EVIDENCE OF MAGNETIC CORONAE IN OTHER STARS

S. SERIO
Istituto e Osservatorio Astronomico
Palermo, Piazza del Parlamento 1, 90134 I

Abstract. X ray emission and activity in late type stars are generally believed to be caused by magnetic fields generated below the stellar photosphere. Coronal magnetic fields should induce structuring of the coronal plasma in loop like structures, as observed in the Sun. Do we have evidence of such structuring? I shall discuss how spectrally resolved X ray observations can evidence the existence of stationary stellar coronal loops. I shall also discuss how the lengths of stellar loops can be inferred by spectrally resolved observations during flare decay, and how the presence of coronal magnetic fields might influence the thermal stability of the transition region and induce characteristics signatures in line profiles.

1. Introduction

The evidence that the whole X-ray emitting solar corona is made out of magnetic loops has been derived from solar observations pioneered by the ATM mission, and now solidly established with the most recent *NIXT* and *YOHKOH* data.

The widespread observation of X ray emission from late type stars since the early results of the *Einstein* mission has been almost paradigmatically interpreted as evidence that stellar coronae should be similar to the sun, i.e. made up of loop like structures. However, the detailed interpretation and model fitting of stellar X ray spectral distribution and variability has only limitedly been based on loop models. For example, most of the analysis of Imaging Proportional Counter stellar spectra are usually presented in terms of one- or two-components isothermal models.

The reasons for this attitude - we firmly believe in loop coronae, but do not use this information for the interpretation of the data - is certainly to be found, but perhaps only in part, in the low count rate statistics and moderate spectral resolution generally available in stellar X ray observations.

2. Static Coronal Loops

2.1. THE DEGENERACY PROBLEM ...

One problem with the lack of popularity of loop modelling stays in a fundamental limitation. In fact, loop models are based on the two equations of hydrostatic equilibrium and energy conservation which, for a loop with constant cross section, take the form:

$$\frac{dp}{ds} = -nmg_s \tag{1}$$

$$E_H = n^2 P(T) - \frac{d}{ds}(\kappa T^{5/2}\frac{dT}{ds}) \quad , \tag{2}$$

where s is the coordinate along the field line and g_s the component of gravity along the same direction, p is the pressure, n the gas number density, m the average ion mass, E_H is the volumetric heating rate, T the temperature, $P(T)$ the energy loss function per unit emission measure, and κ the Spitzer coefficient of thermal conductivity. When the half-length L of the loop is much smaller than the pressure scale height $s_p = 2KT/mg$, where K is the Boltzmann constant, Rosner, Tucker and Vaiana (1978, RTV) scaling laws apply:

$$E_H = \frac{\kappa {T_{max}}^{7/2}}{L^2} \; = \; 10^5 p^{7/6} L^{-5/6} \quad , \tag{3}$$

$$T_{max} = 1.4 \cdot 10^3 (pL)^{1/3} \quad . \tag{4}$$

Using the RTV scaling laws, and $x = s/L$, it is easy to see that equation 2 becomes:

$$\frac{{T_{max}}^{1/2}}{3.1 \cdot 10^{19} \kappa K^2} P(T) - \frac{1}{{T_{max}}^{7/2}} \frac{d}{dx}(T^{5/2}\frac{dT}{dx}) = 1 \quad . \tag{5}$$

Hence, the distribution of temperature along the loop is independent on loop length and base pressure. If we assume that a stellar corona is dominated by a system of identical loops, then their dimensions cannot be determined by the spectral distribution of the observed photons. There is, essentially, a degeneracy in the loop model, that prevents to extract the information one ideally would like to obtain, i.e. how a stellar corona looks like.

2.2. ...AND ITS CURES

This problem was recognized since the earliest attempts to fit stellar X ray data with loop models (see for example Schmitt *et al.*, 1985). Of course, the degeneracy is rigorous only within the framework in which eq. 5 has been derived, and in particular, (i) when the loops are much shorter than the pressure scale height, (ii) when they have a constant cross section, and (iii) when Spitzer conductivity can be used with confidence.

2.2.1. *Gravity*

One contribution to breaking the degeneracy is gravity in equation 1, which becomes important when the height of the loops is comparable to the pressure scale height, or higher. When fitting a degenerate loop model to an observed proportional counter spectrum, the contours of constant χ^2 values in the p, L plane are open lines running parallel to the lines of constant effective temperature. Taking into account the pressure equation 1, they become closed at lengths comparable to the scale height, while remaining open for high pressure and short lengths (see, however, Maggio and Peres, 1995, for loops longer than the star radius). So, while the fits are able to determine well the values of the effective temperature, they give typically high formal values of the loop length, although lower values are also compatible even with stringent confidence levels.

2.2.2. *Widening Loop Cross Section*

The degeneracy of loop models is also removed if the cross section of the loops increases with height. In this case (e.g. Vesecky, Antiochos and Underwood 1979; Serio *et al.*, 1981), the thermal stratification is the same as in a toroidal loop, although with slightly lower values of maximum temperature. The larger volume available to the hotter plasma near the top of the loop, however, results in larger values of effective temperature.

As an example, Fig. 1 shows the dependence of the *Rosat PSPC* effective temperature on cross section expansion, assuming that it varies according to

$$\sigma = \sigma_o(1 + r/R_*)^\alpha \quad , \tag{6}$$

(of course, $\alpha = 2$ corresponds to radial expansion of the loops).

Although the data do suggest that solar coronal loops do not generally show any substantial variation with height of their cross section, successful fits have been obtained for stellar data, using model loops with variable cross section (for example Stern *et al.*, 1988, Lemen *et al.*, 1989).

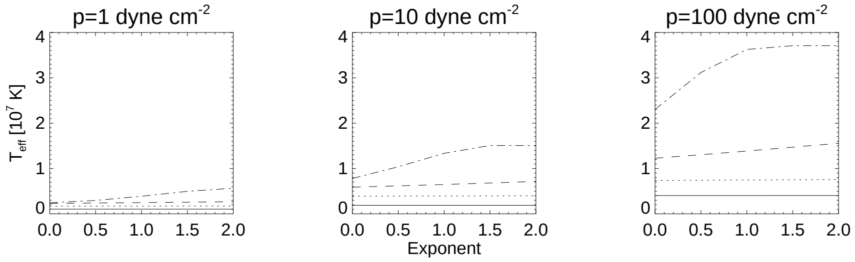

Figure 1. Dependence of the effective *Rosat PSPC* temperature on the loop expansion parameter α defined in equation 6 . Solid lines: loops of semilength $L = 10^9 cm$; dotted, $L = 10^{10} cm$; dashed $L = 10^{11} cm$; dot-dashed, $L = 10^{12} cm$.

2.2.3. *Deviations from Spitzer Conductivity*

Deviations of heat conduction from the Spitzer regime are important when the ratio of electron mean free path to temperature scale height is greater than $\approx 10^{-3}$ (Gray and Kilkenny, 1980). As shown by Ciaravella *et al.* (1995), however, these deviations play only a minor role in determining the observed spectrum, since they are large enough only at heights much larger than the pressure scale height, and therefore where the emission measure is very low.

2.3. BUT ..., DO WE NEED CURES, AFTER ALL?

Independently of the effects described above, which contribute to remove the degeneracy in loop modelling of stellar coronae, a simple physical description of a loop dominated corona can be made, at the price of using appropriate variables.

In particular, I will show the equivalence of isothermal and loop models, for loops lower than the pressure scale height and of uniform cross section. The problem is only to interpret in terms of a loop model the parameters derived from the one-T fit, which we know to work reasonably well, at least at first order: the temperature $T \propto (p_o L)^{1/3}$, and the luminosity

$$L_x \propto \frac{{p_o}^2 P(T)}{T^2} \, L f S_* \quad , \tag{7}$$

where S_* is the surface area of the star, and f the surface filling factor of loop like structures. Using the scaling law in equation 4, we easily see that $L_x \propto T P(T) f p_o S_*$. Therefore, a description of a degenerate one loop corona in terms of its maximum (or effective) temperature, and of the product of filling factor times base pressure, is essentially equivalent to a one-T model. The left panel of figure 2 shows a typical "banana" shaped fit

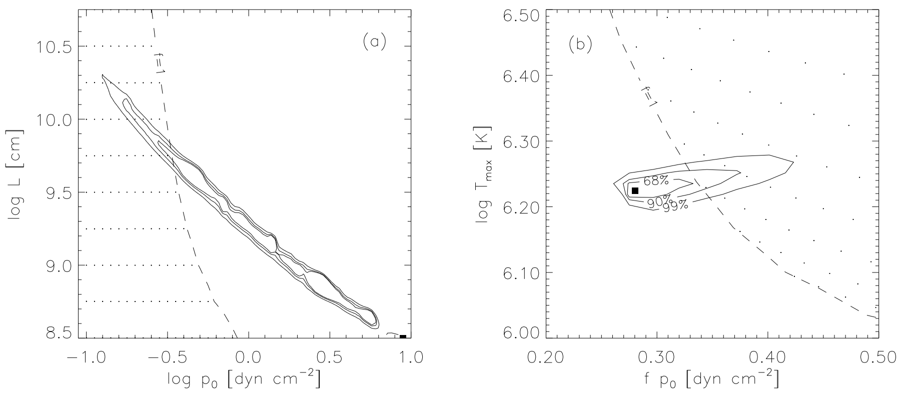

Figure 2. Analysis of the Rosat PSPC spectrum of Procyon with hydrostatic loop models (adapted from Maggio *et al.*, 1995) Confidence regions at the 68%, 90% and 99% levels in the p_0 - L (a), and in the fp_oT (b) loop parameter space. The dashed line shows the locus where the surface filling factor $f = 1$, and the shading the unphysical region where $f > 1$.

of a loop model to Rosat data in the p, L plane, dramatizing the uncertainty in the determination of the parameters of the fitting model (notice that the upper and lower limits in L and in p are accounted for by the fact that only a limited region of the parameter space has ben explored). Similar results are obtained in the LT and in the pT planes. In contrast, the right panel shows that the average coronal pressure fp_o and the maximum loop temperature T_{max} are reasonably well determined.

A further point of interest in this discussion is the possible presence of multiple systems of loops, which has not yet been investigated systematically. The discussion above can easily be extended, and two-temperature fits can be shown to be roughly equivalent to two-loops models.

The main question arising from these considerations, however, is the following: considering that one-loop models give generally χ^2 values better than one-T isothermal models and comparable to two- temperature models (Maggio and Peres, 1995), are not they more acceptable, since they are based on sound physical concepts, or should we continue to prefer isothermal models?

3. Evidence from Transients

It is well known that the size of a flaring region can be somewhat constrained by the decay time of the light curve. For instance, Reale *et al.* (1988) gave a picture of a coronal loop in Proxima Centauri obtained by the analysis of an *Einstein* X-ray flare by means of a hydrodynamical code.

The improved efficiency of *Rosat* gives now many more flares accessible to such analysis. Since hydrodynamic modelling is time consuming, we have developed a technique to analyze flares without having to build a specialized model for each event. The technique is based on the finding that the entropy in a flaring loops undergoes a phase of linear decay, whose rate is proportional to the length of the loop. During this phase, temperature and density are related by a scaling law (Serio *et al.*, 1992):

$$T \propto n^{\xi} \quad , \tag{8}$$

where the exponent $\xi = 2$ for the temperature of the top of a solar loop, and assumes different values for the effective temperature measured in the pass band of different instruments, or when excess heat is deposited during the decay phase of the flare (Jakimiec *et al.*, 1992; Sylwester *et al.*, 1993; Reale *et al.*, 1993). Recently Cargill, Mariska and Antiochos (1995) have re-obtained the same scaling law on the basis of an analytical model, and have also discussed the dependence of ξ on abundancies.

It turns out that we can derive the length of loops with a reasonable precision with this method. For example Sciortino *et al* (1995), using *Rosat PSPC* spectra, determine loop lengths for 3 flares observed in Pleiades K stars, and 1 in a field M star. The lengths derived are much smaller than the scale height at flare maximum, indicating confinement. Since we also measure peak emission measure (Σ) and temperature, we can estimate the gas pressure, given the flare volume. Assuming that confinement is obtained from a magnetic field B in a loop with ratio of semilength to cross section radius η, one can estimate $B\eta^{1/2} \approx 5.310^{-8}T^{1/2}(\Sigma/L^3)^{1/4}$.

Although we do not know the value of η, solar evidence and the results of Reale *et al.* (1988) for the Proxima Centauri loop indicate values of the order of .1. Using the values of temperature and loop length derived by Sciortino *et al.* (1995), the inferred magnetic fields are, therefore, $B > 170$ *Gauss* for Hz 892, $B > 35$ *Gauss* for Hz 1100, $B > 360$ *Gauss* for Hz 1516, and $B > 120$ *Gauss* for AD Leo.

It remains to investigate further along this line how these results depend on abundancies and on the assumption, implicit in equation 8, that the flare volume remains constant during the decay.

4. Red shifts in the transition region

Finally, I would like to suggest a novel approach to obtain evidence on the existence of magnetic fields in stellar coronae.

One puzzling result of Skylab and rocket solar UV observations was the discovery of $5 - 10 Km/s$ red shifts in solar transition region lines (e.g. Brekke, 1993, and references therein). More recently, similar results have been obtained on a variety of stars (Linsky, Wood and Andrulis, 1994; Linsky and Wood, 1995).

Reale, Peres and Serio (1995 a) have modelled in details the dynamic evolution of isobaric perturbations in a loop atmosphere. They have shown that condensations in the transition region can cause downdrafts driven by radiative cooling. As a condensation falls through the atmosphere, it tends to cool down and to increase its density, thus enhancing radiative losses. Therefore, falling perturbations emit more than the background atmosphere.

A thorough exploration of the parameter space shows that significant redshifted emission, at speeds of several km/s, can be produced both in active and quiet solar regions. The initial perturbations need to be moderately non linear (with density contrast ≈ 1), and with sizes typically larger than several tens of kilometers (Reale, Peres and Serio, 1995 b).

This mechanism might cause redshifts consistent with those observed, provided some constrains on the spectrum of the sizes of the perturbations and on their frequency are satisfied. As an example, figure 3 shows the distribution of time averaged flux enhancement in one of their models, representing an active region, as a function of velocity, in the hypothesis that the atmosphere is unmagnetized. The largest enhancements occur here for downward velocities of 4 to 7 km/s.

Even a small magnetic field, of the order of 1 *Gauss*, is strong enough to constrain these perturbations to fall along the field lines. When this happens, the falling perturbations can reach even higher values of velocity. In fact, suppression of motions and of thermal conduction in the directions perpendicular to the field lines conspire to make the condensations last longer and, therefore, to let them reach higher velocities.

While the origin of the perturbations has not been studied in detail, it appears unlikely that they could be due to purely hydrodynamic effects. Non linear MHD waves might have to be invoked in their generation. Doubtlessly, detailed measurements of transition region line profiles, together with dynamical modelling of the transition region, have the potential of furnishing some further diagnostic of the existence of magnetic fields in the coronae of stars other than the sun.

5. Acknowledgments

I thank A. Ciaravella, A. Maggio, G. Peres, F. Reale, and S. Sciortino for discussion. This research has been funded by the Italian Ministry of University (MURST) and by the Italian National Research Council (CNR).

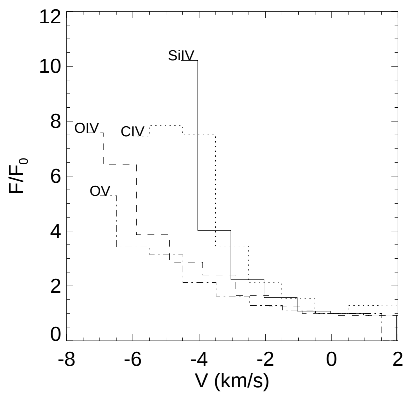

Figure 3. Time averaged flux enhancement in four UV lines (Si IV 1402.77 Å, C IV 1548.20 Å, O IV 1401.16 Å, O V 1371.30 Å), as a function of fluid velocity, during the evolution of an initially isobaric condensation (Radius 3 10^6 cm, initial density contrast 1) inside the transition region of an unmagnetized solar atmosphere with base pressure 3 dyne cm^{-2}.

References

P. Brekke, 1993, *Ap. J.*, **408**, 735.
A. Ciaravella, A. Maggio, G. Peres, and S. Serio, 1995, *A. & A.*, in press.
P.J. Cargill, J.T. Mariska and S.K. Antiochos, 1995, *Ap. J.*, **439**, 1034.
D.R. Gray, and J.D. Kilkenny, 1980, *Plasma Phys.*, **22**, 81
J. Jakimiec, B. Sylwester, J. Sylwester, G. Peres, S. Serio, and F. Reale, 1992, *A. & A.*, **253**, 269.
J.R. Lemen, R. Mewe, C.J. Schrijver, A. Fludra, 1989, *Ap. J.*, **341**, 474.
J.L. Linsky, B.E. Wood and C. Andrulis, 1994, in J.P. Caillault (ed.), *Cool Stars, Stellar Systems and the Suns*, A.S.P. Conference series **64**, 59.
J.L. Linsky and B.E. Wood, 1995, *Ap. J.*, in press.
A. Maggio, and G. Peres, 1995, *A. & A.*, in press.
A. Maggio, G. Peres, J.P. Pye, S.T. Hodgkin, and J.E. Morley 1995, *in preparation*
F. Reale, G. Peres, S. Serio, R. Rosner, and J.H. Schmitt, 1988, *Ap. J.*, **328**, 256.
F. Reale, G. Peres, and S. Serio, 1993, *A. & A.*, **272**, 486.
F. Reale, G. Peres and S. Serio, 1995 a, *A. & A.*, in press.
F. Reale, G. Peres and S. Serio, 1995 b, in preparation.
R. Rosner, W.H. Tucker, and G.S. Vaiana, 1978, *Ap. J.*, **220**, 643.
J. Schmitt, F.R. Harnden, R. Rosner, G. Peres, and S. Serio, 1985, *Ap. J.*, **288**, 751.
S. Sciortino, G. Micela, F. Reale, V. Kashyap, R. Rosner, and F. R. Harnden, Jr, 1995, this volume.
S. Serio, G. Peres, G.S. Vaiana, L. Golub, and R. Rosner, 1981, *Ap. J.*, **243**, 288.
S. Serio, F. Reale, J. Jakimiec, B. Sylwester, and J. Sylwester, 1991, *A. & A.*, **241**, 197.
R.A. Stern, S.K. Antiochos, and F.R. Harnden Jr., 1986, *Ap. J.*, **305**, 417.
B. Sylwester, J. Sylwester, S. Serio, F. Reale, R.D. Bentley, and A. Fludra, 1993, *A. & A.*, **267**, 586.
J.F. Vesecky, S.K. Antiochos, and J.H. Underwood, 1979, *Ap. J.*, **233**, 987.