AN EXOSAT OBSERVATION OF THE MORPHOLOGY OF THE CORONAL X-RAY EMISSION FROM ALGOL

N.E. White(1), J.L. Culhane(2), A.N. Parmar(1), B. Kellett(2), S. Kahn(2), G.H.J. van den Oord(3) and J. Kuijpers(3)

1 EXOSAT Observatory, ESOC, Robert-Bosch-Str. 5, 6100 Darmstadt, W. Germany
2 Mullard Space Science Laboratory, Holmbury St. Mary, Dorking, Surrey, United Kingdom
3 Sterrenwacht Sonnenborgh, Zonnewburg 2, 3512 NL Utrecht, The Netherlands

ABSTRACT. The X-ray emission from Algol is thought to originate in a corona associated with the K star in this system. We report the results of a 35 hr continuous EXOSAT observation through secondary optical eclipse that was designed to measure the structure of the corona. No obvious X-ray eclipse was seen. The spectrum measured by the ME gives a temperature of 2.5x10^7 K, consistent with the hard component previously seen by the Einstein SSS. The soft component previously reported by the SSS would only contribute at most 25% to the count rate seen in the LE (used with Al/P). The lack of a hard X-ray eclipse indicates the dimensions of the higher temperature emission region to be comparable to or greater than the size of the K star. An X-ray flare was detected with a peak luminosity of 1.4x10^{31} erg s^{-1} and a total duration of 8 hours. The peak temperature was 5.0 keV with an emission measure of 9.4x10^{53} cm^{-3}. The thermal nature of the flare is confirmed by the detection of an iron line with an EW of ~2 keV. By equating the observed decay time of the flare to a known cooling law gives a dimension for the flaring loop of ~0.3 stellar radii. This is much smaller than the dimensions of the hard component inferred from the lack of an eclipse. It seems probable that the flare occurred in one of the loops responsible for the lower temperature component seen by the SSS.
1. INTRODUCTION

Algol is a triple system containing a 70 hr eclipsing binary (K IV and B8 V) in a 694 day orbit with an A V star. The X-ray emission from this system (Schnopper et al 1976) is thought to be associated with a corona surrounding the lobe filling and synchronously rotating K IV star. This is based on the similarity of the X-ray spectrum and luminosity of this system to that of the RS CVn binaries which also contain K sub-giants with similar rotation periods and the fact that the luminosity of any coronae surrounding the B8 V and AV companion stars should not be enhanced by rapid rotation (Pallavicini et al 1980, White et al 1980). The Einstein SSS measurement showed the X-ray spectrum to be two component with temperatures of $7 \times 10^6$ K and $3 \times 10^7$ K (White et al. 1980). As discussed by Swank et al. (1981), the problem in understanding stellar coronae in general is how to scale up the solar model to account for the enhanced luminosities. The close to 90° inclination and similar sizes for the B and K stars of 3.6 and 3.8 $R_\odot$ respectively make Algol an ideal candidate for an X-ray eclipse measurement wherein the size of the X-ray emitting coronal structures can be directly measured. In this paper we report a continuous observation through the secondary eclipse of Algol using the EXOSAT Observatory.

2. THE ECLIPSE

The EXOSAT observation began at 0900 UT on 1983 August at the quadrature preceding secondary optical eclipse and continued uninterrupted for one half of a binary cycle. In Figure 1 the background subtracted source count rate measured by the Medium Energy Experiment (ME; Turner et al 1982) and Low Energy Experiment (LEIT; de Korte et al 1982) are shown with a time resolution of 648s. Throughout this observation one half of the array was kept offset from the source to give a continuous monitor of the particle background. The offset array half was twice alternated to optimise the background subtraction. In quiescence Algol was detected in the 1 to 8 keV band. A CMA was used at the focus of the LEIT and, since the CMA has a UV response, an AI/P filter was interposed in the light path to eliminate UV contamination.

An outstanding feature in the LEIT and ME lightcurves is an 8 hr flare that began at 1300 UT. In addition to this event there is in
both the LEIT and ME, low level activity. The continuous background monitoring shows the background to be constant, confirming that the variations are in the X-ray flux. At the start of the observation the count rate decays by a factor of two over a few hours, suggesting that another flare may have occurred a few hours earlier. In addition there are other low level variations of order 20% on a timescale of a few hours. In contrast to this activity there is no evidence for any eclipse of the X-ray source between the indicated times of the first and last contact.

ME spectra of the quiescent state were obtained for the three intervals corresponding to the two array swaps. The third spectrum was curtailed to 4 hr by excluding the flare. The times are summarised in Table 1. The data were in all three cases well represented by a thermal bremsstrahlung model with a temperature of 2.1 keV (2.5.10^7 K) and an emission measure of 5.10^53 cm\(^{-3}\). There was

**Figure 1.** Plots of X-ray intensity against time shown for (a) the 2-6 keV (ME) and (b) 0.02-2.5 keV (LE) bands. LE data taken with the Al/P filter. The time of 1st and 4th contact are indicated.
evidence for an iron line with an equivalent width of 1000 eV, consistent with that expected from a solar abundance plasma. The line parameters are, however, dependent on systematic uncertainties in the background subtraction and while these results are suggestive of a feature, confirmation is required. A typical spectrum is shown in Figure 2. The parameters of the quiescent spectrum are comparable with those of the high temperature component found by the Einstein SSS (White et al. 1980). The contribution to the LEIT counting rate of the $2.5 \times 10^7$ K component was estimated by folding the ME spectrum through the CMA and filter response. This gave for an assumed Hydrogen column density of $1.1 \times 10^{18}$ H cm$^{-2}$, 90% of the observed count rate. This indicates that the LEIT count rate is dominated by the hotter component and the light curve cannot be used to draw any useful conclusion about the size of the coronal structures associated with the $3.1 \times 10^6$ K component.

![EXOSAT ALGOL QUIESCENT SPECTRA](image)

Figure 2. An ME spectrum of the quiescent emission from Algol. The best fitting thermal model is shown as a histogram.

It is clear from both the LEIT and ME light curves shown in Figure 1 that no significant flux decrease in flux occurred around the predicted time of eclipse. The absence of any decrease in count rate during eclipse sets, for an assumed coronal geometry, a lower limit to the size of the region responsible for the $4.1 \times 10^7$ K component. This was done by simulating the eclipse of the K star assuming for simplicity a spherically symmetric corona with a variety of exponential scale heights. When the scale height of the corona is comparable to or larger than the stellar radius it will be limb brightened such that two minima occur either side of the eclipse centre. By fitting to the observed data we set a lower limit to the scale height of $\sim 3$ $R_\odot$ (one stellar radius). Features in the light curve around first and last contact may represent the eclipse of stellar sized loop structures, although it is equally plausible that they are caused by intrinsic variability (cf Fig. 1).
3. THE FLARE

A more detailed light curve of the flare is shown in Figure 3 with a time resolution of 180 s for the ME and 360 s for the LE. Also given is a hardness ratio obtained from the ME by dividing the 4 to 6 keV count rate by that between 2 and 4 keV. The rise to maximum was in two parts, with an initial impulsive rise to one third the peak value in 200 s followed by a more gradual increase to maximum over the following 1500 s. The decay is exponential-like although 90 min after the peak there is a small hump that could be a second small flare. The hardness ratio shows that during the flare the spectrum becomes harder than the quiescent value, reaching a maximum about 1000 s before flare maximum. The spectrum then softens as the flare evolves.

Figure 3. A more detailed light curve of the flare in the ME and LE. A spectral hardness ratio is also shown. Intervals during which spectra were obtained are indicated 1-4 (cf. Table 1).
Multi-channel pulse height spectra were obtained from the ME for the various intervals during the flare indicate 1 to 4 in Figure 3 with the quiescent spectra (that included the quiescent X-ray flux) from either side of the flare subtracted as background. Figure 4 shows the pulse-height spectra from the sum of the first three spectra. A feature around 6.7 keV that represents iron K line emission broadened by the detector resolution of 25% is evident in all the spectra, especially in the summed spectrum. A thermal bremsstrahlung plus narrow iron line model convolved through the detector response gave an acceptable fit in all cases and the results are summarised in Table 1, with the best fitting model shown as a histogram in Figure 4. The temperature declined over 4 hours from a peak value of 5.0keV (5.8.10^7 K) to 2.7keV (3.2.10^7 K). The iron line equivalent width was typically 2 keV and its energy 6.8 keV. The measured equivalent width and line energies are in good agreement with those predicted for the measured temperatures by Raymond and Smith (1978) from a cosmic abundance plasma in ionisation-recombination equilibrium. The peak 0.1 to 10 keV luminosity was 1.4x10^{31} erg/s, a factor of three larger than the quiescent value. The emission measure decreased from 9.4x10^{53} to 5.7x10^{53} cm^3 as the flare decayed.

For the flare we have observed from Algol both the spectral and temporal resolution represent a marked improvement over earlier observations (cf Haisch 1983). While the impulsive rise, subsequent extended rise and the long decay over 8 hrs is reminiscent of the behaviour seen in solar two-ribbon flares, the peak X-ray luminosity is more than two orders of magnitude greater than that of the largest solar events and three orders of magnitude greater than a stellar flare from Proxima Centauri that Haisch et al (1983) classified as two-ribbon. Nonetheless the thermal character of the flare...
typified by the iron K line seen by the ME strongly suggests that as in the solar case the flare is caused by the heating of a solar abundance thermal X-ray plasma. By analogy with the solar example we will assume this plasma is confined by a magnetic loop or loops anchored to the chromosphere of the K sub-giant. If the X-ray heating phase ends at flare maximum and the volume containing the plasma remains constant then the plasma will cool via radiation and/or conduction (Culhane, Vesecky and Phillips 1970; Moore et al 1980; Haisch 1983).

Table 1: ALGOL SPECTRAL RESULTS

<table>
<thead>
<tr>
<th>Date</th>
<th>(n_e) (10^{6} \mathrm{cm}^{-3})</th>
<th>(E_{\gamma}) (keV)</th>
<th>(L_{\gamma}) (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>flare, Dec. 23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09.19-10.57</td>
<td>9.6</td>
<td>9.4</td>
<td>1.540.5</td>
</tr>
<tr>
<td>10.57-11.25</td>
<td>14.0</td>
<td>9.4</td>
<td>1.540.5</td>
</tr>
<tr>
<td>11.25-12.15</td>
<td>9.4</td>
<td>7.0</td>
<td>1.540.5</td>
</tr>
<tr>
<td>12.15-13.40</td>
<td>6.7</td>
<td>5.7</td>
<td>1.540.5</td>
</tr>
</tbody>
</table>

a) All uncertainties are one sigma
b) 0.1 to 10 keV
c) Line energies fixed if no uncertainty given

The timescale for cooling via radiation is given by \(3kT_p/Ne\cdot\Delta\), where \(T_p\) is the peak temperature, \(N_e\) is the density and \(\Delta\) the radiative loss function which for the observed temperature range is \(10^{-26.8} T_p^{0.5}\) erg cm\(^{-3}\) s\(^{-1}\). This can be equated to the observed exponential decay time (Figure 3) of \(\sim 7000\) s to give \(N_e \sim 3.10^{11}\) cm\(^{-3}\). Combining this density estimate with the peak emission measure of \(9.10^{53}\) cm\(^3\) gives a volume of \(1.10^{31}\) cm\(^3\). If the X-ray plasma is contained in \(N_l\) loops of length \(L\) with a height \(H\) above the stellar surface of \(2L/\alpha H\) and a radius of \(\alpha H\), where \(\alpha\) is ratio of the loop radius to its height (typically 0.1 in the solar case), the volume is given by \(\Pi 2 \alpha^2 N_l H^3\). From this we obtain \(H = 5.10^{10}\) cm or 0.19 stellar radii for \(\alpha = 0.1\) and \(N_l = 1\).

For a coefficient of conductivity of \(8.8.10^{-7} T_p^{-2.5}\) erg s\(^{-1}\) cm\(^{-2}\) K\(^{-1}\), the timescale for conductive cooling \(\tau_C\) is given by \(\tau_C = 4.8.10^{-10} N_e L^2 T_p^{-2.5}\) (Culhane, Vesecky and Phillips 1970). Imposing the condition \(\tau_C > \tau_r\) (Moore et al. 1980) requires that \(N_e < 3.10^{11}\) cm\(^{-3}\), such that the loop height must be \(> 2.10^{10}\) cm. Conductivity can be inhibited by up to a factor of ten by constriction of the loop legs and/or chromospheric evaporation (Moore et al. 1980) such that this lower limit would be reduced to \(0.7\times10^{10}\) cm (0.03 R\(*\)). The condition \(\tau_C > \tau_r\) requires for \(\alpha = 0.1\) that the flare occurred in 10 loops, or up to 300 loops if the conductivity is inhibited.
An estimate of how valid the assumptions that went into the above estimates are can be gained from comparing the total energy of the plasma at the flare peak ($3kT_eN_e V$) with the observed integrated luminosity. The inferred density and volume from the radiative cooling time gives a total available energy of $\sim 1.10^{35}$ erg/s which is indeed comparable to the integrated luminosity for the flare (Table 1), suggesting the effects of additional heating to be small. For magnetic containment the gas pressure at flare maximum of 3200 dynes must not exceed $B^2/8\mu$, which gives $B > 200$ G.

The range of dimensions inferred for the flaring loop or loops of 1 to $6 \times 10^{10}$ cm are all much smaller than the lower limit to the size of the $2.5 \times 10^{7}$ K component deduced earlier. This suggests that the flare occurred in one or more of the loops responsible for the quiescent $6 \times 10^{6}$ K component found by Einstein SSS (White et al 1980) but in quiescence below the detection threshold of the eclipse observations. As noted by Swank et al (1981) these loops must have either higher pressures or larger volumes than solar loops. In Table 2 the properties of the Algol flare are summarised and compared with those of the two different types of solar flare typically seen; compact flares and two-ribbon events. The principal differences between the solar and the Algol flare is that the volume of the flaring region is at least two orders of magnitude greater and the temperature a factor of three bigger than the solar case. The density of $10^{11}$ cm$^{-3}$ is typical of a solar event. These numbers can be interpreted in two ways. First that these very energetic stellar events occur in 300 solar sized loops flaring in concert. The loop heights for this case are roughly consistent with those of the largest loops seen during two-ribbon flares, although such a multiplicity of flaring loops is never seen from the sun. Alternatively our results are also consistent with the flare occurring in one large loop with dimensions of $0.3 R_\star$ with $\tau_c$ at least one order of magnitude greater than $\tau_r$.

### Table II Flare Properties for the Sun and Algol

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Solar</th>
<th>Algol August 1984</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compact</td>
<td>Two Ribbon</td>
</tr>
<tr>
<td>$L$ (erg)</td>
<td>$10^{30}$</td>
<td>$10^{32}$</td>
</tr>
<tr>
<td>Rise Time (s)</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Decay Time (d)</td>
<td>$10^{-4}$</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Peak Temp (10 K)</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Peak N</td>
<td>$10^{12}$</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>Peak Volume (cm$^3$)</td>
<td>$10^{3}$</td>
<td>$10^{23}$</td>
</tr>
<tr>
<td>Height of Loop (Km)</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Loop magnetic field</td>
<td>&gt;100 Gauss</td>
<td>&gt;100 Gauss</td>
</tr>
</tbody>
</table>

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
4. CONCLUSION

These observations support the view that the temperature distribution of the coronal emission from Algol measured in the 0.1-10 keV band is bimodal with peaks at $6.10^6$ K and $3.10^7$ K. The dimensions for these two components as inferred from the eclipse measurements and considerations of the flare parameters are quite different. The $6.10^6$ K component appears to be contained in loops with dimensions of $\sim 0.3$ R$_*$, the lack of any eclipse of the hotter component suggests loop dimensions that are greater than the radius of the underlying star. By analogy with the sun we might expect such a range of loop sizes, however, these results suggest that the larger loops contain the hottest plasma. Recent EXOSAT observations of AR Lac show that the same situation occurs in this more conventional RS CVn binary (White et al in preparation). Since the sun lies at the lower end of the range of coronal activity, further eclipse measurements of other binary stars and observation of flares are essential if further progress is to be made in understanding how to scale up the solar model to account for the most luminous stellar coronae.

REFERENCES