EXOSAT OBSERVATIONS OF LATE-TYPE STARS: THE APPLICATION OF CORONAL LOOP MODELS

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ABSTRACT. We apply solar-type coronal loop models to X-ray and UV observations of late-type stars. We derive from EXOSAT and IUE observations constraints on the temperature, pressure and size of the emitting structures.

1. INTRODUCTION

We have carried out a program of observations of late-type stars with the EXOSAT satellite. The observations were performed over the period January-September 1984. Detected sources include solar type stars of spectral type F8 to G5 as well as a number of BY Dra variables. A preliminary analysis of the observations and the derivation of physical properties using an isothermal approximation have been presented elsewhere (Landini et al. 1984a,b). In this paper, we analyze the same set of data in the framework of a coronal loop model and we show that a multitemperature distribution represents a substantial better fit of the observations.

2. OBSERVATIONS

The observations discussed in this paper were obtained using the Channel Multiplier Array (CMA) and the Low Energy Telescope LE1 on EXOSAT. Several filters were used in conjunction with the CMA in order to obtain information on the spectral distribution of the observed sources. All sources were observed with at least the Thin Lexan (# 3) and the Al/Pa (# 6) filters. For a few sources for which sufficiently long observation times were available, we also detected weak signals using the Boron (# 8) filter. The latter has a spectral band more similar to that of the Imaging Proportional Counter (IPC) on EINSTEIN. Except for some BY Dra variables, we found good agreement between our observations with the Boron filter and previous EINSTEIN observations with the IPC. For those stars not observed with the Boron filter, we have used previous IPC observations when available.


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In previous papers (Landini et al. 1984 a,b) we have analyzed our EXOSAT observations in terms of an isothermal model and we have derived average temperatures and emission measures for the detected sources. Most stars in our program have temperatures of the order of $\sim 3-4 \times 10^6$ K. BY Dra variables, however, have a somewhat higher temperature of the order of $10^7$ K. The derived emission measures are one to three orders of magnitude higher than for the Sun, consistently with the active nature and the relatively high rotation rate of all stars in our program (Pallavicini et al. 1981).

The isothermal approximation, although convenient, usually does not represent a good fit of the data. More importantly, it is unable to satisfy at the same time ultraviolet observations such as those obtained for several of our stars by the IUE satellite. In order to fit both X-ray fluxes and UV spectral lines a multitemperature distribution over the range $10^6 - 10^7$ K is required. In the following section, we consider a multitemperature loop model and we apply it to our EXOSAT observations and to previous IUE observations of the same stars.

3. LOOP MODEL

High resolution observations of the solar corona show that X-ray emission originates predominantly from magnetically confined loop structures connecting regions of opposite polarities. These loops extend from the chromosphere to the corona with a thin transition-region in between. It is likely that the same magnetic topology occurs in all late-type stars. The EXOSAT X-ray fluxes originate from the integrated contribution of all material at high temperature inside the loop structure. Similarly, ultraviolet spectral lines are emitted by sections of the loop which are within the relevant temperature range.

The temperature and density distribution inside a magnetically confined loop can be determined by solving the energy, momentum and mass conservation equations with appropriate boundary conditions. The model used by us is that developed by Landini and Monsignori-Fossi (1981). It assumes a cylindrical loop at constant cross-section with conductive flux vanishing at the loop base (at $T = 2 \times 10^6$ K) and with temperature maximum at the loop top. Static and stationary conditions are assumed. The heating is assumed to be constant along the loop. Thermal conduction does not represent an energy source or sink, but simply a way of transferring energy from one part of the loop to another. Radiative losses are evaluated on the basis of the optically thin thermal spectrum between 1 and 2000 Å computed by Landini and Monsignori-Fossi (1984) with revisions. It includes bremsstrahlung, recombination and line emission, and agrees within a factor of two with similar calculations by Kato (1976), Raymond and Smith (1977), Mewe and Gronenschild (1981) and Gaetz and Salpeter (1983).

We assume that all loops on the star are identical and that the total footprint area of all loops covers a fraction $f$ of the stellar surface. We indicate with $P_0$ the pressure at the loop base and with $T_{\text{max}}$ the temperature at the loop top. Since the emission in an integrated X-ray band or in an UV spectral line is approximately proportional to the
product \( p_0 \, f \) times a function of \( T_{\text{max}} \) (see Landini et al. 1984c), the observed X-ray and UV emissions define curves in the plane \((p_0 \, f) \, vs \, T_{\text{max}}\) which are the loci of the points allowed by the observed fluxes. If a description in terms of a network of identical loops is adequate, all curves should cross at one point, thus defining a solution for \( T_{\text{max}} \) and \((p_0 \, f)\). In those special cases (i.e. the Sun) for which additional constraints allow separation of the pressure \( p_0 \) from the filling factor \( f \), a unique model can be determined. In the next section we shall make a specific application of this method to the star \( \kappa \) Ceti (G5 V), which was observed with EXOSAT as well as previously by EINSTEIN and IUE.

4. RESULTS

We first consider a model at constant pressure, i.e. loops much shorter than the pressure scale-height. Fig. 1 shows for \( \kappa \) Ceti the plane \((p_0 \, f) \, vs \, T_{\text{max}}\) with several curves plotted, one for each of the observed X-ray and UV fluxes. It is apparent that all curves cross at one point within the errors, except the EXOSAT Al/Pa curve which runs systematically lower than all the others. We have found a similar systematic effect in all cases examined. Since the response of the Al/Pa filter at typical coronal temperatures \((T \sim 3 \times 10^6 \, \text{K})\) is determined almost exclusively by a few Fe lines around \( \lambda \sim 170-215 \, \text{Å} \), errors of the order of two in the theoretical spectrum may easily explain the difference. Alternatively, instrumental calibration uncertainties may be responsible for the disagreement. Given these uncertainties, we have chosen to exclude for the moment the Al/Pa flux and to consider the best fit obtained using the other EXOSAT filters as well as the EINSTEIN IPC and UV spectral lines from IUE. A \( \chi^2 \) - test gives a maximum temperature \( T_{\text{max}} = 1.1 \times 10^7 \, \text{K} \) and a product \( p_0 \, f = 0.34 \). Fig. 2 shows a comparison of predicted and observed X-ray and UV fluxes for this choice of the parameters. The agreement is excellent within the experimental errors. However, the predicted Al/Pa flux from EXOSAT is about a factor of two higher than observed. When the Al/Pa flux is taken into account, the quality of the fitting is considerably worse. We have found a similar discrepancy between different EXOSAT filters when using an isothermal model (Landini et al. 1984b).

Figs. 1 and 2 show that a loop model is a considerably better approximation than a simple isothermal model. Not only is the loop model able to fit the X-ray fluxes with a level of accuracy roughly comparable to that obtained with an isothermal model, but it allows at the same time fitting of ultraviolet lines observed over a broad range of temperatures. Furthermore, Fig. 1 suggests that the difficulty of reconciling EXOSAT observations obtained with different filters may reside principally in an incorrect evaluation of the Al/Pa flux. Whether this is due to uncertainties in the model spectrum used, or to instrumental calibration problems remains to be determined.

A model at constant pressure does not allow to separate the two quantities \( p_0 \) and \( f \). This can be done with additional assumptions, for instance by prescribing that the pressure decreases by a given
Fig. 1

Fig. 2
Fig. 3

K Ceti \( P_0 / P_{\text{MIN}} = 1/e \)

Fig. 4

\( P_0 = 12.5 \text{ dyne/cm}^2 \)
\( T = 1.9 \times 10^4 \text{K} \)
\( f = 0.028 \)

Fig. 5

\( P_0 = 125 \text{ dyne/cm}^2 \)
\( T = 1.9 \times 10^7 \text{K} \)
\( f = 0.028 \)
Fig. 6 - Predicted surface flux as a function of wavelength over the spectral range 1-2000 Å for the outer atmosphere of κ Ceti. A hydrogen column density $2.0 \times 10^{18}$ cm$^{-2}$ is assumed.

amount along the loop (Landini et al. 1984c). A physically plausible case is when all loops have a length equal to the pressure scale-height (Golub et al. 1982). This is equivalent to prescribing a ratio $P_0/P_{\text{min}} = 1/e$, where $P_{\text{min}}$ is the pressure at the loop top. Fig. 3 gives the results of this model for the star κ Ceti. Again all curves cross at one point except for the Al/Pa filter which runs lower than the other curves. The region of common interception as determined by a $\chi^2$-test gives a maximum temperature $T_{\text{max}} = 1.8 \times 10^7$ K and a base pressure $P_0 = 12.5$ dyne/cm$^2$. From the latter value we derive a filling factor $f = 0.028$. Different combinations of the parameters are obtained using different choices of the ratio $P_0/P_{\text{min}}$. Fig. 4 and 5 give the temperature distribution along the loop and the emission measure distribution for the case illustrated in Fig. 3. The loop semilength is $L = 5 \times 10^7$ cm. Fig. 6 shows the synthetized spectrum of the star between 1 and 2000 Å, taking into account interstellar absorption. The latter is evaluated according to the model of Paresce (1984) which assumes constant hydrogen density $n_H = 0.07$ cm$^{-3}$ in the solar neighborhood.

In conclusion, the application of coronal loop models, although generally not sufficient to identify uniquely the source model, allows us to obtain a family of possible solutions which describe equally well
the transition region and coronal properties of the star. In all cases, it provides important constraints on the temperature distribution in the emitting structures and allows an estimate of the combined effect of loop pressure and area coverage factor, which together determine the XUV flux of the star.

REFERENCES


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