QUIESCENT CORONAE OF ACTIVE CHROMOSPHERE STARS

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ABSTRACT

The *EINSTEIN* Observatory has for the first time provided high sensitivity X-ray measurements of quiescent coronal emission from a large sample of dwarf stars. We now have observed a sufficient number of the nearby M-dwarfs to determine an X-ray luminosity function and we have explored the activity and variability of these stars to the extent of observing, for the first time, X-ray flares with simultaneous ground-based optical and IUE ultraviolet coverage.

The M dwarfs are found to have a much higher degree of variability in X-rays than does the Sun; however, in most cases a quiescent level is definable. We will discuss the quiescent emission from these stars and the changes in quiescent level on time scales from hours to $\sim$ 1 year. We have determined coronal temperatures for many of these stars; they are generally hotter than the Solar corona and some of the more active dM stars have $T_{cor} \sim 10^7$ K.

Arguments are presented in support of the hypothesis that M-dwarf coronae are magnetically dominated, as is the Solar corona. We then examine the usefulness of loop model atmosphere calculations in elucidating the coronal heating mechanism and the ways in which observations may be used to test competing theories. The X-ray measurements can be used to predict magnetic field strengths on these stars, with testable implications.

I. OVERVIEW: SOLAR-TYPE STARS.

In attempting to discuss coronal emission from M-dwarf stars, we are exploring a totally new area, for which there has until now been very little data available and which we can therefore approach with an open mind. The observation of X-ray emission from these stars is an especially recent achievement and it is only with the very high sensitivity available from the *EINSTEIN* Observatory that we are beginning to obtain a reasonably complete initial survey of the coronal properties of these stars.

P. B. Byrne and M. Rodonò (eds.), Activity in Red-Dwarf Stars, 83–108.

In this review I will summarize the presently available data on coronal emission from dwarf M-stars. In so doing, it will be necessary to broaden the discussion somewhat in order to examine late-type dwarfs in general. The discussion will include not only the Solar-type active chromosphere stars which are similar in many respects to the M-dwarfs, but also the larger class of cool stars which are expected to have outer convective zones and the consequent magnetically dominated outer atmospheres related to the presence of Solar-like dynamo activity.

Since we are finding that the properties of red dwarfs are in many respects only an extension of the behavior observed in Solar-type stars, it will be useful to begin this review by examining some of the Solar data. The reasons for doing so are: first, that the Sun is the only star for which we have been able to see any details of the coronal structure and also, because we now have reason to believe that the coronae of dM stars differ from the Sun mainly in an exaggeration of properties which are present in the Solar context, rather than in the appearance of qualitatively new phenomena.

a. The Solar X-ray Corona

Figure 1 shows a typical image of the Solar corona as seen in high-resolution X-ray observations. The wealth of detail to be found in such data has been discussed at length elsewhere (e.g., Vaiana and Rosner 1978 and references therein), so that we will mention here only the basic point that the X-ray emission derives predominantly from closed loop structures. These are seen in Figure 1 in a range of sizes and brightness levels, corresponding in general to the evolutionary history of the surface magnetic fields which control the coronal structure. The most intense emission occurs in active region cores, which contain the strongest magnetic fields. Further away from these areas and also at locations where older, more evolved active regions are found, the X-ray corona is larger, more diffuse, cooler and weaker.

On the basis of such observations, we may argue for an active participation of the magnetic field in coronal formation and heating (see e.g., Vaiana and Rosner 1978). Thus, the emerged surface magnetic fields not only control the coronal topology, but are now viewed as providing the means for direct mechanical heating of the coronal plasma.

This role of B has been tested in a series of quantitative studies involving direct predictions among observable quantities. The first of these relations was a thermodynamic one, which viewed the isolated closed loop structure as a relatively isolated mini-corona. By taking such a loop as a closed system in hydrostatic equilibrium, Rosner, Tucker and Vaiana (1978) were able to derive the now well-known scaling law

$$T_{max} = 1.4 \times 10^3 \ (pL)^{1/3} \qquad (1.1)$$

which provides a quantitative test of the hypothesis that the structuring of the atmosphere into closed loops is a fundamental consideration in coronal formation.

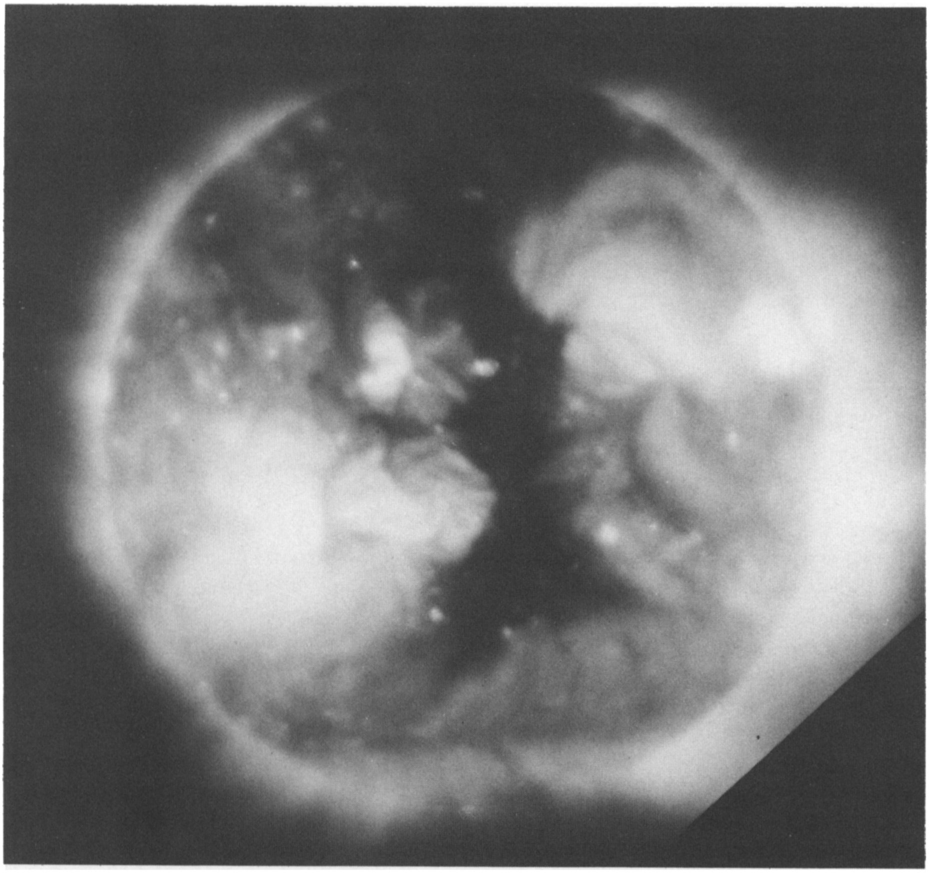

Fig. 1. The Solar x-ray corona, as seen from Skylab on 1 June 1973 (Photo courtesy G. Vaiana).

A test of the direct link to B in the coronal heating process was provided by Golub *et al.* (1980). Using a simple, general model in which magnetic stresses induced by turbulence in the HCA are transmitted into the corona and dissipated *in situ*, and employing the RTV relation (1.1), a scaling law involving B is obtained:

$$p = 63\, B_z^{3/2}\, L^{-1/4}\, V_\phi^{3/2}, \qquad (1.2)$$

where B_z is the average longitudinal magnetic field at the loop footpoint and V_ϕ is the effective twisting velocity of the longitudinal magnetic field and is related to the level of surface turbulence in the $B \gtrsim 1$ region of the Solar atmosphere.

Quantitative studies of this kind are continuing and provide the most direct means of testing the role of the magnetic field in the coronal heating process. Using the Solar observations as a starting point, we will examine in § III below the nature of M-dwarf magnetic fields as deduced from the X-ray

b. Extent of Solar-type Coronae along the M-S

Before turning to the M-star data, it is appropriate to review briefly what we have learned about coronal emission from Solar-type stars in general. As already discussed, I will take the view that all magnetically dominated coronae of the Solar type should be viewed together, as long as we can consider that their coronae are due to the emergence and subsequent activity of magnetic fields, presumably due to a Solar-type dynamo operating in the star's outer convective zone. This category is likely to include all main-sequence stars from late A up to and including the M-dwarfs; it may also include all rotating convective stars, if the observations of evolved cool stars are a guide.

What we have learned about the average level of coronal emission from late-type stars may be summarized by two basic observational facts: 1) all dwarf stars of spectral type dF through dM are X-ray emitters at some level between about 3×10^{26} and 10^{31} erg s^{-1}; and 2) the main factor determining the level of X-ray emission for stars later than about F7 is the stellar rotation rate.

These two basic points are summarized in Figure 2. This figure is from a study under way as a follow-up to the Pallavicini et al. (1981) paper, in which we first reported the quantitative connection between L_x and v sin i. Figure 2 shows the rotation dependence of coronal emission for stars of spectral type F7 to M5 and luminosity classes III, IV and V. The empty symbols indicate spectroscopic determinations of v sin i, and the filled symbols indicate close binary systems and spotted stars for which v_{rot} represents the equatorial rotation rate. The straight line indicates a best-fit to the total data sample and is the relation we found earlier, namely that L_x is proportional to the square of the stellar rotation rate. Note especially that all luminosity classes fall on the same line, which is the basis for the statement above that rotating, convective systems in general may behave in the same way as the Solar-type stars.

The influence of rotation is even more striking if we consider that early-type stars do not show any rotation dependence in the coronal X-ray emission. Thus, for stars all the way from early O through Altair at A7, the X-ray emission is found to be proportional to the stars' bolometric luminosity (Pallavicini et al. 1981 and references therein), the proportionality constant being 10^{-7}. The transition between early- and late-type behavior along the main sequence occurs at spectral type F. It is thus tempting to speculate that the observed sharp rise in X-ray emission at ∿ F0 is due to the onset of convection and the consequent beginning of Solar-type dynamo activity.

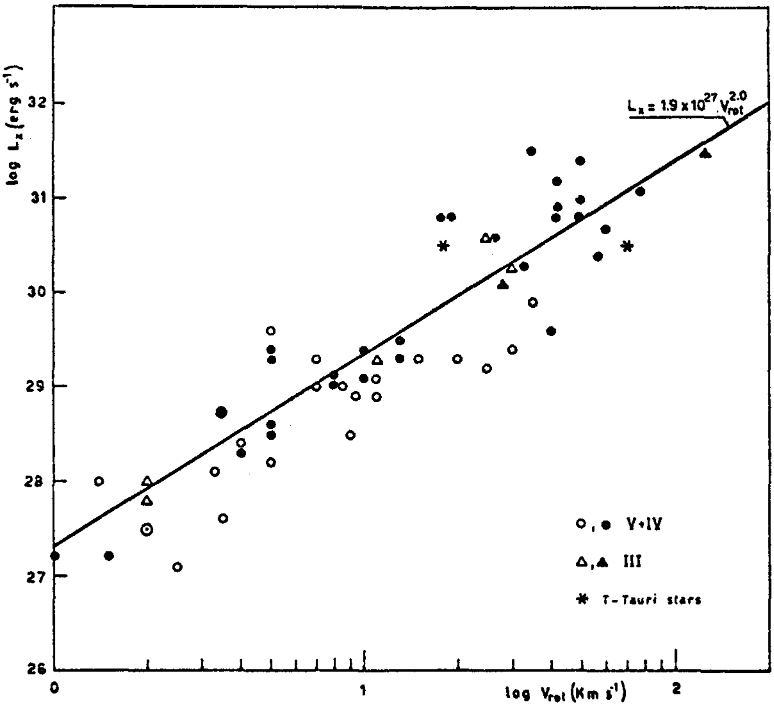

Fig. 2. L_x vs. v sin i for stars detected by the EINSTEIN Observatory.

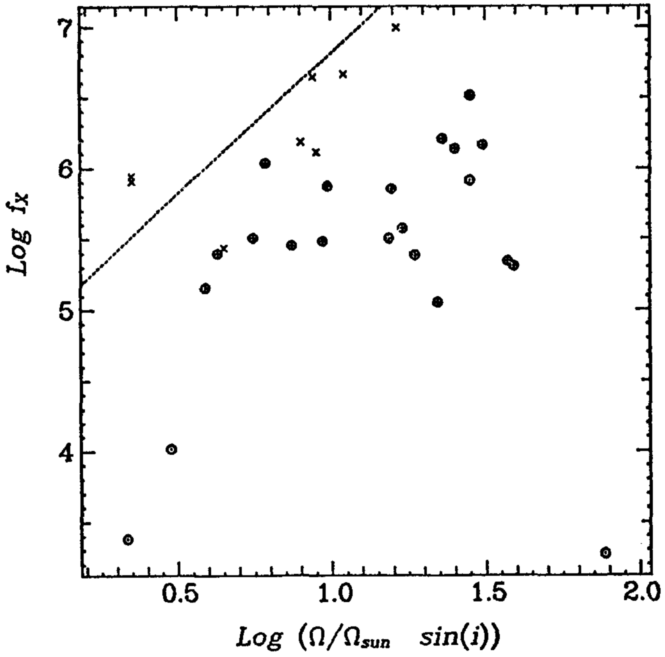

Fig. 3. X-ray surface flux vs. rotation rate for late-A through early G dwarf stars. Circles are A-stars, Circles with plus signs are F0-F5 and Crosses are F6-F9 (courtesy J. Schmitt, CFA).

This idea is being explicitly pursued in a combined theoretical and observational project at the CfA. Figure 3 (courtesy J. Schmitt, CfA) shows preliminary results of a detailed survey of late A and early F star X-ray luminosities vs. rotation rates. The circles at the bottom of the figure show the A-stars, which is mentioned above, have L_x x 10^{-7} L_{bol}; their X-ray emission is therefore relatively weak and independent of rotation rate.

At the other extreme, the dashed line near the top of the figure is the L_x vs. v sin i relation found for late-type stars (G-, K-, and M-stars. The x's represent F-stars later than F6, and they are close to the dashed line, thus obeying the late-type star behavior. The early and middle F stars fall in between, with a smaller slope. By combining these (and more) data with theoretical calculations, we hope to clarify the behavior of dynamos and possibly to understand in a quantitative manner the relationship between stellar rotation and magnetic field production.

II. THE M-STAR DATA

The combination of high sensitivity, high spatial resolution and pointing capability offered by the EINSTEIN Observatory have provided a totally new perspective on coronal emission from M-dwarfs. We now have detected steady X-ray emission from over three dozen M stars; in contrast, the pre-Einstein reports of steady emission included only the triple system 40 Eri (Cash *et al*. 1979) and the likely identification of BY Dra and AD Leo (Ayres *et al*. 1979), all from HEAO-1. Previous reports also included detection of X-ray flares or transients from such well-known flare stars as YZ CMi, UV Cet and Proxima Cen (Heise *et al*. 1975; Haisch *et al*. 1977; Kahn *et al*. 1979). Even in these cases, however, simultaneous coverage at other wavelengths was generally sparse, making quantitative analysis and comparison with Solar flares difficult (cf. Kahler 1977).

A search of the current literature for the available data on M-dwarf emission yields the list shown in Table 1; sources of these data are indicated. This list includes all of the published data and preprints of which we were aware as of the date of this meeting, as well as a number of previously unpublished observations from our own CfA survey.

We are at this moment in the midst of a very active period of data reduction, and there are sure to be several additions to this list during the next year. However, the number of sources which are already available and the quality of the observations allow us to discuss the general characteristics of X-ray emission from M-dwarfs. Our sample is already representative of this class and we can expect that the preliminary conclusions which we are now able to reach will remain fairly accurate.

An indication of the completeness of the present data set is shown in Figure 4, which is an H-R diagram made up of the stars listed in

Table 1. Summary of M-Dwarf Data

Star Name	Sp	log L_x	Ref. No.
+43 44 AB	dM1 + dM6	27.1T	1
UV Cet	dM5.5e+dM5.5e	27.3-27.6T	1
40 Eri C	dM4.5e	27.8	1
Ross 47	M6VI	27.1	1
Ross 986	dM5e	27.5	2
YY Gem	dM1e-dM1e	29.6	1
YZ CMi	dM5e	28.6	8
AD Leo	dM4.5e	29.0	2
CN Leo	dM8e	26.6-27.1	1,2
DM+44 2051	dM2e+dM8e	27.5-28.5T	1,3
DM + 36 2322	dM0e+dM4e	28.9T	1
Prox Cen	dM5e	26.6-27.4	1,4
Wolf 630AB	dM3.5e	29.3	1
DM + 68 946	dM3.5	26.9	2
Barnard's	M5 VI	26.1	1
GL 752 AB	dM3.5e+dM5e	27.1T	1
HD202560	dM0e	27.2	2
HD204961	dM1	26.8	2
Krüger 60	dM3+dM4.5e	27.4T	1
L 789-6	dM7e	26.9	2
EQ Peg AB	dM4e+dM5.5e	28.8T	1
Ross 614A	dM7e	26.9	2
CR Dra	dM1.5e	29.1	5
BY Dra	dM0e+dM2e	29.5T	5
AU Mic	dM2.5e	29.9	6
Gl 867 AB	dM2e+dM4e	29.0T	3
Gl 852 AB	dM4.5e+dM5e	29.5T	3
AT Mic	dM4.5e+dM4.5e	29.3T	3
Gl 229	dM2.5	28.8	3
CC Eri	dK7e	29.3	3
DM+01 2684	dM0e	28.2	7
Ross 476	dM6	28.0	7
DM+40 2208	dK8e	28.4	7
AC+45 217-363	dM2+M5	27.9	7
Wolf 630C	dM5e	26.4	9

1 Vaiana *et al.* 1981
2 Unpublished CfA 1982
3 Haisch & Tsikoudi 1982, preprint (HEAO-1)
4 Haisch *et al.* 1980
5 Vaiana *et al.* 1982
6 Caillault 1982
7 Topka 1981
8 Kahler *et al.* 1982.
9 Swank & Johnson 1982

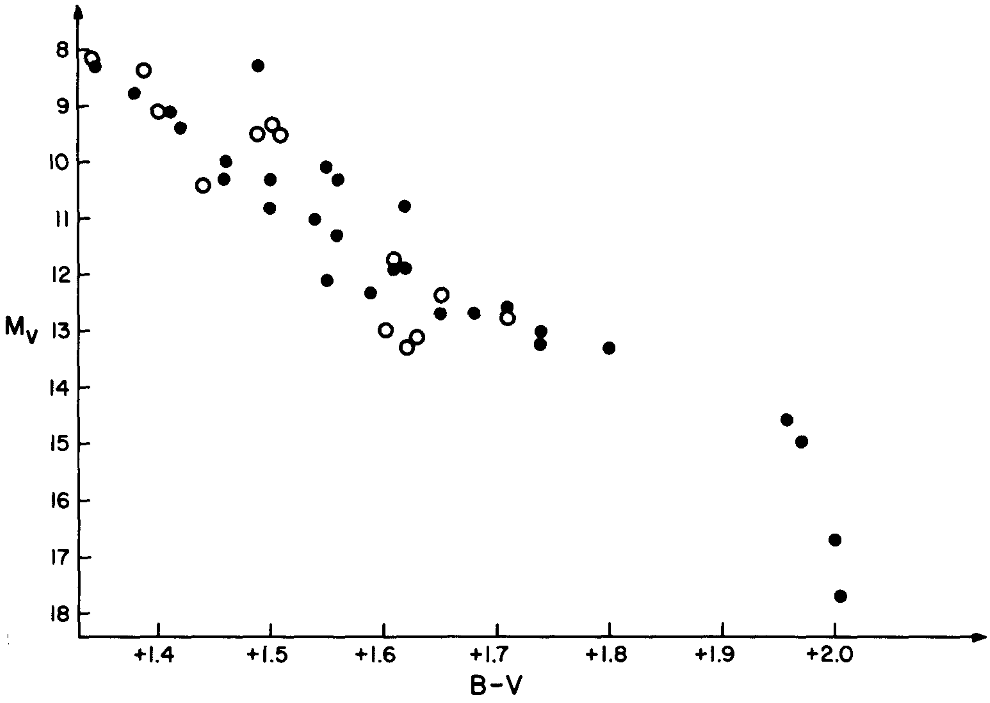

Fig. 4. H-R diagram consisting of M-dwarfs which have been studied in x-rays; filled circles are those seen in the CFA Stellar Surveys and open circles are reported observations from other sources, including HEAO-1 and EINSTEIN.

Table 1. (In some cases M_V or B-V data were not available, and these stars are not listed.) It is clear from the figure that we have good coverage and, aside from selection effects which would not be evident on such a diagram, we are in a position to examine the general properties of coronal emission from M-dwarfs as a class.

a. Quiescent Emission Levels

In order to determine the level of X-ray emission from M-dwarfs we must face the same question which arises in the case of Solar X-ray emission, namely is there any steady emission or is it all due to flares and transients? For the case of the Sun, the consensus view is that there is indeed steady, nonflare coronal emission (Orrall 1981). Likewise, for Solar-type stars such as α Cen, the X-ray emission is often stable to the few percent level for several hours (Golub et al. 1982), thus arguing for a steady and non-transient emission mechanism.

For the case of more active Solar-type stars such as Π^1 UMa, or cooler dwarfs (late K through M), the level of variability in X-ray

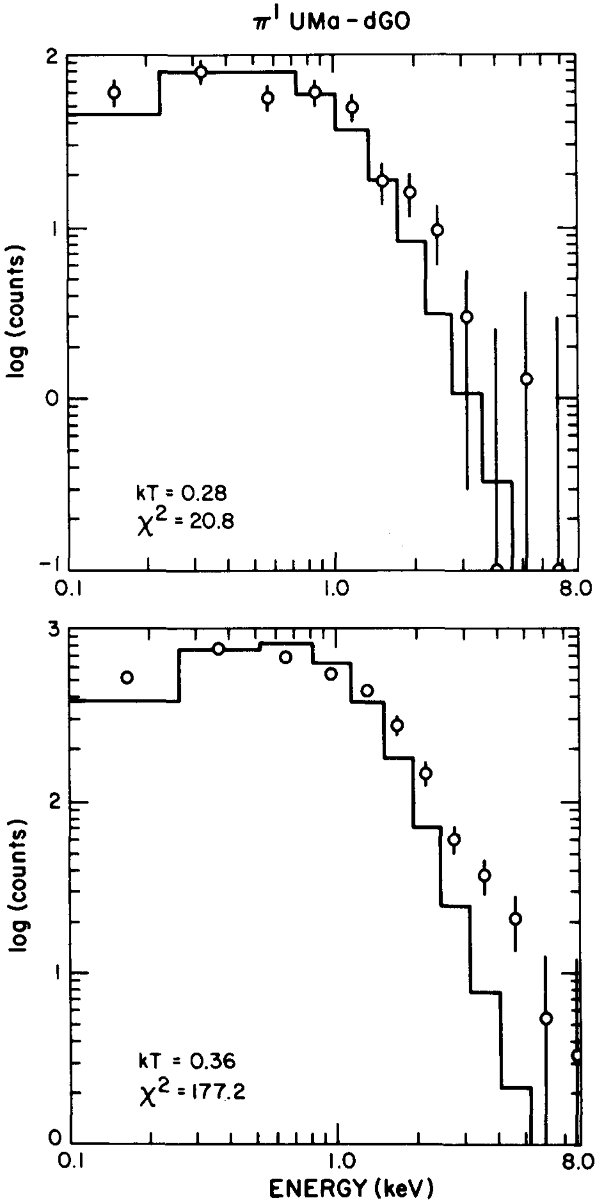

Fig. 5. EINSTEIN imaging proportional counter (IPC) data for the active G-dwarf π^1 UMa, showing spectral data obtained during a quiescent (top) and an active (bottom) orbit. In addition to a change in the x-ray emission level, there is also observed a change in the best-fit temperature kT and evidence of a second high temperature component during active times.

(Data courtesy G. Vaiana).

emission increases, as illustrated in Figure 5. These data will be discussed in more detail below; for now we show them in order to display the type of variability typically observed in stars with high average surface X-ray flux levels. In practice, we have chosen to exclude only obvious flare events when quoting X-ray luminosities. However, we caution that short-term variability is nearly always present in X-ray emission from active chromosphere stars and it will need to be examined in detail when we discuss measurements of the coronal temperatures.

An example of the way in which the quiescent level is determined in the presence of flare events is shown in Figure 6a, b. The figure shows two observations of Prox Cen from Haisch et al. (1980, 1982) and both containing sizable flares. The dashed lines show the quiescent levels determined; note in Fig. 6b that the 1979 quiescent level was substantially higher than that seen in 1980.

A less clearcut type of variability is illustrated in Figure 7, which shows portions of IPC data for two BY Dra-type stars, CR Dra and BY Dra itself. It is clear that variability is present and, as we discuss below, the spectral fitting procedure reflects this variability, but with short pointings there is no obvious way to find a quiescent level. In some cases we have separated the data into "active" and "inactive" periods (usually determined by satellite orbits); however, most pointings were not long enough to permit such a division and we used the total pointing in determining the coronal parameters.

A graphic summary of the basic data on X-ray luminosity is provided in Figure 8, which shows L_x (0.15-4.0 keV bandpass) vs. B-V for the stars listed in Table 1. Binaries are identified by the asterisk symbols and are plotted with the X-ray flux evenly divided between the two components. Data from HEAO-1 are indicated by open circles and the stars observed more than once are connected by solid lines to indicate the range of L_x found. Upper limits are indicated by arrows.

Two properties of the X-ray emission are immediately apparent from examination of this figure. First, as is the case of G- and K-dwarfs, there is a large spread of 3 orders of magnitude in the observed L_x at any particular value of B-V. This spread is presumably linked to the stellar rotation rate and the sparse data on rotation of M-dwarfs tends to confirm this idea (Pallavicini et al. 1982).

The second major feature in the graph is the total absence of high X-ray luminosity sources beyond a B-V of $\gtrsim$ 1.7. There appears to be a pronounced tailing off of the X-ray luminosity function toward later spectral types; however, a large spread in emission levels is still observed. This observation may be taken as an indication that the activity level is decreasing in low-mass stars, with the implication that magnetic flux production is likewise decreasing.

Recently, Giampapa (1983) reported the results of a high spectral resolution search in the vicinity of Hα for a sample of low mass M-dwarfs.

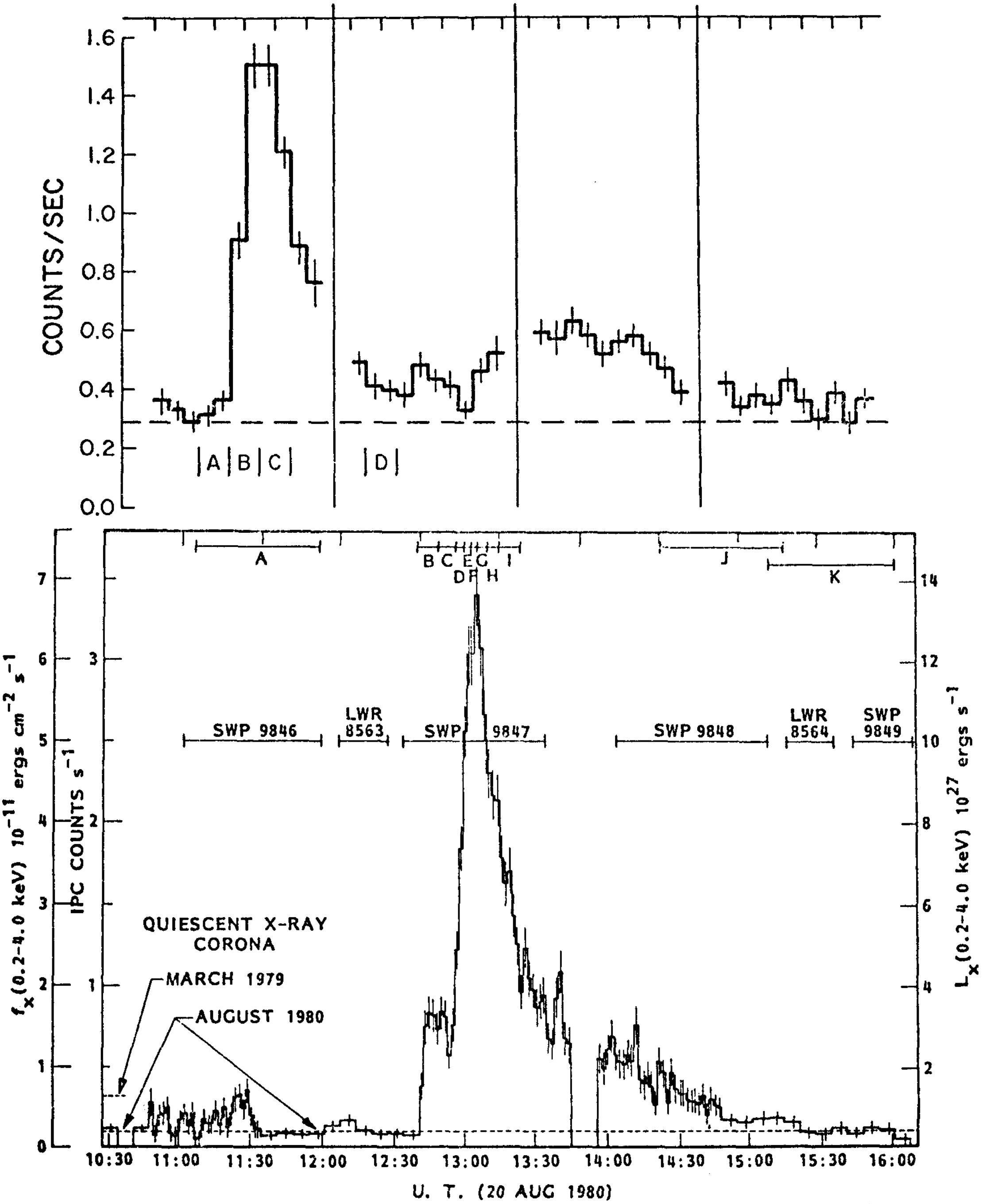

Fig. 6. Determination of a quiescent x-ray level in the presence of a flare event, illustrated by two flares observed on Prox Cen.
a) Dashed line shows quiescent level for the March 1979 event;
b) August 1980 flare, with simultaneous IUE coverage.

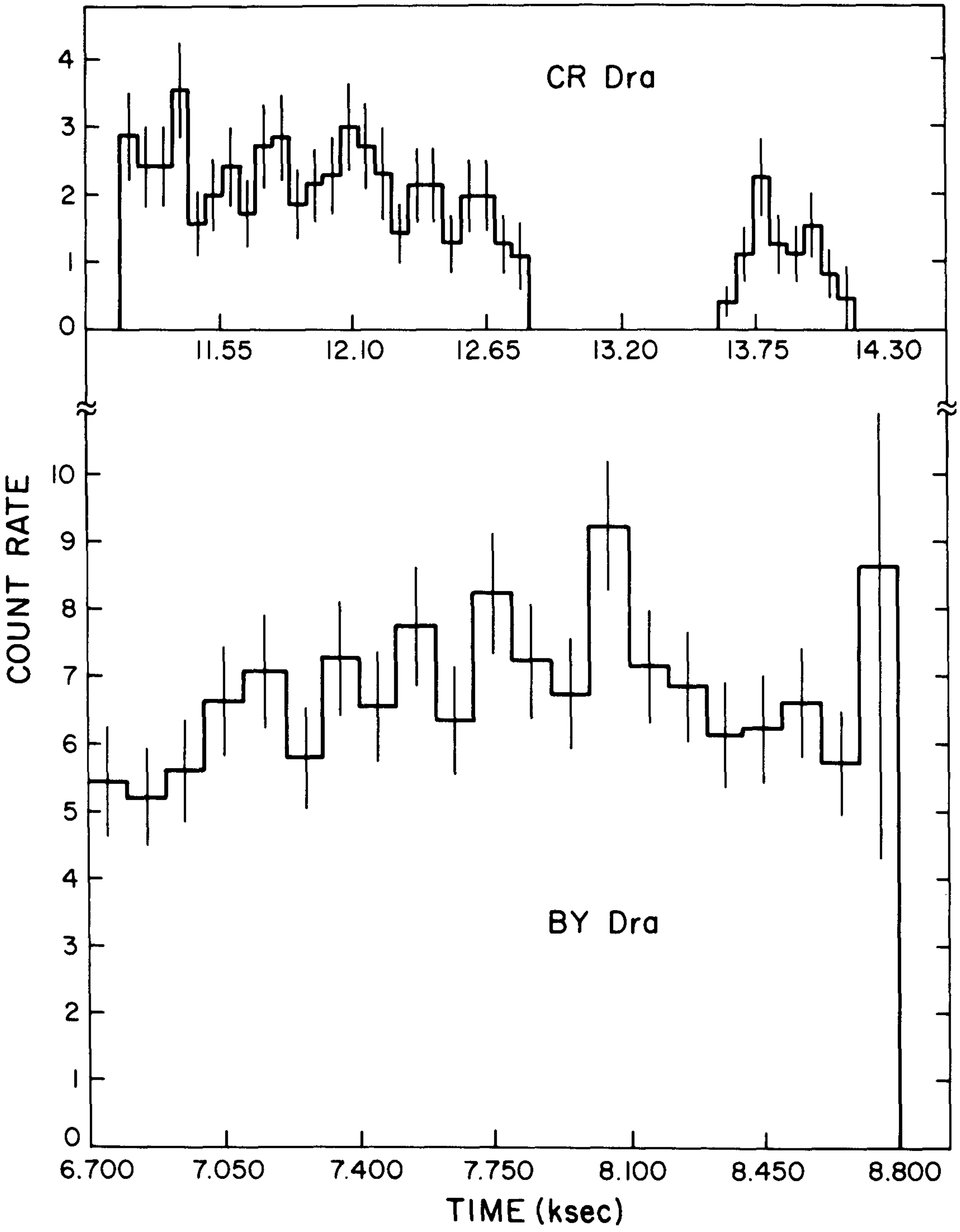

Fig. 7. IPC count rate during portions of two observations, of the BY Dra-type star CR Dra (top) and of BY Dra itself (bottom).

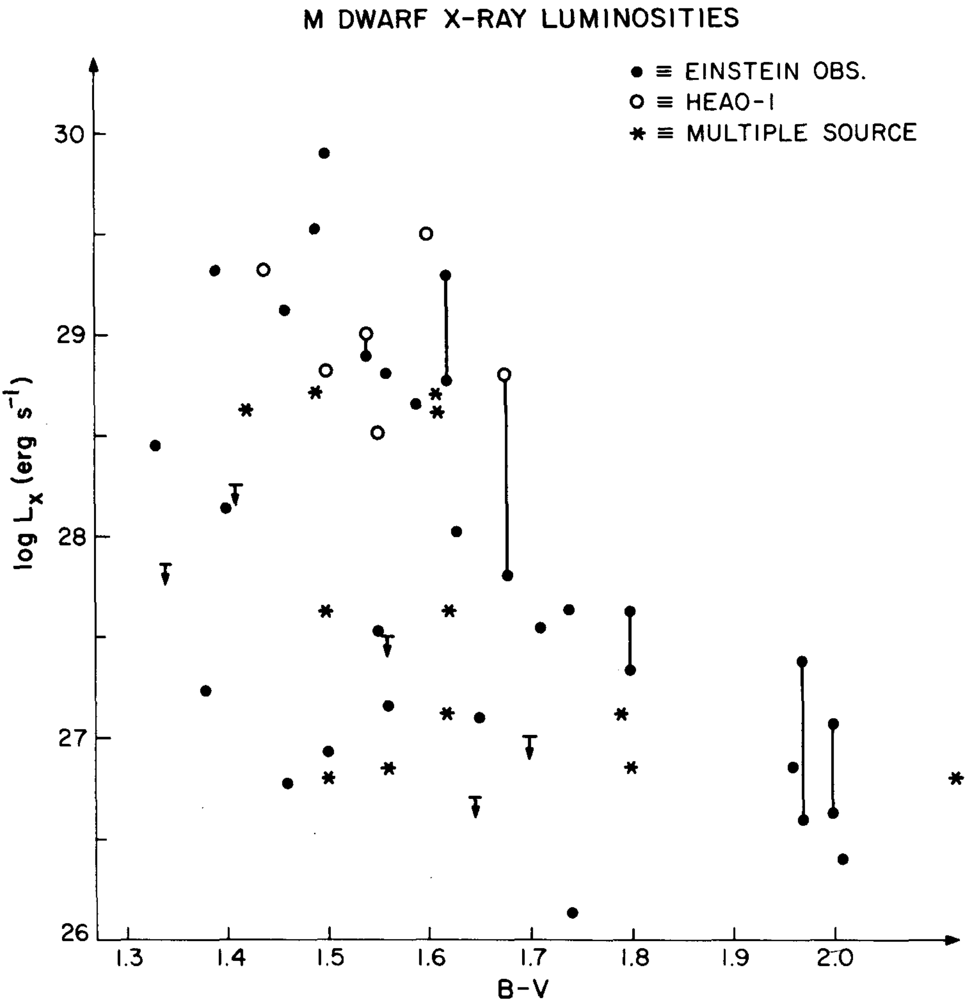

Fig. 8. Summary of all data available to date on x-ray luminosities of M-dwarfs. Closed circles indicate EINSTEIN data, open circles are HEAO-1 data; stars indicate multiple unresolved systems for which the total observed flux has been arbitrarily divided among the known components.

The stars were selected from the Luyten's Proper Motion Survey; the selection criterion used was a determination from the strength of the TiO molecular bands that the stars were later than ∿ dM6 (Liebert 1982). Contrary to prior expectations, these stars showed no Hα emission, implying that the chromospheric indicators of activity can become extremely faint in this sample. If we take into consideration the very high contrast level at which a Solar-strength chromosphere would be detected against a dM6 (or later) photosphere, then we conclude that any coronae or chromospheres on these stars must be extremely weak, even by Solar standards.

Preliminary analysis indicates that the stars observed in this program are OD rather than halo. If this is so, then the likely conclusion is to be drawn from these observations is the same as that from Figure 8, that the level of chromospheric and coronal emission drops for very low-mass dwarfs.

The significance of these results is that we expect that at around dM5 stars will become fully convective (Copeland et al. 1970). Present-day dynamo calculations lead to the expectation that Solar-type magnetic-field generation with a Solar cycle must occur primarily at or near the base of the convective zone (Schüssler 1983, Rosner 1983), although mechanisms also exist to amplify fields throughout the convective zone. In a fully convective star there would appear to be no room for the primary magnetic field amplification to take place, leading at a minimum to a change in the pattern of magnetic flux production. Such Solar-type phenomena as the cycle, polarity reversals and latitude migration of activity could be affected. It will require detailed numerical simulations to determine how the dynamo might change.

However, we show in § III that, although the X-ray luminosity of these stars decreases, the actual amount of magnetic flux produced in the star may be quite high, possibly higher than in G- and K-dwarfs. This apparent contradiction arises from the belief that coronal heating is due to activation of surface magnetic fields by the surface turbulence. In low-mass red dwarfs the surface turbulent velocities decrease, leading to a probable decrease in the amount of heating per unit magnetic flux. Thus, a given level of X-ray emission may imply substantially more magnetic flux on a red dwarf than on a Solar-type star.

Finally, we should note that there may be a selection effect operating in the manner of finding faint red dwarfs, as pointed out by Soderblom (these proceedings). The possibility exists that catalogs utilizing large proper motions of faint red stellar sources will miss the young red dwarfs with low space velocity. Indeed, the stars in Table 1 with the lowest X-ray emission, such as Ross 47 and AC + 79° 3888 are halo stars. However, it is not obvious that the converse statement applies, i.e., that YD stars are the highest X-ray emitters.

A possible resolution of this difficulty may come from the EINSTEIN Observatory "medium survey" (Maccacaro et al. 1982). By searching all medium sensitivity fields for serendipitous sources, this survey finds 3 M-dwarfs in $\sim$ 50 square degrees of sky, about the same number density as in the Wooley catalogue. If these X-ray sources turn out to be high luminosity, low-mass stars, then the selection effect suggestion will be confirmed. However, if none of them are found to be the "missing" red dwarfs in Figure 8, then it will be more difficult to argue the incompleteness of the optically selected sample. The work needed to answer this question is presently in progress.

A more direct means of testing the possible turnoff of dynamo activity for low-mass dwarfs would be to obtain rotation rates for the stars already observed in X-rays. We know that all dwarfs from F6 through M5 adhere strictly to the rule relating X-ray emission to rotation rate (Pallavicini et al. 1981, 1982; Walter 1982). If the same dependence upon rotation is found for dwarfs later than M5, then we argue that the dynamo has not changed character; if less X-ray emission is found at a given rotation value than expected, then we argue that the efficiency of magnetic flux production has gone down. This type of test should be independent of biases due to incompleteness of the sample.

b. Coronal Temperatures

Using the EINSTEIN Imaging Proportional Counter (IPC), we have thus far determined coronal temperatures for twelve M-dwarfs. In addition, Swank & Johnson have reported a temperature determination for Wolf 630AB using the EINSTEIN Solid State Spectrometer (SSS), and Ayres et al. (1979) reported approximate temperatures for three M-dwarfs using HEAO-1. These data are shown in Figure 9, where we have plotted X-ray luminosity vs. coronal temperature. The observed temperatures fall in a narrow range, from log T = 6.3 to 6.7, with only BY Dra and CR Dra above this range; the latter two stars will be discussed separately below.

For quiescent emission, assumed to derive from a large-scale quiet corona, a simple model based on scaling laws obtained in the Solar context can be used to predict a rather steep $T_c^{5/2}$ dependence between L_x and T_c (Rosner, Golub and Vaiana 1982). The model predictions are indicated on the figure as solid lines. The intersecting, nearly vertical lines are the expected rotation rates, based on the L_x vs. v_{rot} law of Pallavicini et al. (1981). Thus, a low emission level of 10^{27} erg s^{-1} is expected to come from M-dwarfs having low coronal temperatures of $\sim 10^{6.0}$K and rotation periods of ∿ 30 days. In contrast, emission at 10^{29} erg s^{-1}, is predicted to come from stars having $T_c \sim 4 \times 10^6$ K and rotation periods ∿ 4 days. For a given rotation period lower mass stars will have a lower L_x and a slightly lower coronal temperature.

It appears likely that the temperature determinations for very active stars such as BY Dra and CR Dra are strongly influenced by a hard component due to flarelike activity. We showed in Figure 7 the highly variable nature of the coronal emission from these stars. The spectrum and temperature fit obtained for BY Dra is shown in Figure 10; the result for CR Dra is similar. In contrast to the lower activity M dwarfs, for which the χ^2 of the fit is generally in the range 5-20 with 10 degrees of freedom, we find a very high χ^2 of 188 for this observation. Examination of the figure shows that the problem is due to an inability of a single temperature to fit the total spectrum. We encounter the same problem in, e.g. fitting the YZ CMi or Prox Cen observations if the obvious flares are included in the total fit; removing flaring portions of the data in those cases allowed an

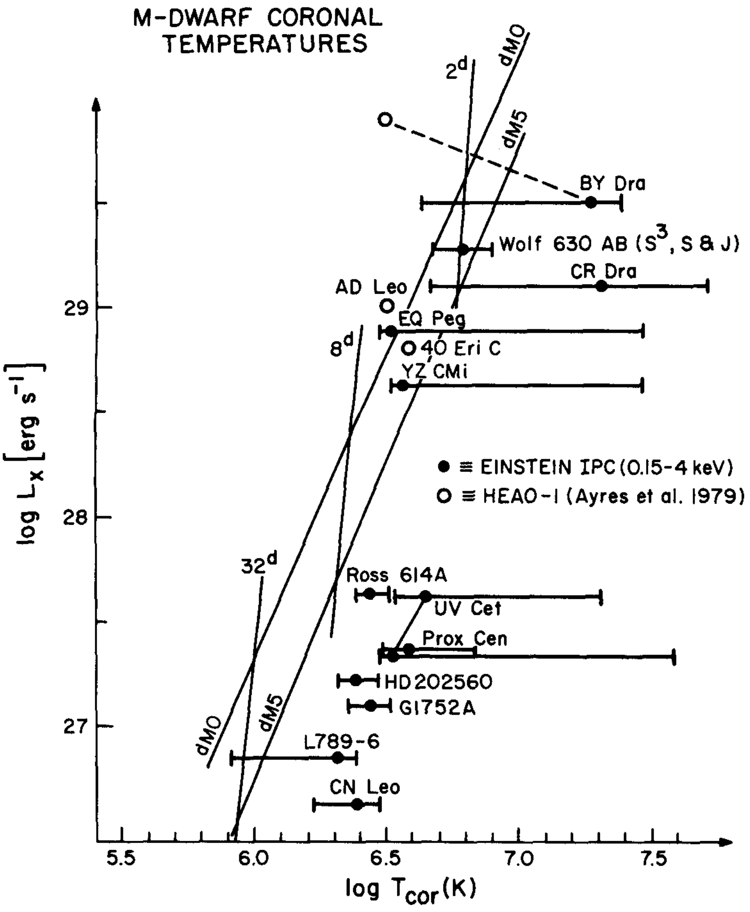

Fig. 9. Level of soft x-ray emission vs. coronal temperature for a sample of M-dwarfs; solid lines are from the theory of Rosner et al. 1982 (see text for discussion).

acceptable (lower temperature) fit to be made. Moreover, SSS observations of Wolf 630 AB by Swank and Johnson (1982) have explicitly found the two temperature components, the lower of which is plotted on Figure 9.

III. THE ROLE OF MAGNETIC FIELDS

In § I we presented arguments to support our contention that M-dwarf coronae are basically the same as the solar corona, but with some of the controlling physical parameters having exaggerated importance. In this section we will examine these ideas in detail, focusing on the properties of the magnetic fields which control coronal formation and heating.

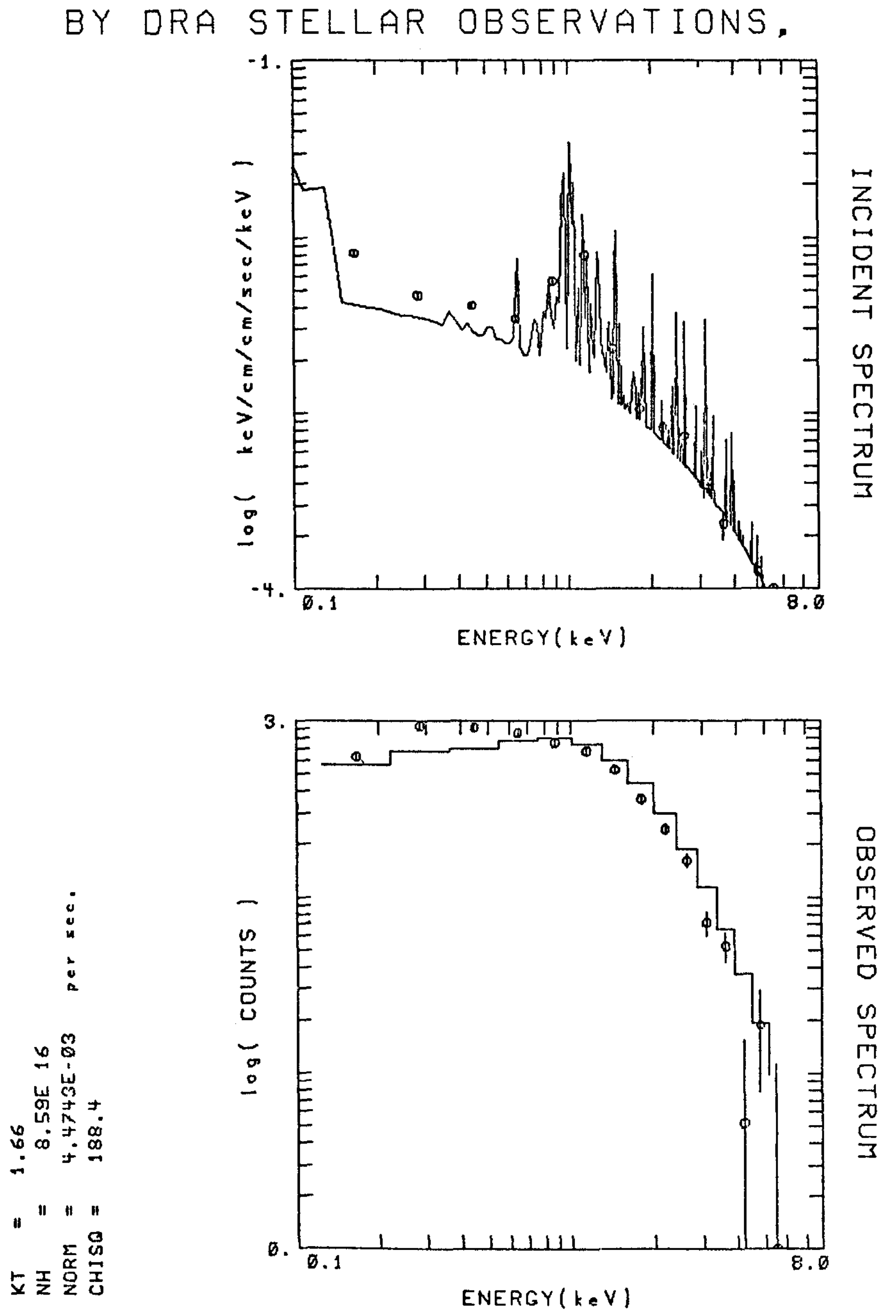

Fig. 10. IPC spectral data for BY Dra, showing best-fit thermal spectrum (bottom) and implied incident spectrum (top). The large value of χ^2 indicates the need for a two-component temperature fit; these data should be compared with π^1 UMa active data (fig. 5). (Courtesy G. Vaiana and S. Sciortino)

In the present discussion we explicitly adopt the view that previous quantitative studies of Solar coronal properties can be used to help in understanding M-dwarf coronae. Thus, scaling laws relating observable quantities such as coronal temperature and pressure (Rosner, Tucker and Vaiana 1978) and magnetic field strength (Golub _et al_. 1980) will be utilized; parameters such as surface gravity and surface turbulence velocities appropriate to low mass stars can be included in the calculations. At the same time we will arrive at predictions for quantities such as magnetic field strengths and filling factors, which may soon be testable by direct observation and which will lead to stringent tests of the heating theory which we have derived in a purely Solar context (Rosner _et al_. 1978; Vaiana and Rosner 1978; Golub _et al_. 1980, 1982).

a. Loop Model and Scaling Laws

The model which we use to relate the level of X-ray emission to magnetic field strength has been discussed in detail elsewhere (e.g., Golub _et al_. 1982 and references therein), so that we present only a brief description here. Figure 11 shows the assumed loop topology.

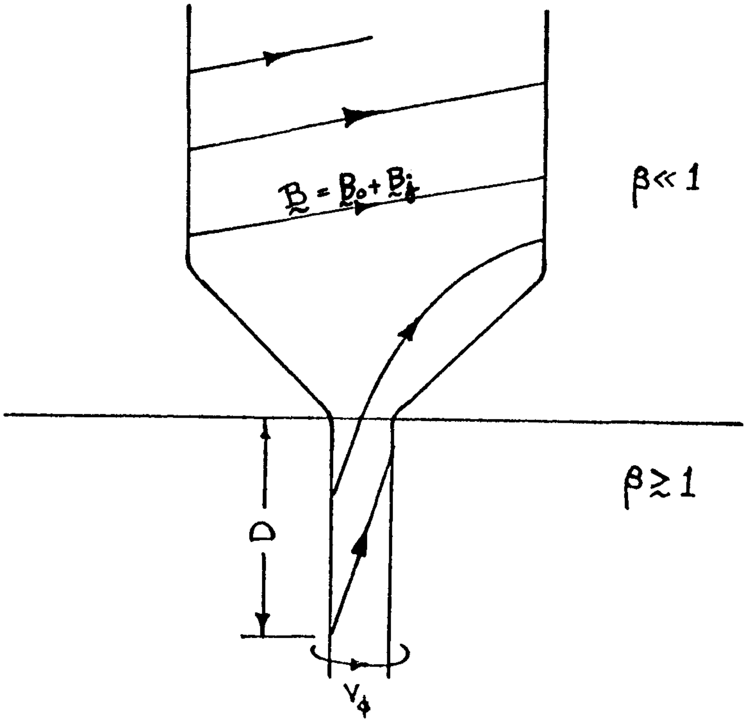

Fig. 11. Schematic representation of the geometry of the magnetic field and labelling of the loop model parameters for the theory described in the text.

The energy available for heating resides in the non-potential component of the magnetic field, which is viewed as being generated from a potential B-field by shear in the $\beta \gtrsim 1$ region of the Solar atmosphere ($\beta \equiv 8\pi p_{gas}/B^2$):

$$B = B_z + B_j, \tag{3.1}$$

$$W_m = B_j^2 V/8\pi \tag{3.2}$$

$$B_j = B_z \frac{\partial v_\phi}{\partial z}. \tag{3.3}$$

The coronal portion of such a loop will have a larger cross-section due to the drop in external gas pressure with increasing height above the Solar surface. Because of this expansion, any twist which is generated in the high-β region will be transmitted upward and amplified, as discussed by Parker (1974). Viewed from the corona, this transmission of stresses becomes an effective twisting velocity at the base of the loop, which we label v_ϕ.

The energy available for heating the corona is then

$$W_m = \frac{1}{4} B_j \cdot B_z v_\phi R^2, \tag{3.4}$$

where R is the cross-sectional radius of the loop in the corona. Combining this result with that of Rosner, Tucker and Vaiana (1978):

$$\frac{W_m}{V} = E_H = 10^5 p^{7/6} L^{-5/6} \tag{3.5}$$

we obtain the scaling relation

$$p = 2.6 B_2^{12/7} L_9^{-1/7} (\alpha v_4)^{6/7}, \tag{3.6}$$

where the subscripts indicate division by the indicated powers of ten and $\alpha \equiv B_j/B_z$.

We have tested two ways of removing B_j from this relation, since it is not a directly measurable quantity. They amount to taking either α or the coronal β ($\beta_j \equiv 8\pi p_{gas}/B_j^2$) as constant. The scaling laws relating measurable quantities which then result are

$$\text{constant } \alpha: \quad p \propto B_z^{12/7} L^{-1/7} (\alpha v_\phi)^{6/7} \tag{3.7a}$$

$$\text{constant } \beta_j: \quad p \propto B_z^{3/2} L^{-1/4} v_\phi^{3/2} \tag{3.7b}$$

In the Solar context, both of these formulations are found to provide acceptable fits to the available data (Golub et al. 1982a).

We may attempt to combine the RTV scaling law (Eq. 1.1) with the magnetic field-related law (Eq. 3.7b) in order to eliminate one of the variables, e.g., coronal pressure p. The result is

$$T_{cor} = 1.2 \times 10^3 B_z^{1/2} L^{1/4} (\frac{v_t}{v_\odot})^{1/2} \tag{3.8}$$

where we have normalized the twisting velocity v_ϕ to the Solar value in order to take into account the variation of turbulent surface velocities for different stars.

For the case of stars such as the Sun with fairly steady quiescent coronal emission, we may calculate an atmospheric model which allows us to use the X-ray measurements to arrive at a direct estimate of the magnetic field parameters. We will see that direct application of the method to more active stars having large short-term variability leads to problems, which can only partially be overcome at the moment; however, we can still get some idea of the important magnetic field parameters on active chromosphere stars and M-dwarfs in general.

b. Predicted Magnetic Field Values

We have shown elsewhere (Golub _et al_. 1982) that for a loop atmosphere in which all of the X-ray emission derives from a single type of loop, i.e. in which all of the loops are specified by the same parameters, a measurement of L_x and T_{cor} is nearly sufficient to fully specify the atmosphere. The only additional requirement is a means of specifying either the loop pressure p, or the loop length L, or the coronal filling factor f. Knowledge of any one of these three will allow us to determine the remaining values by utilizing the RTV scaling law relating T, p and L.

If we are modelling quiescent emission from a low-activity star, then our experience with Solar emission shows that it is reasonable to view the stellar emission as coming from large-scale evolved loops. This is because: (i) during the emergence process, loops tend to be very active and variable in their emission properties and (ii) the evolution of surface fields operates in only one direction, i.e. that of diffusion, with a rapid emergence and growth followed by gradual and sustained spreading of the fields; we may expect that quiescent emission involves large, diffused magnetic loops which may (depending on coronal temperature and stellar surface gravity) be larger than the pressure scale height of the coronal plasma. In that case the total X-ray luminosity, which may be represented by

$$L_x = 4\pi R_*^2 H n_e^2 P(T) f, \tag{3.9}$$

can be rewritten with $H = s_p = 5 \times 10^3 T (g/g_\odot)^{-1}$ and $n_e = \frac{p}{2kT}$. We may solve for f, letting $F_x \equiv L_x/4\pi R_*^2$ and also solve Eq. 3.8 for B:

$$f = \frac{3.4 \times 10^{-9}}{P(T)} F_x [\frac{T^3}{(g/g_\odot)}]^{-1} \tag{3.10a}$$

$$B_{em} = 1.2 \times 10^{-8} \left(\frac{v_t}{v_\odot}\right)^{-1} \left[\frac{T}{(g/g_\odot)}\right]^{1/2} \qquad (3.10b)$$

where the subscript of B_{em} indicates that it is the average field in the regions doing the emitting. The stellar average magnetic field is $\langle B \rangle = f\, B_{em}$, so that the total magnetic flux on the star is

$$\Phi_T = 4\pi R_*^2 \langle B \rangle$$

$$= \frac{4 \times 10^{-17}}{P(T)}\, L_x \left[\frac{T^3}{g/g_\odot}\right]^{=1/2} \left(\frac{v_t}{v_\odot}\right)^{-1}. \qquad (3.11)$$

We have calculated magnetic field values for several stars, based on the X-ray measurements of their coronal luminosity and temperature; the results are shown in Table 2. We have calculated Solar values first as a check of the procedure and the results are quite reasonable. The Solar-type stars α Cen A and B show, not surprisingly, values near those of the Sun; a quiet Sun value for α Cen A and an active Sun value of total magnetic flux for α Cen B.

Table 2. Predicted Magnetic Field Values for Solar-Type Stars

Star	F_x(erg $cm^{-2}s^{-1}$	T(K)	f	B_{em}	<B>	$\log\phi_T$
Quiet Sun	5×10^4	1.8×10^6	0.25	30	8	23.7
Active Sun	3×10^5	3.5×10^6	0.20	80	16	24.0
α Cen A	1.3×10^4	2.1×10^6	0.06	90	5	23.6
α Cen B	6.1×10^4	2.1×10^6	0.18	60	11	23.8
π^1 UMa	1.2×10^6	4.0×10^6	0.22	100	20	24.2
λ And	1.5×10^6	7×10^6	0.75*	1110	830	27.4

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*Filling factor f redefined to take into account the large ratio of coronal scale height to stellar radius.

The active chromosphere star π^1 UMa is predicted to have a magnetic field configuration typical of the active Sun. The emission appears to derive from strong field regions which cover $\sim$ 22% of the surface. The total magnetic flux on the star is only slightly greater than on the Sun during an active period.

We have also calculated a magnetic field value for the active RS CVn type star λ And. The results are markedly different from those obtained for the other stars in the list. λ And seems to be covered over most of its surface ($\sim$ 75%) with very strong field regions ($\gtrsim$ 1000 gauss). Comparison with the results of a direct measurement of the magnetic field on λ And by Giampapa and Worden (reported in these Proceedings) yields surprisingly good agreement, considering the simplicity of our calculation and the difficulties involved in measuring the magnetic field strength. Note that the total amount of magnetic flux which we calculate for λ And is quite high, being more than 1000 times larger than any Solar value yet observed.

If we apply this same procedure to M-dwarfs we will, in general, find that it yields inconsistent results. In particular, the calculated filling factors are consistently larger than unity. This would be acceptable for RS CVn's having lower stellar surface gravity and high coronal temperature, since f > 1 would in those cases be only an artifact of the way we have chosen to define the coronal filling factor. However, this explanation is not viable for M dwarfs which are found to have values of the atmospheric emission scale height generally small compared to the stellar radius. The results of a calculation using Eqs. 3.10 for some M-dwarfs are listed in Table 3 under the columns labelled "L = s_p."

Table 3. Predicted M-Dwarf Magnetic Field Values

Star	F_x(erg cm^{-2}s^{-1}	T(x10^6 K)	L = s_p		B'_{em}
			f	B_{em}	
BY Dra	8×10^7	19	2.0	2300	2960
Prox. Cen	7×10^5	3.5	1.8	155	210
YZ CMi	1.4×10^7	3.7	26	195	950
L789-6	2.5×10^5	2.7	3.6	175	320
CN Leo	3×10^5	2.5	4.1	190	370

We see that, without exception the calculated filling factors are > 1. At the same time we note that the calculated magnetic field values are also quite large by Solar standards; they are all in the 100-200 range. It is clear that our assumption that the emission comes from loops larger than or equal to the pressure scale height is not valid for M-dwarfs. We must look into the case for which the emitting loops are smaller than s_p, i.e., more compact, higher pressure, active region type loops.

Unfortunately, there is no obvious bound on L in this case. Certainly the coronal pressure must be smaller than the photospheric gas pressure, but this limit is not very useful. We can obtain a lower limit on the magnetic field strengths by taking the case f = 1. Then we have

$$B'_{em} \geq 7 \times 10^{-13} \left[\frac{F_x}{P(T)}\right]^{1/2} \left(\frac{v_t}{v_\odot}\right)^{-1}. \qquad (3.12)$$

The values of magnetic field strength determined in this manner are listed in the last column of Table 3. They are, of course, larger than the previously determined values and they represent lower limits, which will increase by a factor $f^{1/2}$ if the filling factor is less than unity.

We may draw some tentative conclusions from our first examination of the M-dwarf data and from our comparison with Solar observations. These are:

1. M-dwarfs are essentially all X-ray emitters, as initially reported by Vaiana *et al*. (1981) and now confirmed by a larger sample. There is some evidence that halo stars are weaker, by at least one order of magnitude;

2. The strong correlation between X-ray emission and stellar rotation rate continues to hold down to late M. For stars later than dM5 there is particular interest in obtaining rotation rates because

3, there is a marked decrease in the observed range of L_x values for dwarfs redder than B-V $\approx$ +1.7, leading to the possibility that we are seeing a decrease in dynamo efficiency toward fully convective stars. A quantitative determination of L_x vs. rotation rate for these stars would provide an unbiased test of this idea;

4. Using quantitative studies relating Solar X-ray emission to magnetic field strength and loop size, we estimate that M-dwarfs in general have active region-strength fields covering most of the stellar surface, or stronger fields over a smaller fraction of the surface; BY Dra stars are similar to the RS CVn's in requiring kilogauss fields and large area coverage;

5. M-dwarfs and active Solar-type stars show substantial variability on short time scales. This is consistent with the results in 4) above, arguing that the X-ray emission is dominated by the continual presence of emerging flux regions, with strong and active magnetic fields covering a large fraction of the stellar surface.

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DISCUSSION

Haisch: (beginning of question lost on tape) ... the energy going into the corona is an additional means of energy dissipation and we have to take this into account apart from the energy going into stellar flares.

Golub: Yes, quite right.

Walter: I have two questions about your plot of L_X vs Temperature. First, the relation is awfully steep. Is that telling us that there is not much of a relation between temperature and luminosity but that coronae exist only at certain temperatures? The second question is what does the relationship look like if you plot, not luminosity, but surface flux? Your diagram plotted both the RS CVn stars and the M dwarfs. These have very different surface areas.

Golub: The first plot that I showed consisted of M dwarf stars only and this was steep. Even the simplest theories are in agreement with this.

Walter: What is the gradient of this relationship?

Golub: I believe it is 5/2.

Jordan: I would like to make a comment. I am alarmed to see that you are building yet again on the scaling law between pressure, temperature and length. That scaling law fails to reproduce the most fundamental property of the solar emission-measure distribution i.e. the minimum at 200 000 K. Moreover it is not generally realized that the boundary conditions used in producing that scaling law fix the ratio of conductive to radiative flux at a constant value of 1.6. This is very similar to the minimum energy-loss method which fixes this ratio at 1. This does not fit the behaviour of the solar atmosphere and there is no reason to think that it will apply to stellar atmospheres. So I think it is time that we stopped using that scaling law and went back to the observations.

Golub: I thought you told me you wouldn't do that! (laughter). Bob (Rosner) might like to comment. For my part I would say that we have results, not just from analytical work but also numerical results from modelling of loop structures, which successfully reproduce the differential emission measure through the transition region and one does get this kind of scaling in the corona. Perhaps Bob (Rosner) would like to say more.

Rosner: I think that this could be a very long discussion.

Jordan: Perhaps we should discuss it privately.

Simnett: The magnetic fields that you infer are very sensitive to the temperature you adopt. A good fraction of the flux observed in the upper energy range of your instrument comes from line emission which is sensitive to abundance. What abundances do you assume?

Golub: We use solar abundances since we are dealing with solar-type stars. We now have the capability in our analyses to vary the abundances but have not done this yet.

Simnett: I thought that we were dealing with cool stars which are not solar-type. Anyway do you know how sensitive you are to these effects?

Rosner: With proportional counter data it is very difficult to distinguish between abundance (next word lost) and temperature. Questions like that are unlikely to be answered by the IPC data but rather by high-resolution spectroscopy.

Simnett: Yes, but abundance is critical in determining coronal temperature and, thence, magnetic field.