CORONAL MAGNETIC FIELDS

R. Pallavicini
Osservatorio Astrofisico di Arcetri
Largo Enrico Fermi 5
50125 Firenze, Italy

1. INTRODUCTION

It is unfortunate that coronal magnetic fields cannot be easily measured, even in the case of the Sun. Except for a few measurements of magnetic fields in the transition region above sunspots, made using the conventional Zeeman effect, and except for the possibility of inferring the direction - not the intensity - of coronal magnetic fields using optical forbidden lines, direct measurements of coronal fields are virtually non-existent. The most promising method appears to be the use of the Hanle effect, i.e. the modification of polarization characteristics of spectral lines induced by magnetic fields. This method has been proposed for future space missions in solar physics, for instance for the European satellite SOHO, but its feasibility depends on the strength of the fields to be measured, which in any case must be higher than a few tens of Gauss.

However, in spite of this rather meager observational situation, there are a number of indirect evidences which all point at the importance of magnetic fields in solar and stellar coronae and which allow us to get some information on the configuration of the fields and even some model-dependent estimates of their intensity. For instance, if we know the distribution of photospheric magnetic fields over the stellar surface - as we do for the Sun - we can extrapolate the fields to coronal levels using a suitable mathematical model (either potential or force-free). Another important method is to use coronal X-ray emission. This is because the coronal plasma is a highly conducting medium, and the magnetic pressure greatly exceeds the gas pressure in typical coronal conditions. The observed coronal structures, therefore, effectively trace magnetic field lines in the corona. In the case of the Sun, we have the great advantage of spatially resolved observations and hence the possibility of inferring directly the magnetic field configuration. In the case of stars, the spatial information is usually lost, but we have another advantage, i.e. the possibility of comparing stars which span a wide range of different physical parameters, such as effective temperature, gravity, rotation, age etc. An example of this approach is the observed correlation between X-ray emission and rotation for

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stars of spectral types later than ~ F5. This correlation is a strong argument in favor of the fundamental role played by dynamo-generated magnetic fields in the heating of stellar coronae.

No less important is the use of radio emission, expecially emission at centimetric and decimetric wavelengths. In principle, thermal (gyro-resonance) and non-thermal (gyro-synchrotron and synchrotron emission) may allow the derivation of the magnetic field strength in the emitting region. The main problem in this case is to identify the correct emission mechanism on the basis of the spectrum and polarization characteristics of the observed emission. Moreover, propagation effects in a magneto-ionic medium may greatly complicate the interpretation of the data. Finally, indirect evidence for the role of magnetic fields in stellar coronae is provided by the stochastic nature of stellar variability (i.e. on time scales much shorter than the evolutionary time scale) and by the observed rapid drop-off of rotational velocities of main-sequence stars at spectral type ~ F5. The latter fact is usually interpreted as a result of magnetic braking produced by the outflowing of winds in the presence of magnetic fields.

In the short length of this review, it will not be possible to treat in detail all the above methods. Instead, I will focus only on one particular topic which I have chosen to be coronal X-ray emission. This is a powerful diagnostic tool for coronal magnetic fields. Since a number of excellent review papers on stellar coronae have appeared in the literature, I will simply emphasize the main physical points and I will report on some more recent results, while referring to the above review papers for a complete list of references (see, for instance, Rosner, Golub and Vaiana 1985, Linsky 1985, Schrijver 1985, Haisch 1985, Pallavicini 1985, Gary 1985, Dulk 1985).

2. WHAT HAVE WE LEARNED FROM SPATIALLY RESOLVED OBSERVATIONS OF THE SOLAR CORONA

Before proceeding, it may be useful to recall briefly what we have learned in the past fifteen years from spatially-resolved X-ray observations of the solar corona. Most of this information has been provided by the SKYLAB mission and, to a less extent, by subsequent space missions such as OSO-8 and SMM. The most fundamental result has been the recognition that the solar corona is extremely inhomogeneous and highly variable (Withbroe and Noyes 1977, Vaiana and Rosner 1978). The observed structures appear to be determined by the topology of the magnetic field. Two kinds of structures must be distinguished: closed structures, usually termed "loops", and open structures, usually known as "coronal holes".

Closed structures, from which most of the X-ray emission originates, are associated with regions of enhanced magnetic field at photospheric level and with regions of enhanced chromospheric and transition region emission. This suggests that magnetic fields may play an active role, not only in confining the observed structures and in controlling the flow of mass and energy, but also in providing for direct heating of the plasma. The heating mechanism is still poorly understood, but there is little doubt at present that the solar corona, as well as the coronae of stars of late spectral type, are heated by a magnetic process (cf. Pallavicini 1984).

Coronal holes, on the other hand, are regions of strongly reduced coronal X-ray emission. They appear to be associated with regions where magnetic field lines are open to the interplanetary medium. Moreover, they appear to be associated with recurrent high-velocity wind streams. It is important to notice that while the global properties of the solar wind can be described in first approximation by the model of a thermally-driven wind, i.e. a wind driven by the pressure gradient in a high-temperature highly-conductive medium, the high velocity streams originating in coronal holes require some additional energy/momentum deposition, possibly by Alfvén waves. The different magnetic topology of coronal structures and the different energy/momentum balance in open and closed field regions need to be taken into account when interpreting spatially unresolved stellar observations.

3. WHAT WE KNOW FROM SPATIALLY UNRESOLVED OBSERVATIONS OF STELLAR CORONAE

Let us consider now our present knowledge of stellar coronae as emerged from X-ray and ultraviolet observations provided by the EINSTEIN, EXOSAT and IUE satellites. The extensive stellar surveys of the EINSTEIN Observatory (Vaiana et al. 1981) have shown that stars throughout the HR diagram are X-ray emitters with flux levels ranging from less than 10^{26} erg s^{-1} to 10^{34} erg s^{-1}. The only notable exceptions are main-sequence A stars, for which there is no convincing evidence of stellar coronae, and late-type giants and supergiants to the right of a "dividing line" which runs approximately from spectral type G1 Ia to K2 III (Linsky and Haisch 1979).

Correlations of X-ray emission with other stellar parameters indicate that there is a dichotomy between early-type stars (O to B), for which the X-ray luminosity is proportional to the bolometric luminosity, and late-type stars (F to M), for which the X-ray luminosity is proportional to the rotational velocity, with no dependence on bolometric luminosity. It is interesting to notice that this change of behaviour appears to occur at about the same spectral type at which a fundamental change also occurs in the internal structure of stars. Early-type stars have no outer convection zones; the latter start to appear at spectral type ~ F0 and become deeper and deeper towards later spectral types. This suggests that the heating mechanism of stellar coronae may be fundamentally different for early and late-type stars. In the remainder of this paper, I will refer only to late-type stars for which there is ample evidence that the heating mechanism is of magnetic nature. Early-type stars for which magnetic fields may or may not be relevant for coronal heating will be excluded from further discussion.

Among late-type stars there is little, if any, dependence on spectral type, while a broad range of X-ray emission levels is observed for stars with the same effective temperature and gravity. This indicates that the heating mechanism cannot be purely acoustic, consistently with what can be inferred from solar observations. It also indicates that other parameters, in addition to effective temperature and gravity, are relevant in determining the level of coronal emission. These parameters may be convection, rotation, magnetic fields and age.

Coronal X-ray emission appears to be well correlated with chromospheric and transition region emission. This is exactly what is observed in the case of the Sun, and can be taken as evidence that magnetic fields emerging at the stellar surface penetrate through all layers of the outer stellar atmosphere and give origin to the observed optical (Ca II), ultraviolet (Mg II, C IV, Si IV, N V), and X-ray emission.

Finally, and most importantly, coronal X-ray emission among late-type stars appears to depend on both convection and rotation. The evidence for that will be discussed in some detail in the next section. In so doing, I will assume the following qualitative scenario as a useful conceptual framework:

- activity in the Sun and late-type stars results from the emergence of magnetic fields at the star surface;
- the emerging fields are produced by a dynamo process involving the interaction of rotation and convection;
- surface fields are stressed by turbulent fluid motions and generate heating by dissipation of DC currents and/or MHD waves;
- mass loss from open field regions (stellar winds) produces loss of angular momentum and stellar spindown.

The above scenario is able to explain qualitatively the available solar/stellar observations. However, better observations and more detailed models are needed to rise this qualitative scenario at the level of a sound quantitative theory.

4. DEPENDENCE OF STELLAR CORONAL EMISSION ON CONVECTION AND ROTATION

Let us consider now the empirical evidence we have of a dependence of coronal X-ray emission on convection and rotation (and hence on dynamo-generated magnetic fields). The most important fact suggesting a dependence on convection is the abrupt onset of X-ray emission among late-type stars at spectral type ~ F0, which sharply contrasts with the virtual absence of X-ray coronae among A-type stars. Schmitt et al. (1985) have carried out a detailed statistical study of X-ray emission for stars in the spectral range ~ A5 to ~ F5 and have shown that the X-ray luminosity function for stars in the color range $0.1 < B-V < 0.3$ is distinctly different from that of stars in the color range $0.3 < B-V < 0.5$. While his sample of stars of spectral types A5 to F0 is dominated by upper limits with only a few detections - particularly significant that of Altair at spectral type A7 -, the sample of stars in the spectral range ~ F0 to F5 is dominated by detections at comparable flux levels. Since outer convection zones are thought to become appreciable only in stars of spectral type later than ~ F0, the above result strongly suggests that the existence of outer convection zones is a necessary condition for coronal emission among late-type stars.

Another possible indication of the importance of convection can be found at the other extreme of the range of masses for late-type stars.

Bookbinder (1985) working with EINSTEIN data has found evidence for a decrease of coronal X-ray activity for stars later than M5. Since stars of spectral type later than ~ M5 are thought to be fully convective, the above result has important consequences for dynamo theories of stellar activity. If the dynamo is a "shell" dynamo which operates in a overshoot region at the boundary between the outer convective zone and the radiative interior - a view now shared by many workers in the field - fully convective stars will not have this boundary layer and may be expected to exhibit a reduced level of magnetic activity. There are several possible observational biases which may affect the results of Bookbinder: however, he has done a very careful analysis of his sample of M dwarfs and has produced convincing evidence that the effect is real. Several observational programs are now being carried on with the EXOSAT satellite to ascertain the reality of this decrease of activity for fully convective stars.

While convection appears to be important in determining the level of X-ray emission in early F stars and possibly in dwarf stars later than M5, there is little evidence for a dependence of coronal emission on convective zone depth for stars located in between these two extremes. This is clearly shown by the little, if any, dependence of coronal X-ray emission on effective temperature. On the other hand, coronal X-ray emission for stars in the range ~ F5 to M5 appears to be well correlated with rotation.

There have been in the literature many different formulations of the relationship between X-ray emission and rotation and some controversy has arisen with regard to the exact functional dependence of this relationship. There is no time and space to discuss here this problem, which to my opinion has been mainly caused by the non-completeness of the data samples used by different authors. Rather, I will simply refer to one of the early relationships, that proposed by Pallavicini et al. (1981, 1982), which is sufficiently good to illustrate the main points. Pallavicini et al. have found a dependence of X-ray luminosity on the square of the equatorial rotational velocity with no obvious dependence on spectral type and luminosity class, but with a very large scatter around the average relationship. The apparent lack of a dependence on spectral type is somewhat surprising, since, if coronal emission is produced by dynamo-generated magnetic fields, one would expect a strong dependence on both rotation and convection zone depth. The question is: is a dependence on spectral type buried in the scatter of the relationship between X-ray luminosity and rotation? The scatter found by Pallavicini et al. is more than one order of magnitude in X-ray luminosity and a factor 2 to 3 in rotational velocity. There are many possible causes of this scatter, including temporal variability - the X-ray luminosity of the Sun varies by about one order of magnitude during the solar cycle! - as well as uncertainties in rotational velocity determination and projection effects for spectroscopically determined rotation rates. However, the possibility exists that part of the scatter may be produced by a dependence of the observed emission on spectral type, as predicted by dynamo models.

An attempt to reveal this dependence on spectral type has been done by Noyes et al. (1984). They have plotted chromospheric Ca II H+K surface fluxes vs rotation period, and have found a reasonably good correlation, in agreement with previous authors. However, if the relationship is dependent also on spectral type, a better correlation would be found by plotting chromospheric emission vs some parameter which depends on both rotation and convection. The parameter they have chosen is the Rossby number defined as the ratio of the rotation period over the convective overturn time, which is a theoretically computed quantity dependent on spectral type. By plotting normalized Ca H+K fluxes vs Rossby number they have found a somewhat better correlation for a particular value ($\alpha = 2$) of the parameter α, the ratio of the mixing length over the pressure scale height in the convection zone. They have taken the reduced scatter as evidence that chromospheric (and coronal) emission depends on both rotation and convection, in better agreement with theoretical predictions.

Although appealing, this result is not completely convincing. Apart the uncertainties in the computation of convective overturn times, the two plots used by Noyes et al. to favour a formulation in terms of the Rossby number rather than one in terms of the rotation period, are not directly comparable. In fact, when plotting chromospheric emission vs rotation period, they have used the Ca II H+K surface fluxes, while they have plotted normalized fluxes, i.e. surface fluxes divided by the bolometric flux σT_{eff}^4, when using the Rossby number. There is no a priori reason to use normalized fluxes, and in so doing one introduces a strong dependence on color in addition to that implied by the use of the convecting overturn time. Actually, a plot of Ca II H+K surface fluxes vs Rossby number for the same data used by Noyes et al. shows no correlation at all (Governini and Pallavicini 1985). Moreover, Basri (1985) has shown that even using the formulation of Noyes et al., the correlation is destroyed when considering evolved stars in addition to main-sequence stars.

Summarizing, while the dependence of chromospheric and coronal emission on rotation is well established, there is at present no compelling observational evidence that convection zone depths play a relevant role in determining the level of magnetic activity, except for early F stars and possibly for very late M stars. It should also be noticed, that for values of the parameter α equal to or larger than 2, the convective overturn time depends very little on spectral type for all stars later than spectral type ~ G0. Thus, a formulation in terms of the Rossby number is essentially equivalent to a formulation in terms of the rotation period for these stars. Things may be different for F stars, for which the convective overturn time is a strong function of spectral type for virtually all reasonable values of α. Schmitt et al. (1985) have produced some evidence that the X-ray luminosity of early F stars, which is only weakly dependent on rotation rate, may show a stronger dependence on Rossby number.

5. PHYSICAL CONDITIONS IN STELLAR CORONAE AND INFERRED MAGNETIC STRUCTURES

X-ray observations of stellar coronae by HEAO-1, EINSTEIN and the

EXOSAT satellite have shown that the observed spectra are thermal. The physical parameters which can be derived in this case are the coronal temperature, the volume emission measure, and the flux and luminosity of the source. A significant - and puzzling - result borne out by these observations is that one-temperature isothermal models are usually a rather poor fit to the data. 2-temperature solutions are a much better fit to the observed spectra, with one component at temperatures of a few million degrees, and the other one at temperatures of several tens of million degrees. This has been shown by EINSTEIN IPC and SSS observations, as well as by EXOSAT broad-band and Transmission Grating observations (e.g. Schmitt 1985, Pallavicini, Monsignori-Fossi and Landini 1985, Schrijver 1985).

This situation is rather unlike that of the Sun. First, even considering the Sun as a mixture of active and quiet regions, the average temperatures of these two types of sources do not differ by more than a factor of 2, and temperatures of a few times 10^7 K are reached only during flares. Secondly, the Sun shows that the observed emission originates from confined magnetic structures which have a continuous distribution of temperatures from the chromospheric value up to a maximum at the loop top, rather than originating from distinct coronal volumes characterized by quite different temperature regimes.

There is at least one observational clue, in addition to the solar analogy, which suggests that the derived temperatures are not physically meaningful. Observations of the same stars by different instruments (e.g. comparison of IPC and SSS observations as well as comparison of EXOSAT broad-band observations and EINSTEIN IPC data) indicate the existence of substantial systematic differences, suggesting that the derived temperatures depend not only on the differential emission measure distribution inside the source, but also on the energy response of the detector employed. A much better physical interpretation of the observed spectra is to assume a distribution of confined magnetic structures over the stellar surface - similar to the structures observed in the solar corona - and to compute the expected X-ray spectrum by folding the resulting continuous temperature distribution inside the structures with the detector response. This has been done by Landini, Monsignori-Fossi and Pallavicini (1985) and by Stern, Antiochos and Harnden (1985) who have shown that an interpretation in terms of confined loop structures is at least as good as, and certainly more physically satisfactory than a description in terms of a 2-temperature model. Landini et al. have further shown that the assumed model is also able to fit ultraviolet emission lines originating in the transition region at the base of the emitting structures.

The above results suggest that most late-type dwarfs of all spectral types may have coronae similar to, although often much more active than the solar corona, i.e. characterized by confined magnetic structures with typical emission scale heights much smaller than the stellar radius. There are cases, however, in which this description certainly fails and the solar analogy does not appear to be valid. This is particularly true for Algol-type and RS CVn binary systems, in which there is evidence for high-temperature emitting regions which are large in comparison with the stellar radius. Such extended regions may be associated with interconnecting loops between the components of the binary system, as predicted by the magnetic field extrapolations of Uchida and Sakurai (1983).

Much information on the spatial structures of stellar coronae has been provided recently by eclipse observations of binary and multiple systems, particularly observations by the EXOSAT satellite which has the unique capability of performing uninterrupted observations for periods as long as four days. White et al. (1985a) have made an observation of Algol at the time when the K0 IV active component was eclipsed optically by the B primary. No eclipse was observed in X-rays, indicating that the high temperature ($T \sim 30 \times 10^6$ K) corona surrounding the K0 IV star extended for at least 3 stellar radii. Walter, Gibson and Basri (1983) using EINSTEIN data provided evidence for an extended corona around the K subgiant, as well as for a confined corona around the G dwarf in the binary system AR Lac. This has been confirmed recently by White et al. (1985b) who have made a 50 hours uninterrupted observation of this system using the EXOSAT satellite. A decrease of the total X-ray flux by ~50% was observed at the time of the eclipse of the G star, while no decrease of X-ray emission was observed at the time of the eclipse of the K star, indicating that the latter had a corona much more extended than the G star.

Further information on coronal emitting structures can be derived indirectly from the analysis of transient flare-like events. X-ray flares have been observed frequently from dMe flare stars (Haisch 1983, Pallavicini, Kundu and Jackson 1985), as well as from Algol-type and RS CVn binary systems (White et al. 1985a,b). Recently Landini et al. (1985) have succeeded in detecting an X-ray flare from a single G dwarf star (π^1 UMa), similar to,although more active than the Sun. The energy emitted in X-rays by this flare was at least a factor of ten higher than the total (thermal + kinetic) energy released in large solar flares. Even so, however, application of the solar analogy shows that the flare may have occurred in a confined structure small with respect to the stellar radius, which cooled by both radiation and conduction.

Finally, mention should be made of late-type giants and supergiants for which no evidence exists of high temperature coronae. From optical and ultraviolet observations, these stars are known to have strong stellar winds with mass losses far exceeding that of the Sun. At first sight, this may suggests an analogy with the case of solar coronal holes, i.e. with regions on the Sun with depressed coronal emission and enhanced wind streams. If so, the coronae of late-type giants and supergiants may be expected to be dominated by open magnetic field regions and by substantial weaker fields, in agreement with the low rotation rate of these stars.

However, a more careful scruting shows that the differences are more numerous than the analogies. In the Sun the wind is hot ($\sim 10^6$ K), has high terminal velocity ($v_\infty \cong 800$ km s^{-1}) and low mass loss ($\dot{M} \cong 10^{-14} M_\odot$ yr^{-1}). In late-type giants and supergiants, on the contrary, the winds are cool ($\sim 10^4$ K), have low terminal velocities ($v_\infty \cong 10$-50 km s^{-1}) and high mass loss ($\dot{M} \cong 10^{-6}$-$10^{-11} M_\odot$ yr^{-1}). Moreover, the upper limits to the X-ray surface flux in these stars are often several orders of magnitude below that of solar coronal holes. Models of wind acceleration in these stars via energy and momentum deposition by Alfvén waves have proven to suffer some fundamental difficulties (Mac Gregor 1983).

An alternative view has been expressed recently by Antiochos, Stern and Haisch (1985) in terms of magnetically confined loop structures. They have found that loop models in energy balance have two types of solutions, one characterized by high temperature ($T > 10^6$ K) and the other characterized by low temperature ($T < 10^5$ K). The discriminating parameter for the two types of solutions is the ratio of the loop height to the pressure scale height at the temperature of maximum radiative efficiency ($T \approx 10^5$ K). In the Sun, there is a large range of possible loop heights and hence a mixture of both hot and cool loops. In low gravity stars, however, the pressure scale height becomes much larger, and all loops on the star may have cool solutions, and hence absence of high temperature plasma. Antiochos et al. have shown that their model is able to reproduce rather satisfactorily the "dividing line" in the HR diagram between stars with and without hot coronae. However, this model, although interesting, decouples completely the problem of the absence of hot coronae from that of the acceleration of cool winds and thus may be only a partial description of the physical processes at work. It is fair to say that at present the topology of coronal magnetic fields in late-type giants and supergiants is virtually unknown.

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