STELLAR X-RAY EMISSION AS AN INDICATOR OF STELLAR MAGNETIC ACTIVITY

G. S. Vaiana
Osservatorio Astronomico di Palermo (Italy) and Harvard-Smithsonian Center for Astrophysics, Cambridge, MA (USA)

ABSTRACT

An overview of recent *Einstein* Observatory observations and theoretical modeling of stellar x-ray emission is presented, with particular emphasis upon the role such studies can play furthering our understanding of stellar magnetic activity. We argue that solar observations can be used to show that coronal emission is morphologically related to surface magnetic field activity; to establish a quantitative link between the observed soft x-ray flux and the mean surface (photospheric) magnetic flux; and, in sum, to demonstrate that soft x-ray emission is a sensitive diagnostic for the presence of surface magnetic fields, uncomplicated by radiative transfer effects and the resulting coupling to the underlying atmosphere (which may introduce unwanted correlations with spectral type and luminosity class). Recent analyses of stellar x-ray observations from the *Einstein* Observatory have focused on the interpretation of stellar coronal emission and possibly-related surface magnetic activity within the framework of our understanding of solar activity; including "loop" models of stellar coronae, observations of coronal emission variability on a wide range of time scales (which provide information on the morphology of the emitting plasma), and observations and modeling of low-resolution spectroscopic x-ray observations (which test the applicability of solar modeling). These recent results, which I review, all reenforce the argument that stellar coronal emission constitutes an excellent probe for studying stellar magnetic activity over a wide dynamic range, one which may prove to be uniquely suited to studying such activity in distant (and hence faint) sources.

1. INTRODUCTION

The problem of stellar surface activity is sufficiently broad and complex in and of itself that it is often easy to overlook its role in larger astrophysical problems. From the stellar point of view, surface activity directly affects the stellar spectral signature (for example, the optical light from dMe stars may be enhanced substantially during flaring; see Byrne 1983 and references therein); is directly responsible for mass and angular momentum loss during main sequence life, and thus affects the course of stellar evolution (Kraft 1967); and may play a significant role in despinning during the formative T Tauri phase of stellar evolution (cf. Imhoff 1978).

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From the galactic point of view, stellar surface activity is responsible for mass input to the interstellar medium via stellar winds; contributes to the galactic component of the soft X-ray background by virtue of X-ray emission from stellar coronae (cf. Rosner *et al.* 1981); and allows us to probe the low mass end of the stellar mass function through the relatively vigorous levels of X-ray emission from very late-type stars, and hence aids in establishing the late-type stellar space density and its contribution to the galactic mass. Finally, stellar surface activity provides us with a virtually unexcelled laboratory for plasma astrophysics: a wide range of plasma phenomena is now known to be taking place in the surface layers of stars as commonplace as the Sun; and the fact that we can now study the range of this behavior over the entire breadth of conditions encountered in the H-R diagram by means of stellar UV and X-ray emission has opened up new opportunities for studying these plasma processes (cf. Vaiana 1981a).

In the following, I will focus on an aspect of stellar coronal emission particularly relevant to this symposium, namely its possible use as a diagnostic tool for probing stellar magnetic activity. This point of view is one which is relatively well-established in the solar context: thus, studies of solar activity – as measured by the level of chromospheric or coronal emission – have long suggested a strong correlation between the vigor of emission and the level of photospheric magnetic field activity, showing in particular that *chromospheric* emission could be quantitatively correlated with the *photospheric* magnetic flux (Skumanich, Smythe, and Frazier 1975).

Our own perspective has been of course strongly influenced by our observational program in solar soft x-ray imaging; from our observational work, we have been led to the conclusion that the structured corona seen in solar soft X-ray images is best understood as the result of plasma heating by magnetic field-related processes. We therefore asked ourselves whether a quantitative connection between the level of soft X-ray emission in a given region of activity could be tied to the local level of photospheric magnetic activity. Using the extensive data base provided by the *Skylab* and earlier rocket flight observations (see, for example, Vaiana and Tucker 1974), Golub *et al.* (1980, 1982) showed that a good correlation exists between the total photospheric magnetic flux in an active region and its total soft x-ray emission (or, alternatively, the total coronal thermal energy content in the active region; Figure 1). If we define the average magnetic field strength in an active region as the ratio of the total flux to the active region area, a similar correlation can be shown to exist for intensive (i.e., non-volume-dependent) parameters characterizing the photospheric magnetic field and the corona, e.g., for the average longitudinal photospheric magnetic field strength and average coronal pressure (Fig. 1). Again, we find fairly good positive correlation, with the coronal gas pressure and photospheric mean magnetic field strength $\langle B \rangle$ related via a power law in $\langle B \rangle$ (Golub *et al.* 1980, 1982). This empirical result can be combined with specific theoretical models for magnetically-coupled heating in order to construct a theory which, given the surface magnetic flux, will predict the luminosity and temperature of the coronal plasma (viz., Rosner, Golub and Vaiana 1982; and Golub 1982 and in this volume) or, conversely, to predict the photospheric magnetic flux if one is given the coronal parameters.

These various morphological and quantitative arguments show that (1) coronal soft x-ray emission can be both qualitatively and quantitatively related to surface magnetic field activity; and (2) soft x-ray emission, as a sensitive diagnostic for the presence of surface magnetic fields, is uncomplicated by radiative transfer effects and the resulting coupling to the character of the underlying atmosphere (which may, as in the case of Ca II, introduce unwanted correlations with spectral type and luminosity class). With these arguments in mind, recent analyses of stellar x-ray observations from the *Einstein* Observatory have focused on the interpretation of stellar coronal emission and possibly-related surface magnetic activity within the framework of solar activity models. These studies have included correlation analyses of x-ray emission properties with other stellar parameters (in particular, with stellar rotation); modeling of stellar coronae with the aid of "loop" atmospheres; determination of coronal x-ray emission variability on a wide range of time scales (which, by comparison with analogous solar data, provides information on the morphology of the emitting plasma); and observations and modeling of low-resolution spectroscopic x-ray observations, which allow us to verify the applicability of the solar analogy. These recent results, which I shall review, are all consistent with the view that solar coronal modeling is an appropriate prototype for studying activity in late-type stars; and hence combine to argue forcefully that stellar coronal x-ray emission is an excellent probe for studying stellar magnetic activity over a wide dynamic range of activity levels, presently constituting one of our best tools for investigating magnetic dynamo behavior on stars other than the Sun.

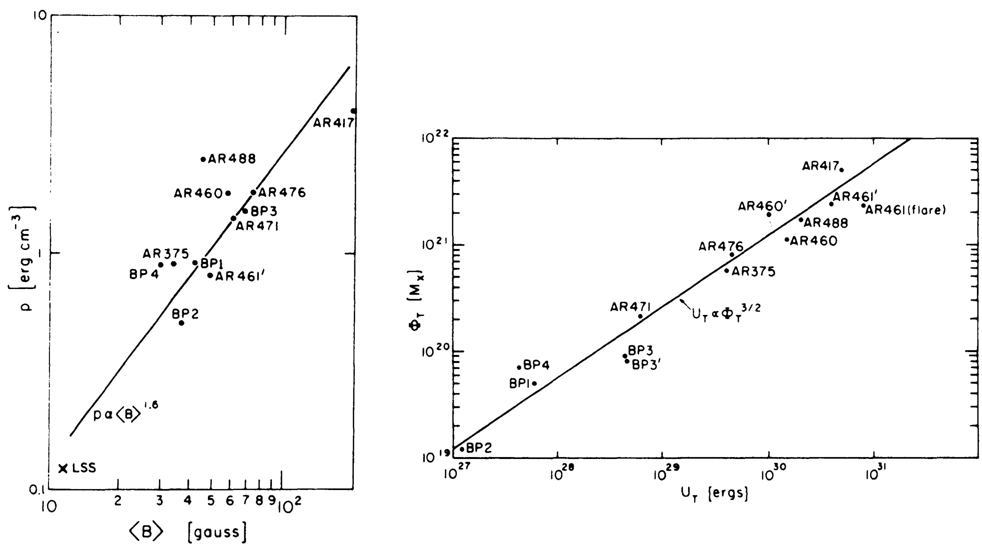

Figure 1: (left) Correlation between the average longitudinal photospheric magnetic field and the average coronal pressure. (right) Correlation between the total energy content in the coronal plasma and the magnetic flux in solar confined regions (from Golub *et al.* 1980).

2. OVERVIEW OF OBSERVATIONS AND MODELING

I begin by first summarizing the status of the observational results as reflected in the published literature, which dominantly derive from observations carried out by the *Einstein* Observatory; and give an overview of the modeling which we have done relevant to the study of stellar magnetic activity. This will set the stage for the presentation of our latest observational results on stellar coronal variability and coronal temperature/luminosity correlations, which will be discussed in §§ 3 and 4.

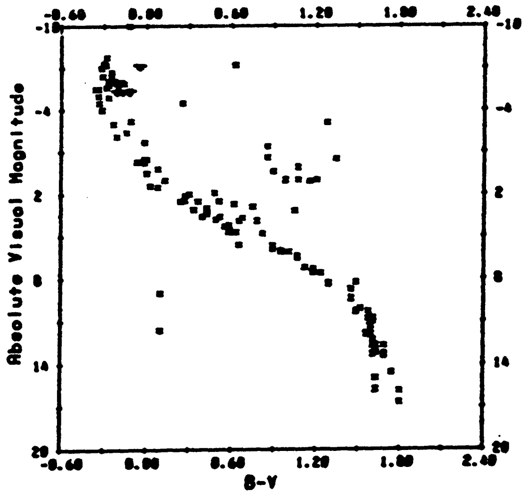

Figure 2: H-R diagram of optically well-characterized stars seen as soft x-ray sources by the Einstein Observatory. The stars shown were observed as part of the CfA stellar x-ray survey (cf. Vaiana et al. 1981), and include stars observed by collaborating guest observers (from Vaiana 1982).

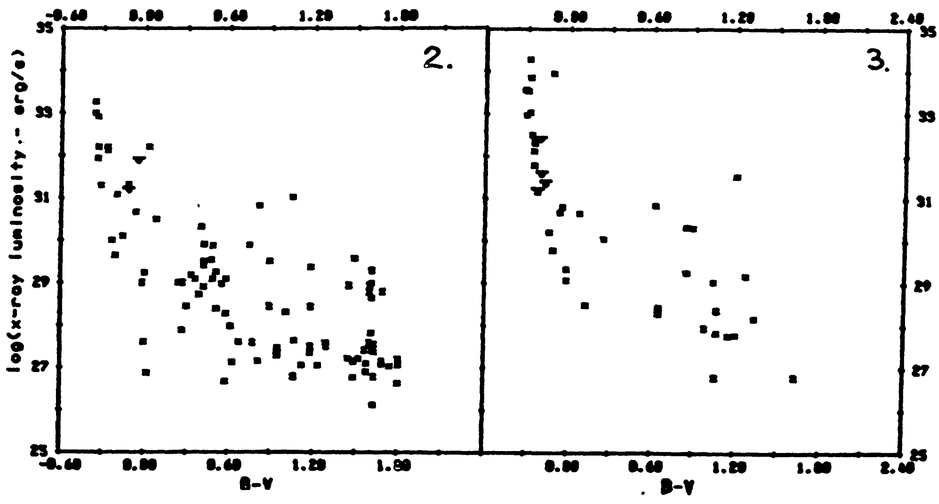

Figure 3: X-ray luminosity (0.2 - 4.0 KeV) versus spectral type for the main sequence stars shown in Figure 2 (from Vaiana 1982).

Figure 4: X-ray luminosity (0.2 - 4.0 KeV) versus spectral type for giants and supergiants plotted in Figure 2 (from Vaiana 1982).

(i) *Status of observations.* The overall behavior of x-ray emission throughout the H-R diagram is characterized (Figures 2-4) by the fact that essentially all stars emit in the range of 10^{26} to 10^{33} erg s^{-1} (Vaiana *et al.* 1981). Differences in luminosities appear to be tied to spectral type only in a gross sense; that is, there is a distinct difference in behavior between early-type and late-type stars, but relatively little differences within these two very general categories. For early-type stars, the behavior of luminosity seems to be dominated by a monotonic decrease from O to A characterized by a virtually constant ratio of X-ray to bolometric luminosity (see, for example, Pallavicini *et al.* 1981). For late spectral types (G to M), the behavior is instead dominated by a broad range of x-ray luminosity for each spectral type, and a lack of dependence on effective temperature.

What general conclusions can we draw from these data, particularly for the late-type (cool) stars? It is evident that x-ray emission is a common stellar attribute, so that nonthermal processes must be operative in the outer atmosphere of essentially all stars. Let us focus for the moment on the late spectral type stars. In order to elucidate the nature of the atmospheric heating processes for these stars, it is useful to ask whether the levels of coronal x-ray emission, as well as the spectral characteristics of this emission, are in any way correlated with stellar attributes other than those which place stars in the H-R diagram. Specifically, we would like to know if there exists a stellar attribute whose variation for fixed

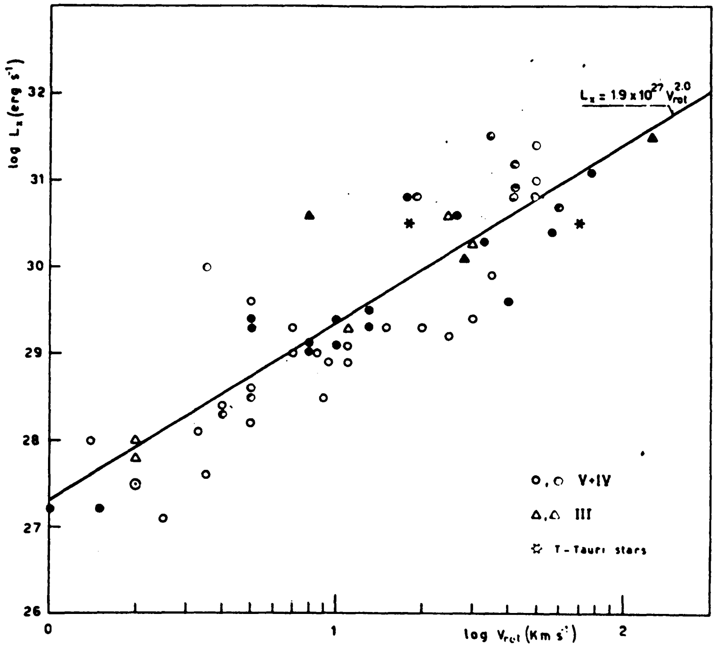

Figure 5: Plot of x-ray luminosity L_x vs. rotational velocity V_{rot} for a sample of late spectral type dwarf and giant stars (from Pallavicini *et al.* 1982). The x-ray observations are from the *Einstein*/CfA stellar survey; rotational data have been obtained with a variety of different methods and are discussed in the reference. The straight line represents a best fit relationship for the entire data sample.

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spectral type and bolometric luminosity could account for the observed spread in soft x-ray luminosity. For present purposes, the most obvious such candidate stellar attribute is, of course, the stellar rotation rate. In fact, preliminary studies by Ayres and Linsky (1979), and more detailed work by by Pallavicini *et al.* (1981, 1982) and Walter (1981) and collaborators, have shown that for late-type stars there is correlation between x-ray emission and stellar rotation rate; and recent further studies have shown a correlation between stellar x-ray emission and stellar age (Vaiana 1981a, c; Stern *et al.* 1982). These results are of course reminiscent of the connection between Ca II h and k emission (Wilson 1966), activity, and rotation rate found almost a decade ago by Skumanich (1972). For example, the most recent study (by Pallavicini *et al.* 1982), has extensively investigated the correlation between observed stellar x-ray luminosities, total bolometric luminosities, and projected rotational velocities $v \sin i$ for a large group of late spectral type stars of various luminosity classes drawn from the *Einstein*/CfA stellar survey; the results of this study are shown in Figure 5. The apparently strong rotational dependence of stellar x-ray emission for late-type stars (whose precise functional form remains to be established by studies of statistically complete samples drawn from our survey) argues for a coupling mechanism between rotation and coronal heating which is naturally provided by coronal heating processes dependent on stellar magnetic fields, as already suggested by solar observations (Rosner and Vaiana 1980).

In light of the correlation of x-ray emission with rotation for late-type stars, one would expect a similar correlation between Ca II emission strength and x-ray luminosity as well. This is found, and has been reported by, among others, Mewe and Zwaan (1980) and collaborators, and by us (cf. Vaiana 1981b; Pallavicini *et al.* 1982). Figure 6 shows the corresponding result taken from the CfA data sample; note the steep dependence of x-ray emission on Ca II flux (Pallavicini *et al.* 1982). The observed correlation of coronal x-ray emission with calcium emission strengthens the hypothesis that the plasma heating processes leading to soft x-ray emission in late-type stars are largely governed by stellar magnetic fields coupling to surface turbulence.

(ii) *Status of modeling.* The ubiquity of x-ray emission throughout the H-R diagram raises the general problem of accounting for the presence of the hot plasma which must give rise to the observed emission. Several distinct experimental and theoretical questions are involved:

1. What are the basic processes that produce hot plasma under the very wide-ranging conditions found on stars' surfaces throughout the H-R diagram?

2. What are the appropriate plasma diagnostics for testing the various hypothesized energy supply and loss mechanisms?

3. What insights can we glean for understanding related plasma processes in other astrophysical systems?

4. How do these stellar x-ray observations impact our notions of stellar structure and evolution?

Some of these questions have been addressed in a number of recent studies of late-type stellar coronae (Walter and Bowyer 1981; Belvedere *et al.* 1981; Landini and Monsignori-Fossi 1981; Stein 1981; and Golub *et al.* 1982). Most of these models are distinguished by the fact that the coronal plasma is assumed to be con-

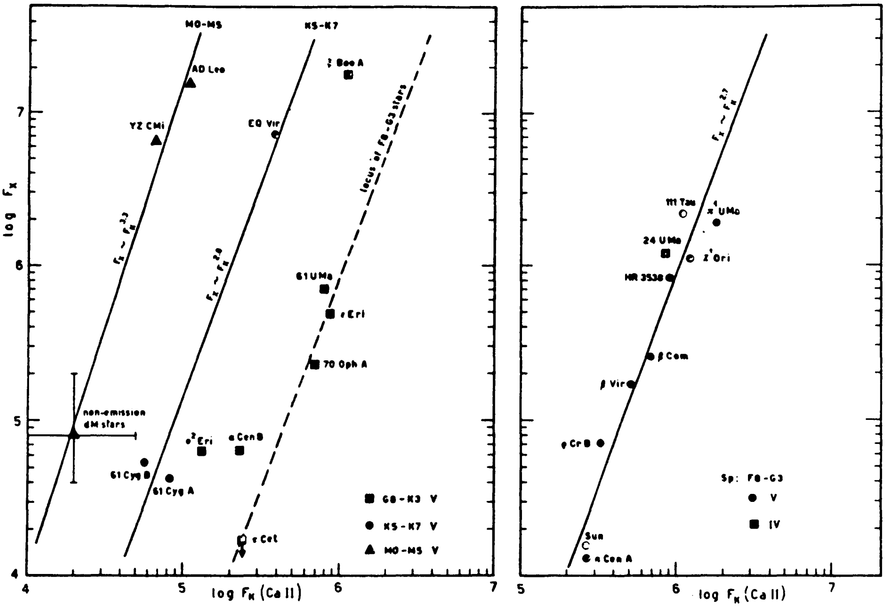

Figure 6: Plots of x-ray surface fluxes F_X (ergs/cm^2 sec) vs and Ca II K fluxes(ergs/cm^2 sec) for main sequence stars. The right-hand panel refers to stars of spectral types F8-G3; the straight line is a least-square fit. In the left panel, which refers to stars later than G8, different symbols are used to indicate subgroups of stars of similar spectral type. The two solid lines are best fit relationships to K5-K7 and M0-M5 stars, respetively. For reference, the locus of F8-G3 stars is plotted as a dashed line (from Pallavicini *et al.* 1982).

fined by surface magnetic fields. Because of this confinement, the coronal temperature is no longer constrained to be less than the stellar "escape" temperature, as defined by equating the thermal and surface escape velocities. In that case, one can take advantage of scaling laws connecting the temperature, pressure, and size scale of the confined plasma structures to "assemble" a prototype corona; and, by adopting a dynamo model for magnetic field generation, use the kind of magnetic field-coronal emission scaling discussed above to predict, for example, the variation of coronal emission along the main sequence (as has been done recently by, for example, Belvedere et al. (1981).

This sort of modeling does, however, have the disadvantage of applying dynamo calculations for magnetic flux production which are relatively poorly constrained by solar observations in and of themselves. A possible alternative procedure is to work backwards, and use the stellar coronal data, together with coronal models, to infer the rate of stellar magnetic flux production, and then to use this result – in the absence of sufficiently numerous direct observations of stellar magnetic fields (see however Marcy 1983 and Worden 1983) – as a constraint for stellar dynamo theory. We have recently carried out such an analysis (Rosner, Golub & Vaiana 1982; see also Golub *et al.* 1982, and Golub 1982, 1983), and I would like to briefly summarize the principal results.

We begin by assuming that the bulk of observed stellar coronal emission comes from "closed" coronal structures, in analogy with the Sun. If one adopts as a typical coronal scale length the emission scale height,

$$\ell = k_B T / 2\mu m_H g_o , \tag{1}$$

where T is the coronal temperature, μ is the mean atomic weight, and g_o is the effective gravity, and if the atmosphere is in hydrostatic equilibrium, one can solve

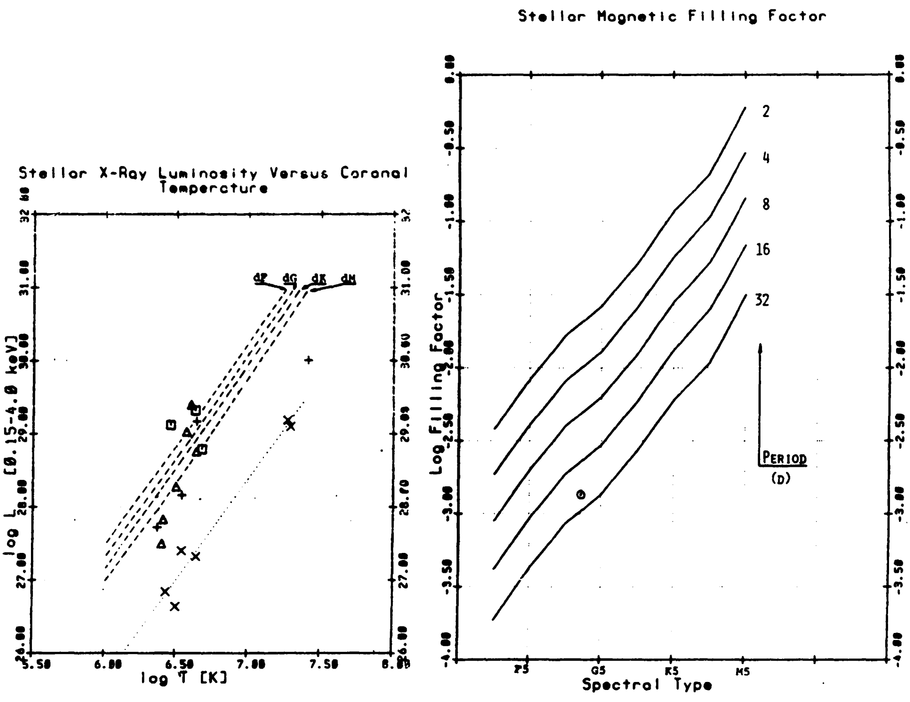

Figure 7: (left) Relationship between coronal x-ray luminosity and temperature, derived on the basis of a "loop" model for stellar coronae. (right) Variation of surface magnetic filling factor versus spectral type (with stellar rotation period as parameter). (from Rosner, Golub and Vaiana 1982).

the energy balance equation in the bounded coronal volume, and obtain a scaling law connecting the coronal soft x-ray luminosity with its temperature,

$$L_x = L(T ; M, R) , \tag{2}$$

with the stellar mass M and radius R as parameters. This result is independent of any assumption regarding the coronal heating process. An example of the results of such a calculation is shown in Figure 7 for late-type main-sequence stars, in which we have also used the Pallavicini *et al.* (1981) rotation-emission analysis to calibrate the curves. These results can be directly tested against observations (as will be discussed in § 4 below); the agreement appears to be rather good.

If one, now, applies the Golub *et al.* (1980, 1982) scaling connecting x-ray emission with the average photospheric field strength, then, depending on the assumed coronal heating mechanism, one can derive the coronal temperature and luminosity as functions of photospheric stellar parameters; for the class of so-called non-resonant heating processes (Kuperus, Ionson & Spicer 1981), coronal temperature and luminosity depend on the typical surface convective velocity v, the surface equipartition magnetic field strength B, the stellar mass M and radius R, and the surface magnetic filling factor f_B (defined as the ratio of the mean surface field strength to the surface equipartition field strength)

$$T = 3.9 \times 10^7\,K \cdot \delta(v, B, M, R)^{1/3} \cdot f_B^{2/3} \tag{3}$$

$$L_x = 5.3 \times 10^{31} \cdot \delta(v, B, M, R)^{5/6} \cdot (M/M_o) \cdot f_B^{5/3} \cdot q(\ell/R) \tag{4}$$

where q is a slowly-varying function of ℓ/R, and $\delta = (v/1\ \mathrm{km\ sec}^{-1})^2\ (B/10^3\ \mathrm{G})^2\ (M/M_o)^{-1}\ (R/R_o)^2$. If one adopts standard stellar models, the only unknown parameter is then the magnetic field filling factor f_B. Now the data have, as I've just mentioned, allowed us to correlate the level of coronal emission with the stellar rotation rate

$$L_x = L_x(\Omega); \tag{5}$$

this additional, purely empirical relation thus allows us, together with our model, to connect the stellar rotation period with the surface filling factor, or equivalently, the total surface magnetic flux

$$f_B = \eta(v, B, M, R, \ell) \cdot (\Omega/10^{-6})^{6/5}, \tag{6}$$

where η is determined by Eqs. (3)-(5). This is a fundamental constraint for stellar dynamo models because, if B is defined (as above) as the equipartition magnetic field strength, then the relation

$$\Phi = f_B \cdot B \cdot 4\pi R^2 \tag{7}$$

gives the total magnetic flux Φ predicted by the coronal model; this flux ought then to be compared with that predicted by models for stellar dynamos.

As an example, Figure 7 shows the result of such an analysis of coronal x-ray emission applied to late-type stars. Shown is the variation in filling factor as a function of spectral type and rotation period. The qualitative behavior corresponds to expectations (more rapid rotation leading to larger filling factors); and in quantitative terms, our results agree fairly well with observations in the very few cases to date in which comparison with data can be usefully made. For example, the model predicts filling factors of 1/10 or larger for rapidly rotating dM stars, which, of course, tend to be the well-known "spot stars", whose surfaces are in fact thought to be covered to a significant extent by surface magnetic field features.

We expect that a similar analysis will be carried out using other diagnostics, such as in the UV; it will then be of great interest to see if a consistent picture can be assembled.

3. NEW RESULTS: VARIABILITY

It has long been recognized that variability in coronal emission is a direct reflection of highly localized coronal plasma heating; the most obvious (and extreme) example is of course the solar flare. Let us however exclude such impulsive phenomena for the moment, and ask on what time scales one would expect to observe solar coronal variability if the Sun were regarded as a star. Figure 8 (adopted from Vaiana and Rosner 1978) gives a hint of some of the expected variability characteristics:

(i) *Very long-term fluctuations* related to the variation in amplitude of the rotationally-modulated integrated coronal flux occurs on a time scale of years; such variations are presumably related to a modulation in surface activity during the course of the solar (or stellar) magnetic dynamo cycle, and can be clearly seen in, for example, Wilson's (1978) classic Ca II monitoring data.

(ii) *Long-term fluctuations* related to the rotation of active regions and active region complexes onto the visible hemisphere occur on a time scale of several days to a month; this variability is especially noticeable in the solar record because it carries the (periodic) signature of the Sun's rotation (Fig. 8).

(iii) *Medium-term fluctuations* related to the emergence of active regions or active region complexes take place on the time scale of hours to days; such variations become accessible to *Einstein* observations on the orbital time scale.

(iv) *Short-term fluctuations* related to the impulsive brightening of individual "loop" structures (in the most extreme case, referred to as a flare) may take place on a time scale of minutes; these can be seen within a single orbit's coverage by the *Einstein* Observatory.

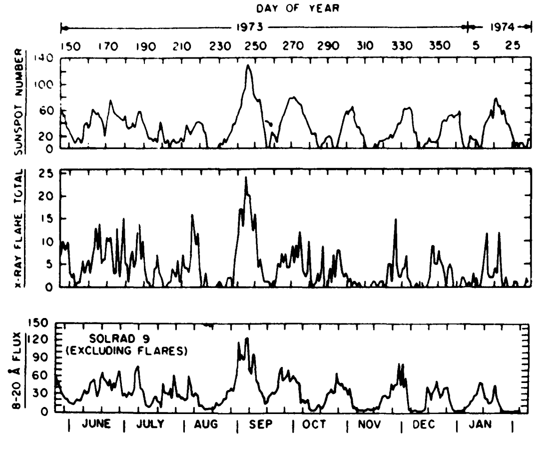

Figure 8: Correlation between sunspot number and x-ray solar variability. Solar rotation can be seen both in the flare component and the active region component (from Vaiana and Rosner 1978).

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The *Einstein* data provide the most exacting constraints on stellar surface (coronal) variability to date; typically, one is able to test the hypothesis that a given star's luminosity is constant in time on some specified time scale to the 10-20% fluctuation level (3σ). Aside from the trivial limitation imposed by photon statistics (which constrains the ability to pick up fluctuations on very short time scale), the only other major constraints were the very tight scheduling demands imposed by the large variety of scientifically-distinct observation programs (which limited the ability to track, for example, rotational modulation) and the limited duration of the mission itself (which placed an absolute upper bound on the possible time scale of observable fluctuations of roughly two years). Within these constraints, we have been able to investigate variability on time scales ranging from the short-term to the long-term (though in a very few selected cases, data separated by up to roughly two years were obtained); what then was seen?

The basic algorithm underlying our variability analyses involves sorting the data into successive time bins of width Δt, and then to test the hypothesis that within some confidence level determined by a χ-square test, the count rate per bin is constant as a function of time. Typical bin widths range from Δt = 20 sec to 1,000 sec, and the available total time intervals over which variablity can be tested range up to 2 years. For a typical source, the actual count rate determines a sensitivity level for variability detection, which corresponds to the 3σ fluctuation level (expressed as a percentage of the mean count rate) about the mean bin count rate. The results presented here (some examples of which are shown in Figures 9-11) are preliminary, and reflect only a small portion of the available information; here I would only like to summarize some of the key results which are now emerging from our work.

(a) Long-term variability. Figure 9 illustrates some of the classic examples of long-term variability in coronal emission we have found for late-type dwarf stars, ranging from changes seen on a weekly (*EQ Peg*), monthly (*CN Leo*, *UV Ceti*, *YZ CMi*), and yearly (π^1 *UMa*, *EQ Vir*) time scales. The basic result is that most such sources which were observed by the *Einstein* Observatory on well-separated occasions appear to be variable at the level of 20-100%; however, notice that π^1 *UMa* appears to have had a constant luminosity for the three observations stretching over a period of 2 years. Some of the variability shown here is actually attributable to the occurance of a flare during one (or more) of the observing periods; but upon detailed investigation, we now know that this is not generally the case: late-type dwarfs are indeed substantially variable on time scales of weeks to years.

(b) Medium-term variability. A very convenient method for testing for medium-term variability (as defined above) is to compare the total source count rate on a orbit-by-orbit basis. Some examples from our survey which have been treated in this way are shown in Figure 10; from this figure, it is immediately clear that the targets available for such analysis can be segregated into two categories: those stars which have been specifically targeted for variability analysis in the original observing programs (typically, flare stars, such as *UV Ceti*), and those stars (such as *Capella*, *HR 1099*, and *Wolf 630*) chosen for detailed spectroscopic analysis by the Objective Grating Spectrometer (OGS) because they were x-ray luminous (so that extremely long exposures in the 0th order – which can be treated as a standard image – were available). The actually observed behavior is remarkably varied. Thus, *UV Ceti* appears to vary very smoothly over the course of six orbit (which can be interpreted either as the reflection of the emergence and subsequent dispersal of an active region or, more likely, as the reflection of rotational modula-

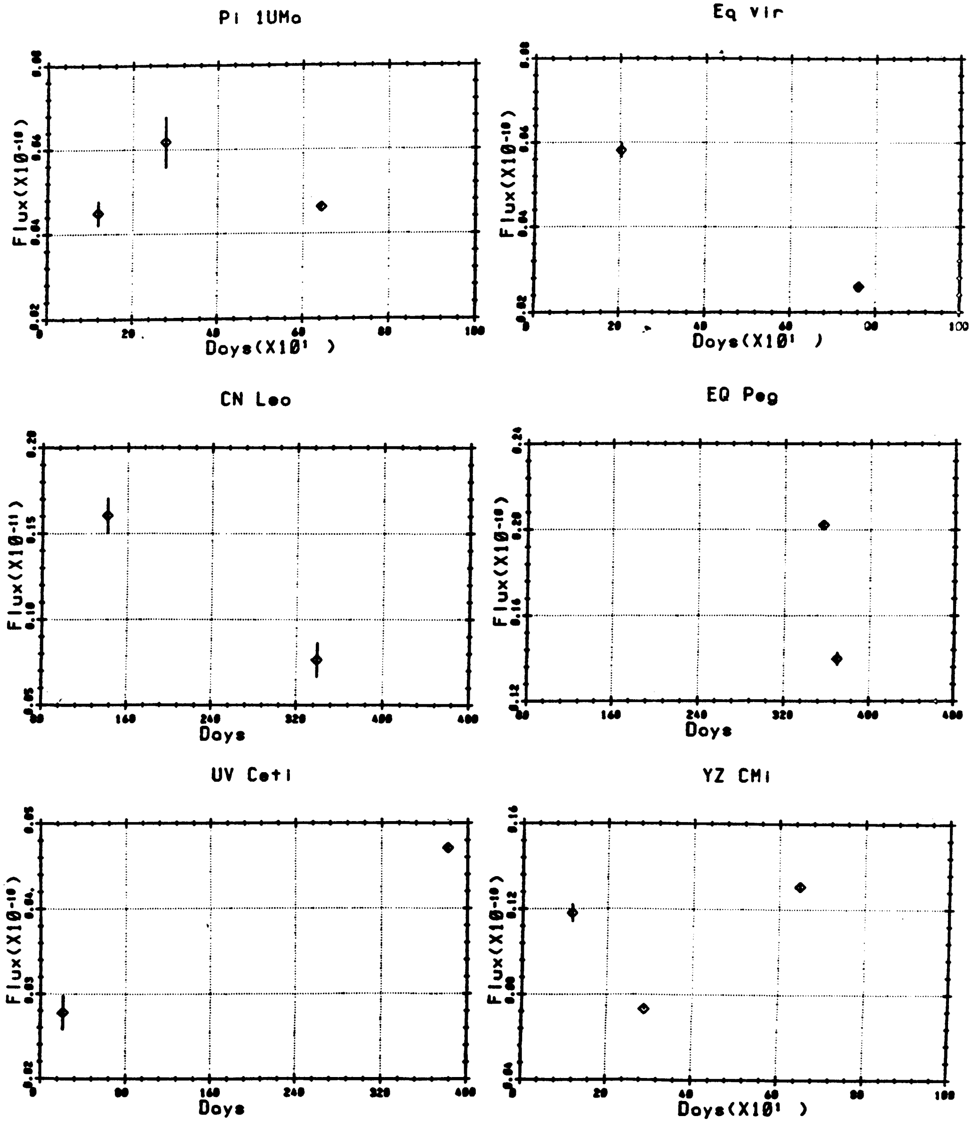

Figure 9: Example of long term variability in x-ray fluxes (erg cm^{-2} sec^{-1}) obtained from the Einstein Observatory for a number of late type stars sampled more than once at intervals ranging from a few weeks (EQ Peg), to months (π^1 UMa, CN Leo, YZ CMi) or years (π^1 UMa, EQ Vir, UV Ceti, YZ CMi). Most of the sources reobserved show substantial change in flux level well in excess of 3σs up to factors of two (π^1 UMa change is < 3σ). Some of the change is observed to be due to flaring behaviour, but base level changes of 10% to 50% are common.

tion of inhomogeneous surface x-ray emission). In contrast, the remaining three sources displayed in Figure 10 show no systematic behavior: both *HR 1099* and *Wolf 630* show large-amplitude variations on time scales of hours to a day; but *Capella* shows substantially smaller, if any, variability, and no long-term trends, in this section of the data.

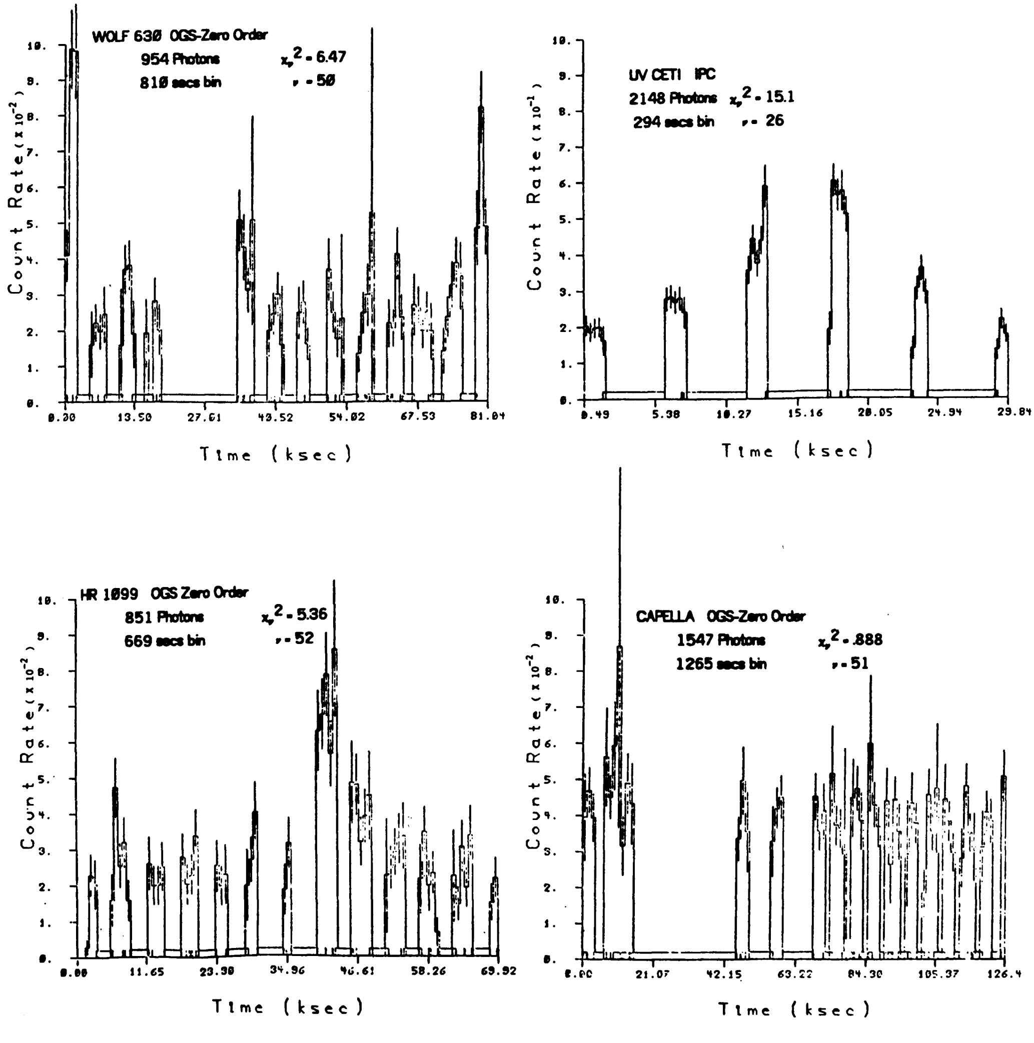

Figure 10: These four sources were observed more or less continously by the Einstein Observatory for periods ranging from 30 Ksec (6 orbits for UV Ceti with the Imaging Proportional Counter) to some 120 Ksec (16 orbits for Capella in the zero order of the Objective Grating Spectometer). The count rates shown here indicate orbit-to-orbit variability. Both UV Ceti and HR 1099 have increases of factors of 2 to 3 changes (in less than an orbit) lasting several orbits (3 to 4). A χ^2 test for flatness on several hundred seconds time-binning also indicate variability on this time scale for Wolf 630, UV Ceti and HR 1099 well above the sensitivity (at a level > 23%, > 24% and > 12% respectively), Capella does not vary on this time scale at fluctuation sensitivity level of 30%.

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(c) Short-term variability. Finally, consider the variability of stellar soft x-ray emission on short time scales, as shown in Figure 11a, b. Several interesting and instructive results emerge: *first*, it is apparent that although a source may appear to be constant on long time scales, it may well be extremely variable on short time scale, as illustrated by π^1 *UMa*; this star shows variability at roughly the 20% level

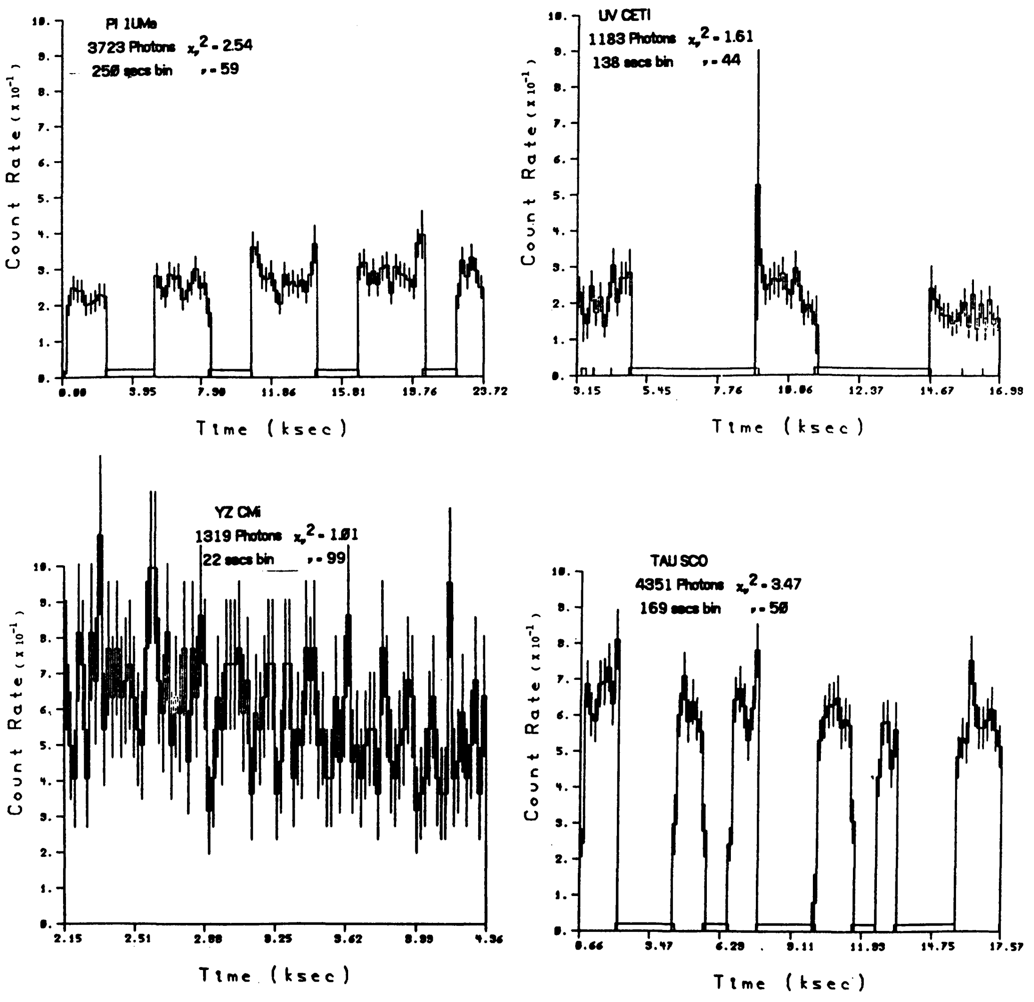

Figure 11a: Test for flatness with χ^2 statistics on a number of sources conducted with short time scale (binning of 25 to 250 seconds) show that variability on these time scales is also common in most sources at significant levels (> 10% - 20% levels). Variability in several orbits of both UV Ceti and π^1 UMa is here shown to be in excess of 15%. YZ CMi instead does not show sufficient excess χ^2 at the 30% level with a 22 second binning. This figure shows that variability is also present in early type stars: the hyphotesy that τ Sco's count rate is constant, for data binned on a 170 sec time scale, fails the χ^2 test severely.

when studied on short time scales. *Second*, the amplitude of long-term variability is little guide to the amplitude at short time scales, as shown by the virtually identical fluctuation levels at short time scale of π^1 *UMa* and *UV Ceti* (compare with Figures 9 and 10). *Third*, absence of variability at any given time is no guarantee that subsequent observations will not reveal substantial levels of variability; *EQ Peg* is a nice example of such change in variability level. Finally, *fourth*, I thought it instructive to show that one's (theoretical) notions of what ought to be are not always the most reliable guide: although x-ray emission from OB (early-type) stars is commonly thought to be due to rather different processes than are associated with x-ray emission from late-type stars, processes with which one would hardly associate fluctuations in x-ray emission on the minute time scale (viz. Cassinelli *et al.* 1981), it is nevertheless the case that *OB stars do vary on the minute time scale*, as shown by observations of τ *Sco.*

On a more detailed level, one can ask for the possible correlation between the fluctuation level ΔL and the stellar x-ray luminosity L; our results are still somewhat preliminary, but do suggest that the fluctuation level ΔL is correlated with the stellar x-ray luminosity, with $\Delta L/L$ in the range 0.2-0.6 for the luminosity range $L_x \sim 10^{28} - 10^{30}$ erg sec^{-1}. Furthermore, one can ask whether the fractional variability $\Delta L/L$ is correlated with other stellar attributes; the most obvious is of course

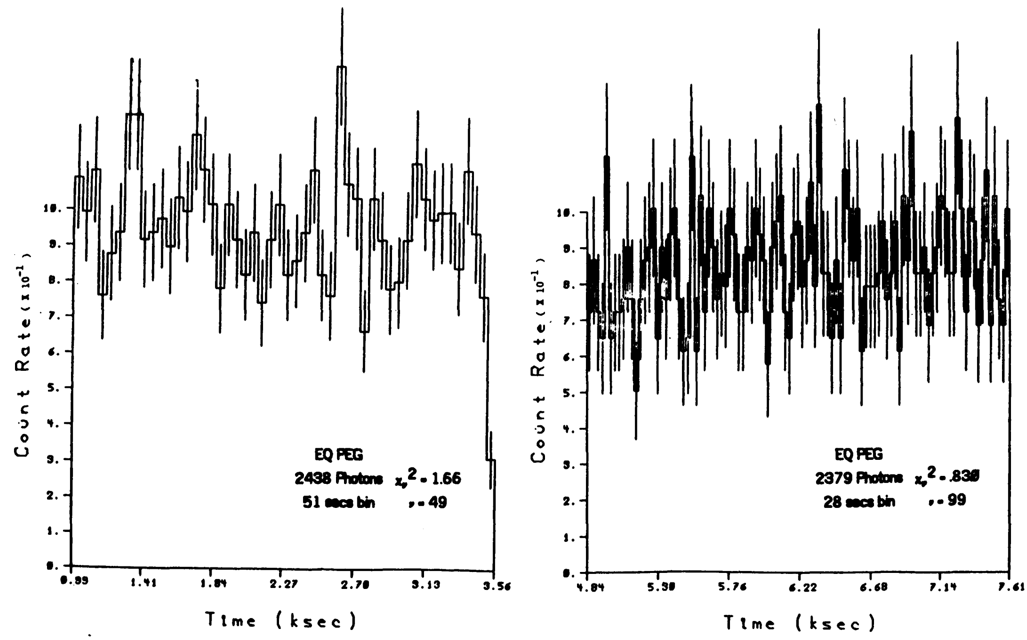

Figure 11b: Similar flatness tests are shown here for EQ Peg on two different orbits (weeks apart). In the first (left) a significant level of variability is shown at > 20% level, while in the second (right) no such variation is seen. This source behaviour is not uncommon in other sources.

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spectral type. Our results are here still very preliminary; there is a suggestion that the "basement" level of variability seems to be fixed at roughly the solar level (and so is independent of spectral type), but that the maximum variability does show a trend with spectral type: the active low-mass stars seem to have exaggerated variability when compared with corresponding solar-mass stars.

What do we then conclude regarding stellar x-ray variability? Our basic conclusion is that *essentially all stars show variability on virtually all time scales*, given sufficient sensitivity. This conclusion encompasses not only the cool, solar-like dwarf stars, but also evolved late-type stars and hot, early-type (OB) stars of all luminosity classes. In retrospect, this result ought not be surprising – at least for the late-type dwarfs – if we recall our previous discussion of the underlying cause for stellar activity of such stars as revealed by the activity-rotation correlation; indeed, we here simply receive yet further confirmation of the aptness of the solar model.

4. NEW RESULTS: STELLAR CORONAL LUMINOSITIES AND TEMPERATURES

The *Einstein* Observatory carried four spectrometers onboard: the Imaging Proportional Counter (IPC), with $\Delta E/E \sim 1$; the Solid State Spectrometer (SSS), with $\Delta E/E \sim 50\text{-}100$; the Objective Grating Spectrometer (OGS), with $\lambda/\Delta\lambda \sim 50\text{-}100$; and the Bragg Crystal Spectrometer (BCS), with $\Delta E/E \sim 1000$. Of these four instruments, only the IPC carried out a sufficiently large number of observations so that systematic diagnostic studies and correlation analyses can be presently pursued for well-defined data samples. For this reason alone, I will focus in the following on the IPC results; it should, however, be kept in mind that high-resolution observations of a few selected (very active) stars were carried out by the other spectrometers (see, for example, Holt *et al.* 1979).

Typically, given sufficient counts, an *Einstein* stellar x-ray image could be analyzed by comparing the observed IPC spectrum with model spectra which assume a thermal source spectrum, take into account interstellar absorption, and are folded through the calibrated instrument response. The particular model spectra used include continuum and line contributions for an optically-thin plasma in ionization equilibrium, provided by Raymond (1981). In the simplest case, we assumed that the stellar x-ray emission could be attributed to a plasma characterized by a single temperature; for such single temperature component fits, we typically constrained the interstellar hydrogen column density $N_H < 10^{18}$ cm^{-2} for nearby sources, so that the only remaining free parameters are the (emission measure-weighted) mean coronal temperature and the corresponding total emission measure. What are our results?

Let me begin by considering several specific cases which illustrate both the procedures of analysis and the range of results we have obtained. Figure 12 shows the IPC spectral data for four stars: twice for *UV Ceti* and *EQ Peg* (showing the difference in spectral characteristics for quiescent and active periods), and once for π^1 *UMa* and τ *Sco*. In each case, we show both the actual binned IPC spectrum and the best-fit (in the χ-square sense) single temperature model. Three major results are apparent:

(1) *There is a perceptible change in spectrum as the stellar activity level varies*: as shown by both the *UV Ceti* and *EQ Peg* observations, increasing activity level is accompanied by a hardening of the spectrum.

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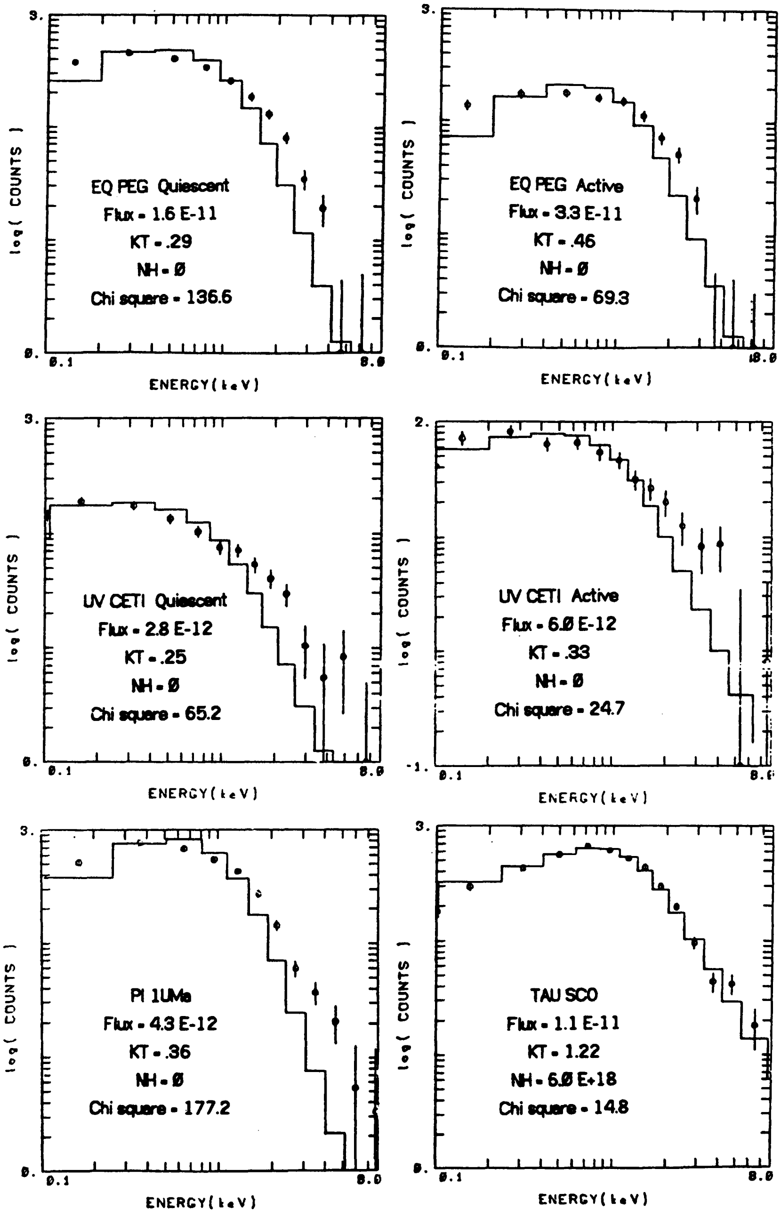

Figure 12: Single temperature best fit to IPC spectra for a number of sources are shown here. Indicated are the resulting flux in the 0.2 - 4.0 KeV energy band in ergs cm^{-2} sec^{-1}, the KT in KeV, the hygrogen column density NH, and the total χ^2. The poorness of the single temperature fits for these and many other sources suggests two temperature components. This is a remininiscent of the results obtained with the Solid State Spectometer for the RS CVns by Swank et al. 1981. It is also interesting to note that the active phases of UV Ceti and EQ Peg shown here correspond to those observations (Fig. 11) showing higher variability and fitted by harder spectra. Also shown for comparison is a best fit spectrum to the early-type star τ Sco.

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(2) *In the overwhelming majority of cases, simple single temperature component models fail to give an adequate fit to the data*; in the cases shown, the fitting spectrum gives a good account of the soft portion of the observed spectrum, but seriously underestimates the flux at high (> 1.5 keV) photon energies. This inadequacy of the single-component models is apparent in all of the spectra for late-type dwarf stars shown in Figure 12. A hint of what might be going on is of course contained in the SSS observations of *RS CVn* stars reported by J. Swank and collaborators (cf. Swank and White 1980; Swank *et al.* 1981): these higher-resolution data show fairly clear evidence for the simultaneous presence of at least two distinct temperature components in the source spectrum. It is therefore tempting to argue that this effect is the cause of the discrepancy under discussion. We have in fact attempted 2-component fits to the data for those cases in which single-component analyses clearly failed; and it does appear that the multi-component fit gives substantially better account of the data (in particular, the improvement in the fit is substantially larger than would be expected on the basis of simply increasing the number of available degrees of freedom). How are we to interpret these results? In general, we must consider two distinct possibilities:

(a) Every one of the "two-component" x-ray sources is a binary, in which the low-mass secondary has not as yet been identified (or recognized); this situation might occur especially in those cases in which the primary is of relatively early spectral type (typically, earlier than G0), and relatively faint (typically, fainter that $m_V \sim 6$), so that detailed spectroscopic studies of the system in the optical are not as yet available. Because the later-spectral type secondary will tend to be active (it will be relatively young for its spectral type because of its presence in a binary dominated by a much earlier spectral type main-sequence star), and because of the above-mentioned connection between x-ray luminosity and temperature, it is likely that the secondary will be a harder x-ray source than the primary; hence the presence of two distinct temperature components.

(b) In the case of the Sun, it is well-known that there are two distinct classes of coronal structures: the active component, associated with compact regions of recently emerged magnetic flux, which has a relatively-high surface brightness and temperature; and the inactive ("Quiet") component, which consists of larger, evolved structures whose surface brightness and temperature are relatively lower. If we are to extend the solar analogy, it would not be farfetched to argue that a similar evolutionary segregation of coronal structural types occurs on stars other than the Sun. Hence, one is tempted to relate difficulties of fitting a single temperature models to the presence of this kind of "multi-component" corona, particularly for stars in which the above binary hypothesis does not seem appropriate. A good example is the apparently single active G0 star π^1 *UMa*, whose IPC spectrum shows precisely the kind of difficulty discussed here (Figure 12).

Which one of the two above cases actually holds in a given, specific instance cannot of course be determined on general grounds.

(3) *In spite of the supposed distinction between mechanisms accounting for x-ray emission from early and late spectral type stars, simple single-temperature thermal fits to IPC spectra of OB stars such as* τ Sco (Figure 12) can give an adequate description of the data. In fact, as is apparent from the figure, such a model gives better account of the spectrum of τ Sco than of the

spectra of the other (late spectral type) stars! I am of course not arguing that OB star x-ray emission ought to be modeled by using theories for late-type stellar coronae, but rather simply cautioning that both the variability and spectral data we have in hand are not to be easily accounted for by current models for x-ray emission from early-type stars.

Let me now turn from the details of the spectral fitting to an overview of these detailed results. Figure 13 shows our principal result to date, the correlation of stellar x-ray luminosity with mean coronal temperature. Comparison with the theoretically-predicted result, shown above in Figure 7a, suggests that what we are seeing is indeed appropriately described (at least to the level of detail allowed by the present data) by the solar analogy; that is, the data show a positive correlation between luminosity and temperature, with temperature varying over a rather narrow range, while the luminosity spans over three orders of magnitude (rather reminiscent of the brightness-temperature correlation observed for individual solar structures).

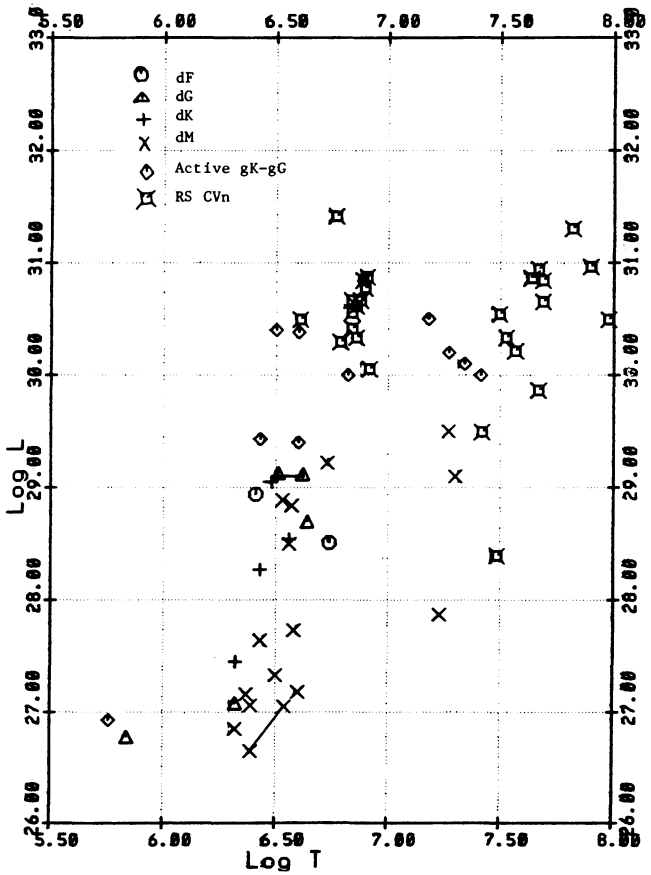

Figure 13: Luminosity vs. temperature results for a number of single temperature fit IPC spectra. RS CVn data points are from the two temperature fits of Swank et al. 1981. Present uncertanty for the IPC gain result in an uncertanty in the temperature determination of 0.5 in Log T for soft spectra. The general trend of L_x vs. T is quite suggestive of the model results of Fig. 7.

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On a somewhat more detailed level, can one see the correlation between temperature and spectral type (for fixed luminosity) predicted by the model (Figure 7a)? Recall our original model assumption that the filling factor for coronal emission is unity, or at least fixed (neither assumption is likely to be universally applicable); and note that even in the ideal case that the filling factor is indeed fixed, the spread in temperature for fixed luminosity resulting from spectral type dependence is smaller than the uncertainty in a typical temperature determination. It is therefore evident that it is premature to use the present data to test for this particular correlation.

5. SUMMARY

It seems that, by using solar observations to establish the quantitative correlation between coronal activity (as reflected in the level of soft x-ray emission) and photospheric magnetic activity, observations of soft x-ray emission from late spectral type stars are able to shed light on the extent of stellar surface magnetic activity. The extensive data provided by the *Einstein* Observatory have been used to define a sequence of independent, redundant tests of the "solar hypothesis", using both the observed variability in emission, and the detailed luminosity-temperature dependence.

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DISCUSSION

MULLAN: Can you comment on the coronal structure in cool giants, where X-rays have not been detected? Do static loop models apply there?

VAIANA: You and others have advanced suggestions for these stars to have open coronae dominated by winds. Static loop coronae would not apply at all in this case.

MOUSCHOVIAS: Have I missed a point? In your talk you first mentioned that there is a wide range of X-ray luminosity at a given spectral type. Later on, if I understood you correctly, you said that spectral type very much determines the mean X-ray luminosity, as well as its variability. Could you, please, restate what the case is?

VAIANA: Experimentally, spectral type in late-type stars does not in a first approximation determine the X-ray luminosity; indeed, in this approximation, the population mean luminosity is independent of spectral type. Instead, it appears that rotation, or age, are far more important parameters in determining the luminosity. However, it may be that there is a residual dependence on other parameters, such as mass (or spectral type). Our model includes such a weak dependence. At present, however, this is not testable. With respect to variability, the preliminary data seem to indicate that M stars vary more than earlier solar-type stars.

MALTBY: Could you tell us how the stellar scaling laws you presented compare with the observations?

VAIANA: Within the limits of the present errors, the agreement is good. The present systematic errors are due to uncertainty in the IPC gain. This uncertainty will soon be removed, and we will be able to make a more detailed comparison. A two-temperature analysis will also help to subject the model to meaningful tests.

LINSKY: Could you comment on whether there are indications that coronal temperature depends on stellar gravity, and whether an active star is a member of a close binary system or is single?

VAIANA: We do not have many late-type giants that can be fit. Since they are not particularly strong sources as compared with main sequence stars, and because they are much more distant, we do not have many photons to consider. From the few giants I have seen, my impression is that their spectra are not harder: for instance, β Lep seems to be softer than π^1 UMa. In the early-type stars, κ Ori seems softer than τ Sco. Of course, the interesting comparison will have to be done along evolutionary sequences: β Lep may turn out to be softer than π^1 UMa, but harder than the Sun. With respect to single vs. binary stars, again π^1 UMa is a good example of a single star having a hard component as well. The difference between such single stars and active binaries such as RS CVn's may then be quantitative (rather than qualitative), but this remains to be looked at.

MEGESSIER: The first detections of X-rays in the stars indicated a gap in the H–R diagram near the A type. Is that always the case?

VAIANA: There will be a forthcoming paper by Cash and Snow and our group on A stars. Stars like Vega and Altair are at the bottom of the luminosity scale for early-type stars. Jurgen Schmitt and Leon Golub are investigating where the onset of the high luminosity regime associated with F dwarf stars is.