mean observed temperature. Although loop scaling laws such as those of Rosner, Tucker & Vaiana (1978) are probably not strictly valid in this situation, they serve to give a useful order-of-magnitude estimate of 2.6×10^7 K for the expected plasma temperature, which is in reasonable agreement with the observed 1.9×10^7 K.

5 Conclusions

We have obtained X-ray light curves and spectra of the single, rapidly-rotating K0 dwarf AB Doradus with complete or nearly complete rotational phase coverage. Two large stellar flares were observed, one during each observation.

From our analysis of these data we find that:

(i) During quiescence, the 1–10 keV spectrum observed by the ME experiment is well-fitted by a thermal bremsstrahlung spectrum at a temperature of 1.9×10^7 K and emission measure of $1.5 \times 10^{53} \text{ cm}^{-3}$, assuming a distance of 20 pc.

(ii) The extension of the ME spectrum to the 0.05–2 keV energy range to which the LEIT is sensitive with the Lexan 3000 filter, indicates that the 1.9×10^7 K component can account for at least half the flux seen by the LEIT.

(iii) During the early part of the 1984 December observation, variability was seen in the LEIT which was not present in the ME, indicating the presence of a variable X-ray component at temperatures too low to be detectable in the ME, i.e. below about 0.6×10^7 K. The phase at which the maximum in the LEIT flux was observed coincided with the optical photometric minimum. This would be expected if the variability was caused by rotational self-eclipse of relatively short loop structures associated with the cool starspots causing the optical variation.

(iv) The long rise-times for the flares suggest that much longer loop structures, extending several stellar radii above the stellar equator, are also present. We have isolated the spectrum of the 1986 January flare during its rise, by subtracting out the quiescent spectrum along with the background. The resulting spectra are well-fitted by a thermal model whose emission measure rises at more or less constant temperature. This behaviour and the time-scale of the rise are consistent with a model in which the flare heating mechanism remains operative throughout the rise, evaporating a column of flare plasma off the chromosphere via electron beam heating. The length of the flaring region is between 6 and $12R_*$, if the flare plasma is propelled along the loop at the ion sound speed. Although the decay of the flare was not observed, the decay time was probably between 0.5 and 1.0×10^4 s. If the principal flare cooling mechanism is conduction, electron densities in the range 4×10^9 – $1.4 \times 10^{10} \text{ cm}^{-3}$ are implied. These values give a more reasonable radius-to-length ratio (between 0.07 and 0.09) for the loop in which the flare occurs, than do those obtained assuming radiative cooling which requires much denser, narrower loops.

(v) The X-ray observations alone do not allow us to determine the sizes of the loops giving rise to the quiescent 1.9×10^7 K component. However, lower and upper limits can be placed on the extent of the emitting region, if (i) the plasma is to be confined at a reasonably low pressure, and (ii) the magnetic tension in the confining loops is to exceed the outward centrifugal force on the plasma, keeping the field lines closed. These two requirements imply that the emitting volume probably extends some three stellar radii above the equator, at pressures similar to solar active-region pressures (10 – 20 dyn cm^{-2}), and with a high volume filling factor. Scaling laws for loops in hydrostatic and thermal equilibrium predict loop temperatures under these conditions within a factor of 2 of those observed. It is possible that the 1.9×10^7 K component could arise in continuous, low-level flaring in much shorter loop structures. However, the similarity of the spectra and emission measures obtained more than a year apart, and the lack of evidence for any rotational modulation of this component, make the former interpretation the more attractive.

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