SOLAR ACTIVITY — THE SUN AS AN X-RAY STAR

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ABSTRACT

The existence and constant activity of the Sun’s outer atmosphere are now thought to be due to the continual emergence of magnetic fields from the Solar interior and the stressing of these fields at or near the surface layers of the Sun. The structure and activity of the corona are thus symptomatic of the underlying magnetic dynamo and the existence of an outer turbulent convective zone on the Sun. On this view, a sufficient condition for the existence of coronal activity on other stars would be the existence of a magnetic dynamo and an outer convective zone. However, theoretical estimates of the level of activity to be expected on other stars are extremely uncertain at this time, so that tracers of activity and their scaling relations must be sought. The theoretical relationship between magnetic fields and coronal activity can be tested in detail by Solar observations, for which the individual loop structures can be resolved. However, a number of parameters which enter into the alternative theoretical formulations remain fixed in all Solar observations. In order to determine whether these are truly parameters of the theory we need to extend our observations to nearby stars on which suitable conditions may occur.

1. Introduction

A substantial fraction of the papers presented at this conference are being devoted to the subject of how Solar observations can be used to help stellar studies. I feel it appropriate in the present contribution to address the specific question, how can stellar observations help us to understand the formation and heating of the Sun’s corona? This is clearly an area which could be the subject of a meeting itself.

In the following I will select only a single well-defined topic, namely observational testing of magnetic field-related Solar coronal heating theories and discuss in some detail the ways in which stellar observations may be helpful in testing the correctness of such, theories proposed within the context of Solar coronal observations. I will then discuss some of the complications which we know to exist in the case of the Solar corona, the ways in which these complications may make interpretation of stellar data more difficult and some possibilities for simplification which may allow us to use stellar data in testing Solar-derived theories.
2. Magnetic Fields and Coronal Structure

Certainly the most important advance in our understanding of the Solar corona in the last twenty years has been the close association found between the location on the Solar surface of strong magnetic field regions and the enhanced x-ray emission above those locations. The fact that loops of hot plasma were located above active regions was known many years ago (Billings 1966). However, it has been the ability to observe the corona on the disk without line of sight integration effects, which has allowed us to determine the precise nature of the interaction between the magnetic fields and the coronal x-ray emitting plasma.

The connection between bipolar surface fields and coronal x-ray loops is illustrated in figure 1. This figure shows four different exposures of an active region, chosen to show the inner core loops and the larger, fainter loops connecting more widely separated portions of the active region. The magnetogram, which is coaligned and to the same scale as the x-ray images, shows that the x-ray loops do indeed connect opposite polarity areas, as expected.

![Figure 1. Four x-ray images of an active region, showing inner core loops and larger, weaker outer loops interconnecting regions of opposite magnetic polarity, as shown by the bottom magnetogram (from Rosner et al. 1978a).]
The rapid evolution and possible complexity of these coronal loops structures is shown in figure 2. The four images cover two days in the history of three active regions; one of them is large and well-developed at the start of the observing sequence, while two small regions emerge during the observation. We see that the large region develops a series of complex loops, some of which interconnect to nearby surface areas on the Sun. The smaller active regions grow rapidly and one of them flares early in its development (top right). The large range of scale sizes for coronal loops and the even larger range of surface brightness values encountered in the Solar corona is evident even from this example.

Fig. 2. Two days in the evolution of an active region and two emerging flux regions. Note the rapid and complex development of the x-ray loops, the flare in the young emerging region and the development of interconnecting loops between the regions. (Photo courtesy of G. S. Vaiana)

Figure 3 is a full disk view of the x-ray corona and illustrates most of the major (non-flare) features seen on the Sun. The bright, overexposed areas are active regions such as those shown in figures 1 and 2. The larger scale, more
diffuse emission is the evolved state of such large active regions and is often called quiet corona, although no part of the corona is truly quiet in x-rays. The elongated dark north-south region is a coronal hole. It is a large region on the surface dominated by a single magnetic polarity, so that the magnetic field becomes open to interplanetary space. Coronal holes are thus associated with high speed streams in the Solar wind, recurrent geomagnetic substorms and other terrestrial disturbances (Krieger, Timothy and Roelof 1973).

Fig. 3. X-ray image of the Solar corona, obtained from the S-054 x-ray telescope on Skylab, 1 June 1973. Most of the major non-flare features of the Solar atmosphere can be seen, including active regions, bright points, coronal holes and large-scale (quiet corona) structures. (Photo courtesy G. S. Vaiana)
The numerous small bright features throughout the corona are the so-called x-ray bright points. These are now known to be small bits of emerging magnetic flux, just as are the larger active regions (Golub et al. 1977). They form a continuous spectrum of scale sizes with active regions so that the distinction between them and the larger regions is somewhat arbitrary. However, the shape of the size distribution is such that the small regions account for most of the emerging magnetic flux on the Sun, except near times of maximum sunspot number. Equally surprising, there is an anticorrelation observed between the large and small regions (Golub, Davis and Krieger 1979), so that the emergence of magnetic fields on the Sun throughout the Solar cycle is more an oscillation of the wavenumber distribution of the emerging fields than a variation in the total quantity of flux emerging.

Fig. 4. Five Solar rotations of the x-ray corona as seen from Skylab. Columns are arranged to show the same quadrant on successive rotations. Note the eruption of a complex of activity in early September and the very low level of activity in the corona at 90\degree longitude separation.
If we ask the question, what does the typical Solar corona look like in x-rays?, the answer will depend on exactly when you look. This is illustrated clearly in figure 4, which shows five Solar rotations observed from Skylab image across is ~90° separated from the adjacent images. Thus each of the vertical columns show the evolution of the same Solar longitude during the five rotations. It is clear from examining these data, that the corona is highly variable, even during the relatively brief duration of the Skylab mission. The rapid variability is particularly evident during the fourth and fifth rotations, in which a large complex of activity emerged on one side of the Sun while there was a marked absence of activity on the other hemisphere. Thus the corona was observed to vary from a Solar maximum type to a Solar minimum type configuration during a period of only seven days.

The conclusions which we draw from studies of the type briefly reviewed above are:
- The Solar corona consists of a complicated mixture of structures, both topologically closed and open, with enhanced x-ray emission coming from closed loop regions.
- The coronal topology is determined by the stochastic emergence of strong magnetic fields from the Solar interior and the subsequent diffusion of these fields across the Solar surface.
- Significant variability of the x-ray emission (outside of flares) can occur on times scales of the order of the Solar rotation period, or less.

3. Tests of Heating Theories

We will now briefly examine the way in which stellar observations can help to evaluate theories which are developed in the Solar context. We chose magnetic field-related heating as an example and show that there are parameters which enter into the theory which may be constant for all Solar loops, but which vary significantly on other stars. Thus the possibility exists that this class of theories can be tested by stellar observations, if enough of the other relevant parameters are measurable quantities.

Fig. 5. Parameters of loop model.
The simplified model consists of a single loop of magnetic field, as shown in figure 5. We assume the following (see Golub et al. 1980 for a more detailed discussion):

- The energy necessary for confinement and heating of the plasma derives from shear at the base of the loop,
- The potential field, labelled $B_z$, does no heating or confinement,

$\beta$ above is done by the current-related azimuthal field $B_j$.

The energy available for heating is

$$ W_m = B_j^2 V / 8 \pi $$

and

$$ dB_j / dt = B_z \partial v_\phi / \partial z $$

The energy balance in the loop is obtained by assuming that all of the energy generated in the shearing process is dissipated in the corona:

$$ dW_m / dt = E_H $$

where

$$ E_H = 10^6 \rho^{7/6} L^{-5/6} $$

is the heating function obtained by Rosner et al. (1978b) and assumed in the following to apply to the full range of loops discussed in that paper.

Combining all of the above relations, we obtain the following general relation, which does not depend on a particular heating mechanism provided that eq. 3.3 holds:

$$ p = 2.6 (B_j B_z v_\phi)^{6/7} L^{-1/7} $$

For the Solar case, eq. 3.5 involves some quantities which are measurable, namely the coronal plasma pressure $p$, the loop length $L$ and the longitudinal magnetic field $B_z$ at the base of the corona, i.e., in the upper chromosphere. The quantity $v_\phi$ is the "effective twisting velocity" (Tucker 1973) and may not be directly observable; however, it should be related to the fluid velocity at the $\beta \sim 1$ level.

The quantity $B_j$ is not at the present time directly measurable in the corona and theory does not provide definitive limits on the range of values which it can assume. In Golub et al. 1980 we assumed arbitrarily that $B_j$ is a constant fraction of the longitudinal field $B_z$ for all loops:

$$ B_j = \alpha B_z $$

Subsequently, Galeev et al. (1981) showed that, for a broad class of heating mechanisms the azimuthal field is related to the coronal plasma pressure:

$$ B_j = 8.8 p^{1/5} $$

The latter relation leads to

$$ p = 63 B_z^{3/2} L^{-1/4} v_\phi^{6/7} $$

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This equation may be integrated over an entire bipolar region to yield an integral relation among observable quantities:

$$ U_T = 42 \Phi_T^{3/2} L^{-1/4} v_\phi^{6/7}, \quad (3.9) $$

where the quantity $U_T$ is the total thermal energy content in the corona:

$$ U_T = \int \epsilon \, dV = \int 3p/2 \, dV. \quad (3.10) $$

We note that the relation between $U_T$ and the total magnetic flux $\Phi_T$ is dominated by the trivial dependence between area and volume, since the respective integrations involved those quantities. However, the fact that the loop pressure $p$ and the longitudinal magnetic field $B_z$ in eq 3.8 are related by the 3/2 power is specific to the heating mechanism assumed and does contain true physical content. Comparison of eq. 3.8 with the previous relation 3.5 is sufficient to demonstrate this point.

It is at present not possible to test the question whether $v_\phi$ is truly a parameter in coronal heating. Even if it were in principle possible to observe the direct interaction between the fluid flows which provide the energy for heating and their interaction with the magnetic field in producing a shear, it appears at the present time that such processes occur at a spatial scale which is below the best resolution limit achieved to date in Solar observations. Moreover, it is likely that the process of interest occurs at a depth in the Solar atmosphere which is not directly observable by any known means.

Thus, we are forced to consider other means of testing the model. The obvious method, which now seems to be within reach, is to observe other Solar-type stars with coronal emission and for which the relevant parameter, in this case $v_\phi$, is very different from the Solar value. The attempt appears feasible, since the quantity $U_T$ has now been measured on a large number of stars of spectral type dG through dM (Vaiana et al. 1981; Pallavicini et al., this volume) and it now appears that $\Phi_T$ may be measurable on at least some of these stars (see contributions in these proceedings). At the same time, the level of surface turbulence in late-type stars varies by an order of magnitude, which may be enough to decide the question.

4. Are Attempts at Modelling Unresolved Coronae Realistic?

(i) The Division into "Active" vs. "Quiet" Regions

When we consider the extremely complicated mixture of loop structures which are formed in the Solar corona, it seems reasonable to ask whether unresolved stellar observations which necessarily average over the entire ensemble of structures in the stellar atmosphere can really be of any use in explicating the properties of the Solar corona. In the following, we will examine some of the limited information available and assess the feasibility of such work. In particular, we will find that within certain limits there is still a good possibility that unresolved stellar observations can answer some Solar questions and that continued close interaction between the two fields will be fruitful.

The usual way in which structure is introduced into unresolved observations of the emission in a particular line or radiative passband is to arbitrarily assign the total emission to two atmospheric components, "active" and "quiet" (see, e.g. Giampa 1980). The question whether such a division is reasonable in the Solar atmo-
sphere has specifically been examined by Cook et al. (1980), in the wavelength region 1175-2100 Å. They used Skylab data from the S-082B instrument and balloon rocket data, to cover the period 1973-79. Thus the study examined the usefulness of the active/quiet division both at a single point in the cycle and as a function of the cycle.

For our purposes, the major result of the study was that the integrated full disk flux can reasonably well be represented by:

\[ F_\lambda \cong \pi \langle I_\lambda \rangle_{\text{disk}} [ f C_\lambda + (1-f) ] \quad , \quad (4.1) \]

where \( C_\lambda \) is a wavelength-dependent contrast factor \( \frac{I_{\text{active}}}{I_{\text{quiet}}} \) and \( f \) is the fraction of the disk occupied by plage. As a byproduct of the investigation, Cook et al. used data from Sheeley (1967) to relate the fraction \( f \) to another activity indicator, the Zurich relative sunspot number \( R_z \):

\[ f \cong 6.3 \times 10^{-4} R_z \quad . \quad (4.2) \]

A study of more direct relevance for XUV and x-ray observations was performed by Pallavicini et al. (1981), using Skylab S-054 and S-056 x-ray and XUV data. A typical set of XUV rasters of an active region is shown in figure 6, which

Fig. 6. Spectroheliograms of a Solar active region in XUV lines observed by the HCO S-055 experiment on Skylab. (from Pallavicini et al. 1981)
illustrates the appearance of a plage region in lines ranging in temperature from chromospheric (C II) to coronal (Mg X); the x-ray appearance of such regions has been illustrated in figures 1-3 above. In this study we examined the question whether there exist intensity values of coronal emission, such as x-rays or Mg X, which can be used as cuts to separate active vs. quiet areas in the underlying transition region and chromosphere. Such a procedure is clearly a necessary step in attempting to interpret unresolved stellar observations and the success of this effort is necessary if we are to proceed with the analysis of the stellar data.

The findings of the study are illustrated in figure 7; we have chosen the line of O VI at λ1032, but the result is similar for the other lines as well. We find that the very high contrast in the corona between active and quiet regions on the Solar surface is translated down throughout the entire transition region and into the chromosphere. That is, a spatial mask made by applying an intensity cut to a coronal emission line serves nearly as well in defining a spatial mask for the lower temperature emission. The procedure allows us to not only divide the XUV integrated emission into active and quiet contributions, but also determines automatically the appropriate value of the intensity value to be used as a cut in each line and the values of the ratio $I_{\text{active}}/I_{\text{quiet}}$.

![Graph of observed frequency distribution of intensities in the line of O VI at 1032 Å.](image)

**Fig. 7.** (left) Observed frequency distribution of intensities in the line of O VI at 1032 Å. "Active indicates an area centered on active region structures as seen in a coronal line (Mg X) and "quiet" refers to the remaining picture elements in the raster image.

(right) Percentage contribution to the integrated intensity over selected areas of the XUV raster, from data points brighter than I as a function of I. The three curves plotted are for the entire raster, for a subarray centered on an active region and for the remaining area of the raster.

(from Pallavicini et al. 1981)
(ii) Atmospheric Components and Their Variation Throughout the Activity Cycle

We have so far examined the question, whether coronal emission from unresolved observations can be represented reasonably well by two-component models. More precisely, we are asking whether it is possible by unresolved observations to determine the values of parameters which are of interest in testing Solar-derived theories for the formation and heating of the corona. To this point it appears that the approach is a promising one if we are seeking to differentiate a particular type of Solar feature, such as a large active region, from the weaker and more diffuse large scale structure generally referred to as "quiet corona".

Unfortunately, we must now face another complication. The Solar atmosphere does not form itself neatly into just two types of structures. As pointed out in §2, there are many different types of magnetic structures in the corona, both large and small, open and closed and with substantially different temperatures, densities and evolutionary timescales. A skeleton outline of the range of different atmospheric constituents found on the Sun is shown in Table 1:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Size (10^9 cm)</th>
<th>Lifetime (sec)</th>
<th>Magn. Φ (Mx)</th>
<th>Distrib.</th>
<th>Flux Contrib. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>at min</td>
</tr>
<tr>
<td>XBP</td>
<td>1</td>
<td>&lt;3x10^4</td>
<td>&lt;10^19</td>
<td>Uniform</td>
<td>70</td>
</tr>
<tr>
<td>ER</td>
<td>2-5</td>
<td>&lt;10^5</td>
<td>&lt;10^20</td>
<td>Peaked</td>
<td>20</td>
</tr>
<tr>
<td>AR</td>
<td>10</td>
<td>&gt;10^5</td>
<td>&gt;10^20</td>
<td>Peaked</td>
<td>10</td>
</tr>
<tr>
<td>AR Compl.</td>
<td>20-50</td>
<td>&gt;10^7</td>
<td>&gt;10^22</td>
<td>Peaked</td>
<td>0</td>
</tr>
</tbody>
</table>

This table lists the atmospheric components which are important in terms of the amount of magnetic flux which they bring to the Solar surface. We note that the relevant quantity is the flux per unit time, denoted above as "flux contribution". If we consider the effect on coronal structure of the emerged flux, then it is necessary to consider the lifetimes of the various emerging features; thus, the longterm structure of the large scale corona is controlled by the largest active regions, even though they account for only a small percentage of the total emerging magnetic flux.
During the ascending and descending phases of the Solar cycle, a single loop size/single temperature model is not adequate to characterize the emission properties of the corona, except within the limits noted above.

Even at Solar maximum and minimum, there is significant short term variability, on time scales from seconds to days (see figure 4).

In order to produce an overall representation of coronal emission in terms of the various known atmospheric components, we need to consider the evolutionary histories of the different types of emerging field regions, including their lifetimes, temperatures, surface distribution patterns and their interaction with nearby atmospheric components. In addition, it is necessary to consider the Solar cycle variation of all of these quantities, since the relative importance of, e.g., large vs. small active regions is known to be a strong function of phase in the cycle. Moreover, the fraction of the Solar surface area covered by coronal holes is strongly dependent on the cycle, as is the scale size of the quiet corona since this depends on the properties of the active regions which are feeding the large scale structure.

A first rough attempt at modelling all of these complications is shown in Table 2. We have listed not only the emerging field regions from Table 1, but also the structures into which they evolve, namely large scale structure from active regions and complexes of activity, coronal holes from large active regions, and XBP remnants representing the equivalent of the large scale structure at Solar minimum (fig. 8).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Luminosity at min</th>
<th>Contrib. (%) at max</th>
<th>Phase wrt Cycle</th>
<th>T (10^6 K)</th>
<th>( \int n_\text{e}^2 dl ) (cm^-5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBP</td>
<td>2</td>
<td>0</td>
<td>180°</td>
<td>1.8</td>
<td>10^{28}</td>
</tr>
<tr>
<td>ER</td>
<td>2</td>
<td>1</td>
<td>none</td>
<td>2.0</td>
<td>2 \times 10^{28}</td>
</tr>
<tr>
<td>AR</td>
<td>5</td>
<td>40</td>
<td>0°</td>
<td>2.4</td>
<td>2 \times 10^{29}</td>
</tr>
<tr>
<td>AR Comp.</td>
<td>0</td>
<td>30</td>
<td>0°</td>
<td>2.4-4.0</td>
<td>10^{30}</td>
</tr>
<tr>
<td>XBP Remn.</td>
<td>20</td>
<td>3</td>
<td>180°</td>
<td>1.6</td>
<td>2 \times 10^{27}</td>
</tr>
<tr>
<td>LSS</td>
<td>70</td>
<td>25</td>
<td>0°</td>
<td>1.8</td>
<td>3 \times 10^{27}</td>
</tr>
<tr>
<td>CH</td>
<td>1</td>
<td>1</td>
<td>±90°</td>
<td>1.3</td>
<td>3 \times 10^{26}</td>
</tr>
</tbody>
</table>

Table 2
Properties of Atmospheric Components vs. Solar Cycle
Fig. 8. Solar cycle variations of the major components of the Solar corona. Top curves show the variation throughout a cycle of the percentage area coverage for the largest atmospheric features. Bottom curves indicate the relative percentage contribution to the total integrated Solar coronal emission for the features indicated above and their evolved forms, where applicable.

From examination of this "composite corona" model, we may draw the following preliminary conclusions:
- The average Solar corona is dominated by a single type of structure approximately 50% of the time.
At Solar maximum, we may characterize the entire coronal emission by the properties of large active regions, with $T \sim 3 \times 10^6$ K and emission measure $\sim 10^{50.6}$.
At times of Solar minimum, the corona is characterized by $T \sim 1.8 \times 10^6$ and EM $\sim 10^{49}$. 
5. Conclusions

In answer to the question we have posed, namely are attempts at modelling unresolved coronae realistic?, the answer with caution seems to be, yes there is hope. This implies that there is also hope for the larger question, whether stellar observations can be of use in helping us to understand the physical processes involved in the formation and heating of the Solar corona. The parameters involved in testing Solar coronal theories - such as magnetic flux, X-ray and XUV emission, rotation rates, optical, EUV and x-ray spectral features, surface turbulent velocities - can be measured, at least on some stars. It is therefore not only legitimate, but imperative, that Solar physics make use of the vast new opportunities now opening in the stellar area as a means of advancing our understanding of the Sun's outer atmosphere.

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6. References


