STELLAR CORONAE, CHROMOSPHERES OF COOL STARS

OBSERVATIONS OF STELLAR CORONAE

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ABSTRACT.

We present an overview of recent stellar X-ray observations, with some discussion of the requirements for future observations. We argue that solar observations indicate that coronal X-ray emission is strongly related to surface magnetic field activity; we show that the interpretation of X-ray stellar coronal emission from late-type stars within the framework of models analogous to those developed for the solar corona is viable, and it is supported by many experimental results. The extension of this solar analogy to the early-type stars is quite questionable and remains an unsolved problem, while the working hypothesis of an X-ray phase, related to phenomena of magnetic field-related activity, as contrasted to a wind phase during the PMS evolutionary stage is suggested by the present status of observations.

1. INTRODUCTION

Over the past two decades, the study of the very hot component of solar and stellar atmospheres has widened in its scope, range and perspective. In particular, over the past decade a new astronomical discipline has emerged: stellar X-ray astronomy. It is set at the crossroad of several major areas of astrophysical research. In the solar physics context it provides not only a major testing ground for theories but also motivates major readjustment in the perspective of the solar discipline. In the more general astrophysical context, stellar X-ray astronomy is a testing ground for several plasma processes and magnetic field-related mechanisms (magnetohydrodynamics and plasma physics of activity in flares and transients, energy release and wave propagation, magnetic field generation in self gravitating bodies and evolutionary effects of activity). In the stellar context, X-ray emission is one of the most sensitive monitors of activity, and relates to most of the major area of stellar research, covering almost all stellar masses and evolutionary stages.

In this paper, we will review and summarize the work in progress, with an emphasis on the experimental and on the observational perspective; for other aspects not covered here, we refer the interested reader to the specific literature and to some other recent reviews (Rosner, Golub and Vaiana 1985; Linsky 1985; Serio 1985; and reference therein).

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Prior to the *EINSTEIN* launch (1978), the domain of stellar X-ray astronomy was limited to only a few "odd" stars: compact binaries, as well as relatively larger samples of dwarf novae, cataclysmic variable and RS-CVns (Catura *et al.* 1975; Mewe *et al.* 1975; Nugent and Garmire 1978). If the Sun had really been prototypical, based on the 10^3 increase of *EINSTEIN* Observatory sensitivity over previous spacecrafts, we expected to detect few solar-like stars at 10-20 pc with exposure times of $\sim 10^3$ s, while, with exposure time of $\sim 10^4$ s, we expected to detect thousands of times more intense sources up to distances of few kpc. The Sun turned out, not surprisingly, to be prototypical in the sense that a majority of solar-like stars emitted nearly at the same level of the Sun. Yet a major element of surprise was that the Sun lies near the bottom end of the observed range of X-ray luminosities of late-type stars, which spans over three decades. A second element of surprise was the ubiquity of the X-ray emission from all kinds of stars (cf., Fig. 1) independent of their mass and stage of evolution (Vaiana *et al.* 1981, Helfand and Caillault 1982).

As X-ray emission emerged as a general phenomena in all types of stars and an exceptional emission levels (with respect to the Sun) was detected for a substantial fraction of stars, a numbers of obvious questions arose: Why do most stars chose to put a fraction of their energy in high energy photons? Why do some stars chose to emit thousand times more high energy photons than others of identical mass and luminosity class? Why does this sort of behavior seem to be relatively independent of gravity (at least up to some spectral type)?

In the following we first review and update the general properties of stellar X-ray emission as deduced from the observations; and then discuss the specific characteristics of group of stars, with a particular emphasis on late spectral type and pre-main sequence stars.

2. WHAT HAVE WE LEARNED FROM THE SUN ?

In order to answer the questions posed above we need a closer look at the phenomena of the solar corona, with the aim of understanding if the physics of these phenomena can guide us in explaining stellar X-ray emission, at least for the case of late-type stars.

Here we limit ourselves only to a brief summary of the results from early rockets flights and from the X-ray telescopes on board *SKYLAB*; for a detailed discussion, we refer the reader to the extensive review of Vaiana and Rosner (1978) and the references therein quoted:

- The outer atmosphere of the Sun is hot, structured and magnetized. The spatial contrast is highest at X-ray wavelengths, with clear evidence of magnetic confinement of plasma (loops). Within these loops the temperature T and the electron density n_e attain higher values than in the surroundings. The X-ray images of the Sun reveal regions of open magnetic topology: the coronal holes; less luminous in X-ray, they are found to be the sources of high speed solar wind streams. In general, higher values of the magnetic flux are correlated with higher values of L_x and higher values of L_x/L_v.
- The atmosphere is dynamic, with variations on a remarkably wide range of time scales (even excluding flare variability).
- The magnetic field has also an active role in *in situ* heating of plasmas within loops.

3. GENERAL PROPERTIES OF OBSERVATIONS

The stellar X-ray data have added many more new problem areas to those derived from the solar realm alone. We now have to contend with emission from early-type stars, from pre-

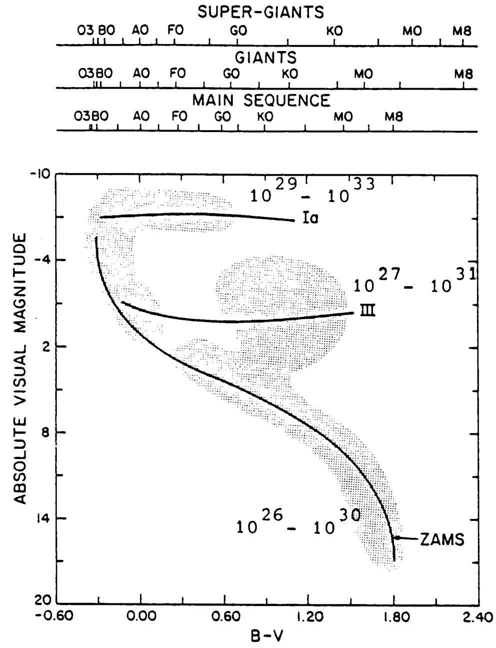

Figure 1. Schematic illustration of where stellar X-ray emission has been detected along the H-R diagram. Ranges of observed luminosities are also indicated.

main sequence and young cluster stars, from giants and WD stars, and finally from the host of low-mass dwarf stars. At the spectral type transition region between early and late type stars, the observations are so well defined that we can address the question of the onset of convection along the main sequence . A summary of the prototypes of the activity runs as follows:

- Dwarfs in the spectral type range from F to M are X-ray emitters. L_x is, to first order, independent of T_{eff} and surface gravity. The values of L_x range between 10^{26} and 10^{30} erg s^{-1}, and scale with the stellar surface angular velocity Ω (cf. Fig. 2) as $L_x \sim \Omega^n$, where $1 < n < 2$ (Vaiana *et al.* 1981, Walter 1982, Pallavicini *et al.* 1981).
- Stars earlier than B5 are X-ray emitters, at emission levels ranging between 10^{29} to 10^{34} erg s^{-1}, L_x is independent of surface gravity and scales with L_{bol} as $L_x \sim 10^{-7}$ L_{bol} (Harnden *et al.* 1979; Seward *et al.* 1979; Long and White 1980, Pallavicini *et al.* 1981).
- In the spectral type range from B8 to A5 detailed analysis has shown that, contrary to earlier reports, there is no credible evidence of X-ray emission from normal main sequence stars and Am stars (Schmitt *et al.* 1985a); however, there is some evidence for emission from Ap stars (Cash and Snow, 1982).
- Late giants and supergiants show a cutoff in X-ray emission levels as one moves to later spectral type (cf. Fig. 3), in particular, the M giants and the G and M supergiants have not been detected (Ayres and Linsky 1980, Ayres *et al.* 1981: Vaiana *et al.* 1981; Haisch and Simon 1982).

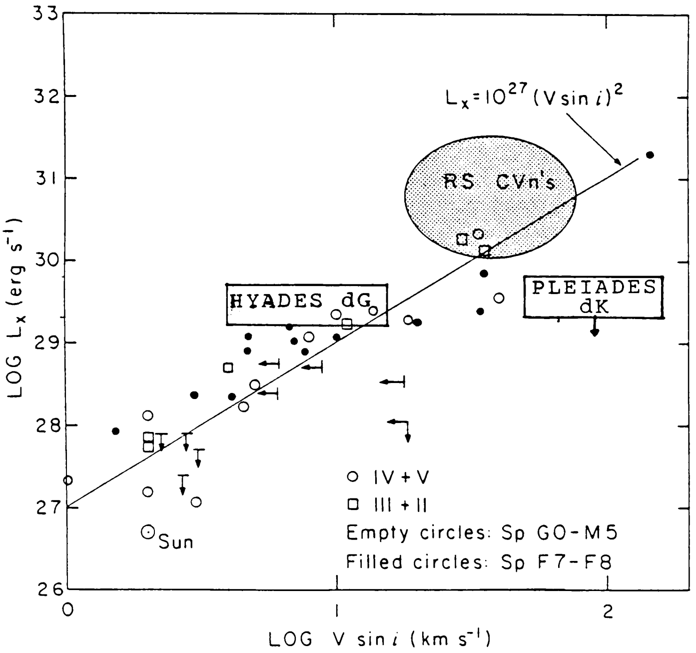

Figure 2. Scatter plot of soft X-ray luminosity versus rotation rate (adapted from Pallavicini *et al.* 1981) and extended to newly analyzed *EINSTEIN* and *EXOSAT* data. Note that independent of spectral type, the correlation is quite good, except for the data points of the Pleiades fast rotating K stars.

- The X-ray luminosity is a function of stellar age, the dependence is not simple and, in general terms, is consistent with the decline of Ω with stellar age (Vaiana 1983, Stern 1983, Micela *et al.* 1985, Caillault and Helfand 1985).
- Pre-main sequence stars have X-ray luminosities more than a thousand times the X-ray luminosities of normal main sequence stars (Feigelson 1984 and reference therein).
- The X-ray spectra of late-type stars are thermal, with single temperature components in the range 0.2-2.0 keV (10^6-10^7 K); however, many spectra show evidence for multi-temperature plasma (Holt *et al.* 1979; Swank *et al.* 1981; Vaiana 1983; Mewe *et al.* 1982; Schrijver *et al.* 1984; Majer *et al.* 1986), consistent with a continuous emission measure distribution in temperature; such emission measure distributions have been considered more appropriate for loop modeling analysis by some authors (Majer *et al.* 1984; Mewe 1984; Schmitt 1984; Schmitt *et al.* 1985b; Stern *et al.* 1986).
- Solar-like transients have been detected in late dwarfs (Haisch *et al.* 1980; Haisch 1983, Kahler *et al.* 1982) and in evolved stars which are members of close binary systems (e.g., RS-CVns; Walter *et al.* 1980; Agrawal *et al.* 1983); moreover, more energetic events named superflares, in which the release of energy as total soft X-ray luminosity is 10^2-10^3 times that in the solar case (Stern 1983, Montmerle *et al.* 1983; Stern *et al.* 1983; Caillault and Helfand 1985), have been detected in a few young dwarf stars and in pre-main sequence stars (cf. Fig. 4).

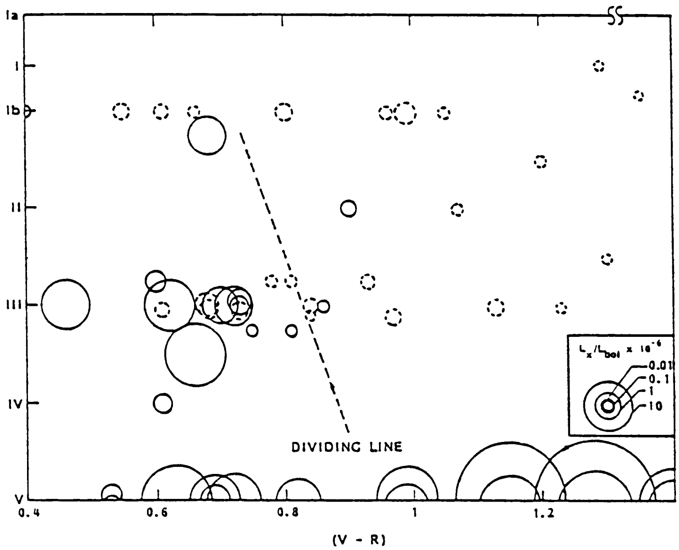

Figure 3. H-R diagram of a sample of single late-type stars observed with the *EINSTEIN* Observatory (adapted from Antiochos *et al.* 1986), showing detections (solid circle) or upper limits (broken circle). The size of a circle is proportional to the bolometric luminosity. Note the lack of detections to the right of the dividing line (dashed).

- X-ray emission from close binary system, such as the RS-CVn (Walter *et al.* 1980) and the W UMa stars (Cruddace and Dupree 1984), in which the accretion should not play a major role, are substantially more intense than those from single stars of similar stellar structural characteristics.

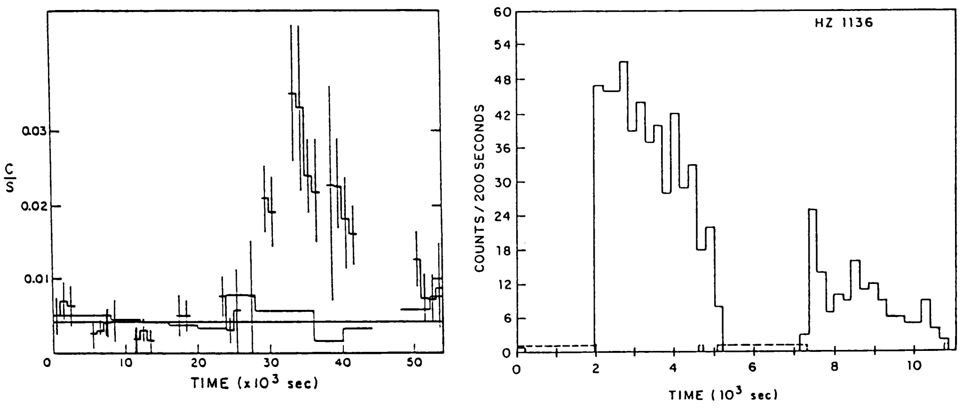

Figure 4. (right) X-ray light curve of a complete flare-like event seen in AS205 within 4 hours (Walter and Kuhi 1983). (left) Superflare seen in the K Pleiades stars Hz 1136 within 2 hours (Caillault and Helfand 1985).

4 EARLY TYPE STARS

Because the solar analogy is not immediately applicable to the early type stars, the problem of the physical mechanism responsible for their emission is more intriguing, and our understanding is quite primitive as compared to the case of late type stars. Two points are essential for model-building, and have not as yet been definitely established:

- The X-ray source location, especially within the context of the stellar wind geometry; here spectral studies will play an essential role.
- The spatial geometry/distribution of the emitting plasma (i.e., is the emitting gas diffuse, or does it occur in the form of fairly well-defined hot "bubbles" or shock structures); here variability studies will be of considerable interest.

In addition to the constraints already cited above, other observational constraints for modelling the X-ray emission from OB stars can be summarized as follows:

- There is some evidence that L_x does not scale as $\dot{M}$ (Ramella *et al.* 1986);
- The spectra are not absorbed at 0.5 keV (Cassinelli and Swank 1983);
- There is some indication of long-term (Snow, Cash and Grady 1981) and short-term (Collura *et al.* 1986) variability of the X-ray emission.

The model originally proposed for OB star X-ray emission, namely that a hot corona lies near the stellar surface, underlying a far cooler high-speed wind (Hearn 1975; Cassinelli and Olson 1979; Waldron 1984), cannot easily reconciled with the absence of absorption features at 0.5 keV (cf., Fig. 5). More recent models attempt to explain the X-ray emission by considering that the massive radiatively-driven wind might be unstable to density perturbations, with the blobs of enhanced density produced by the instability shocking, and thereby producing material distributed throughout the wind, which in turn leads to the observed X-ray emission (Lucy and White 1980; Lucy 1982). However, Cassinelli (1985) has interpreted the evidence for very hot plasma ($T > 1.5\ 10^7$ K) as a requirement for confinement of this hot gas, and hence hypothesizes that this confinement may be magnetic in character.

Much work is now in progress on the problem of understanding the origin of X-ray emission from early-type stars. For example, Ramella *et al.* (1986) are reinvestigating the correlation of L_x with stellar and wind parameters, based on a larger sample of stars than in the original *EINSTEIN* investigations; and Collura *et al.* (1986) are investigating the short-term variability of a sample consisting of a dozen OB stars.

5. LATE GIANTS AND SUPERGIANTS

The major problem raised by the observations is whether there is really a change of character of X-ray activity in evolved stars with respect to main sequence stars, i.e., whether the applicability of the magnetically-confined corona prototype to the atmospheres of late giants and supergiants can be maintained (e.g., Dupree 1982, Linsky 1982). Beyond the cutoff in the X-ray emission level at later spectral type (cf. Fig. 3), the scaling of the X-ray emission for some of the detected giants with Ω^2 is the major observational constraints to date. This latter experimental result supports the notion that magnetic activity is the driving mechanism of the chromosphere-corona activity in evolved stars as well. Indeed, if this is the case, we will expect (as in the case of the main sequence stars) a good correlation of X-ray luminosity level with stellar parameters such as the rotational surface velocity, which are related to dynamo activity. Unfortunately, the present status of data at hand does not allow us to study these correlations in detail.

An ongoing program to survey the total sample of late giants and supergiants listed in the bright stars catalogue (Hoffleit 1982) and observed with the *EINSTEIN* IPC is in

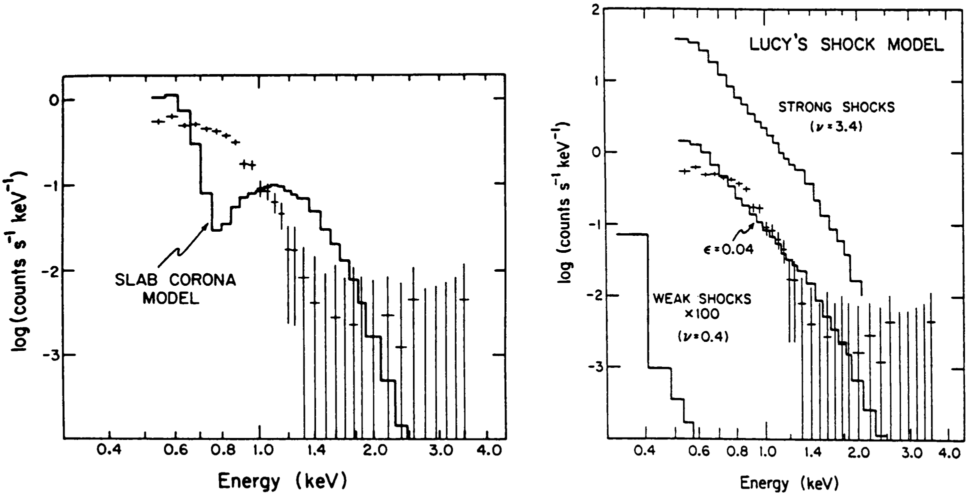

Figure 5. (right) SSS spectrum of ϵ Ori, with the best fit based on the slab corona model plus cool wind of Cassinelli and Olson (1979). Note the lack of the absorption feature at ~ 0.5 keV in the experimental data. (left) Same spectrum with the best fit derived from Lucy (1982) model in which both weak shocks and few isolated stronger shocks are included (adapted from Cassinelli and Swank 1983).

progress (Maggio *et al.* 1986). The preliminary results support the previous finding of the existence of a dividing line also in the X-ray emission.

Present modeling of X-ray emission from evolved stars addresses the problem of the weakening of X-ray emission at later spectral type. Some authors have suggested that the coronae of the evolved stars are more analogous to solar coronal holes than to solar loops (Linsky and Haisch 1979); Linsky and Haisch noted that the appearance of cool winds (as seen in UV lines) coincides with the disappearance of hot coronae (as seen in soft X-rays). A different description (Ayres *et al.* 1981), originally suggested to explain the presence both of coronae and cool stellar wind in the so-called hybrid-spectrum supergiants (Hartmann, Dupree and Raymond 1980), assumes that the X-ray emission derives from magnetic loops extending to some given distance above the star's surface, and that above that height a flow of cool wind develops; this wind will significantly absorb the softer X-rays emitted by the compact coronal structures. More recently, Antiochos *et al.* (1986) have proposed that because of the low surface gravity of the stars without X-ray emission, a hot ($T > 10^6$ K) corona is thermally unstable, and must cool down to lower temperatures, thus explaining the (apparent) lack of coronae.

However, due to the drastic reduction of the *EINSTEIN* IPC sensitivity as one goes from 0.25 keV to 0.10 keV, which results in poor IPC sensitivity to X-ray emission when the coronal temperature is less than 10^6 K, the actual status of our knowledge does not rule out the existence of warm coronae ($T \sim 10^5$ k) in supergiants; this problem will remain for future telescopes, which are sensitive in a softer energy band than the *EINSTEIN* Observatory was.

6. SOLAR-TYPE STARS

Turning to the subject of solar-like stars, the fundamental question which arises is related to the extrapolation of solar modelling to the stellar case: how appropriate is the solar analogy? In addition to this central problem, other questions emerge; for example:

- How do the parameters of coronae (L_x, T, n_e) vary with stellar parameters such as M, T_{eff}, Ω, Z?
- Is there any evidence for a dependence of stellar X-ray activity on stellar age?
- What happen to activity in the very low mass stars and in the close binaries?
- At what spectral type does the onset of surface convection occur?

All of these questions are related to larger underlying problems, such as the dependence of stellar surface activity on the stellar dynamo, the nature of surface activity in itself, the structure of the convection zone in low-mass stars, and the general problem of flaring in astrophysics. Many of these questions can now be addressed with the aid of new (at least within the astronomical realm) statistical techniques which allow one to study unbiased (or, in general, volume-limited) samples of stars with the use of survival analysis; these techniques, which permit the inclusion of upper limits to detections, have enabled one to construct maximum likelihood integral X-ray luminosity functions. For a detailed description of these techniques, we refer the reader to Schmitt (1985), Feigelson and Nelson (1985), Isobe *et al.* (1986), and extensive applications of these techniques can be found in Schmitt *et al.* (1985a), Micela *et al.* (1985), Maggio *et al.* (1987), Bookbinder (1985), Micela *et al.* (1986). In the following, we limit our discussion to a summary of some of the major results, including new data not yet published.

6.1. X-ray Emission and Rotation

A dependence of X-ray emission level on rotation rate is expected on the basis of stellar dynamo theory; indeed, the observed correlation between X-ray luminosity and stellar rotational velocity is quite striking, notwithstanding the typical scatter of approximately one order of magnitude in the correlation. However, larger deviations are evident, as in the case of the Pleiades dK stars (which are rapidly rotating, and lie much below the trend line connecting X-ray emission levels with rotation rate; Micela *et al.* 1984, 1985). Both the observed scatter and the behavior of Pleiades dK stars seem to indicate that other parameters are relevant in determining X-ray emission levels, such as for example stellar age; this indeed seems to be the case for the dK Pleiades stars (cf., Fig. 2)

6.2. Age Dependence of X-ray Emission

The dependence of X-ray emission on stellar age is effectively studied by surveying open clusters of distinct age, whose members should be in the same evolutionary stages (at least within each individual spectral type) and have similar chemical composition. X-ray surveys of the Pleiades (Micela *et al.* 1985; Caillault and Helfand 1985), of the Hyades (Stern *et al.* 1983, Micela et al 1986), of Orion (Smith *et al.* 1983, see also Caillault 1987) have been carried on. The results of these surveys show a clear decline of X-ray emission with increasing stellar age, with a possible saturation toward the age of the Pleiades (cf., Fig. 6). Recently Maggio *et al.* have surveyed the sample of the dG stars within 25 pc falling in all the *EINSTEIN* IPC fields, and have found that a similar trend is present if one considers the individual star ages (cf., Fig. 6).

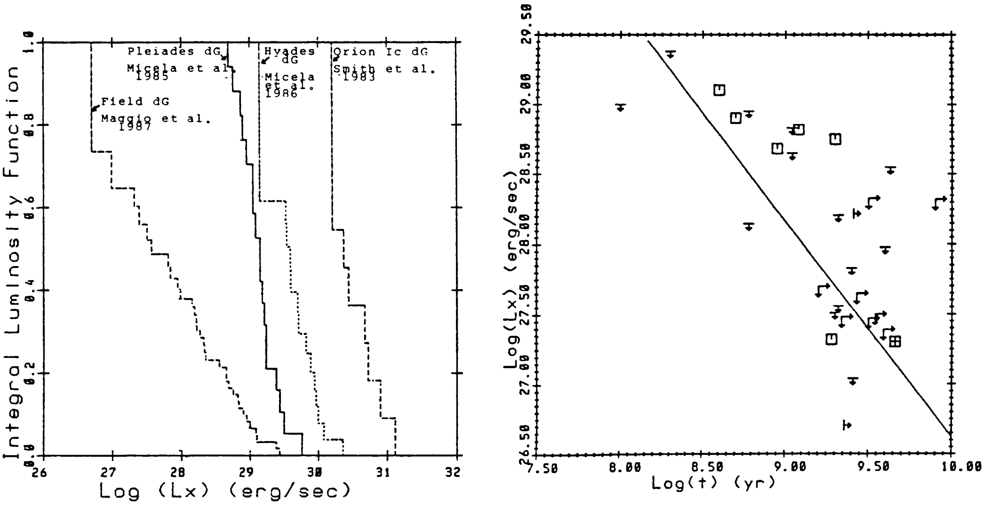

Figure 6. (right) Integral X-ray luminosity functions for four samples of stars well characterized in age: the nearby dG stars (Maggio *et al.* 1987), dG Hyades cluster members (Micela *et al.* 1986), dG Pleiades cluster member (Micela *et al.* 1985), and the slow rotating dG stars of Orion Ic (Smith, Pravdo and Ku 1983) (adapted from Micela *et al.* 1986). (left) Log-Log scatter plot of X-ray luminosity and stellar Lithium age; the straight line shows the best fit power law relation. Note the decline of X-ray luminosity with increasing stellar age (adapted from Maggio *et al.* 1987).

6.3. X-ray Emission in Low Mass Stars

There is some evidence of weakening of X-ray emission for stars later than dM5 (Bookbinder 1985). This phenomenon is easily explained in terms of a change of character of the dynamo mechanism in fully convective stars; in fact the dynamo mechanism is likely to be confined to the boundary layer between the radiative core and the convective envelope (Schmitt and Rosner 1983), where the magnetic field can be stored for the amplification mechanism to work effectively, before the buoyancy force brings the field to the stellar surface (Schussler 1983; Rosner 1983). When the star become fully convective (~ at M5, according to the current models), such a mechanism cannot work, thus explaining the weakening of X-ray emission at the low end of the main sequence.

6.4. The Onset of Convection

Since dynamo activity relies essentially on convection, we expect that X-ray emission should be a sensitive diagnostic of the switch from radiative energy transport to convective energy transport in the outer layers of main sequence stars as one progresses from hot B stars to cooler F stars. The survey of Schmitt *et al.* (1985a) confirms these expectations, and indicated that in the B-V range 0.1 to 0.5, the X-ray luminosity increases rapidly with B-V, the stars in the range 0.1 to 0.3 being weaker X-ray emitters than the stars in the B-V range 0.3 to 0.5 (cf., Fig. 7). Moreover, the X-ray emission is virtually absent (at the sensitivity level of typical *EINSTEIN* images) in stars with B-V ~ 0.0.

7. PRE-MAIN SEQUENCE STARS

During the final phase of star formation, a contracting protostar lies within an envelope of accreting gas, so as to be invisible optically. However, it has been suggested that in this phase such an object might be visible as an X-ray source. Assuming that the outer

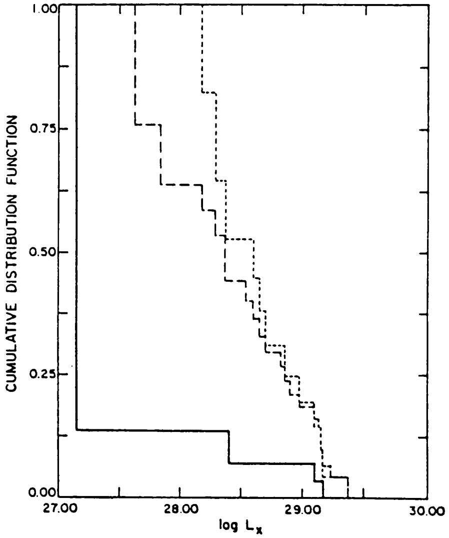

Figure 7. Integral X-ray luminosity functions for single stars in the color ranges 0.1≤B-V≤0.3 (solid line), 0.3≤B-V≤0.5 (long- dashed line), and 0.3 ≤ B-V ≤ 0.42 (short dashed line). It is evident the decline of X-ray luminosity level at lower value of B-V (adapted form Schmitt *et al.* 1985a).

atmospheres of T Tauri stars expand outward (as a stellar wind) and are thermally driven, Bisnovatyi-Kogan and Lamzin (1977) suggested the existence of a hot (10^6 K) corona near the base of the outflow region, with an expected X-ray luminosity of ~ 10^{34} erg s^{-1}. The collision between this outflow and the ambient interstellar medium would generate further X-ray emission (Schwartz 1978). In contrast, models of T Tauri star atmospheres which are dominated by accretion from the ambient interstellar matter predict X-ray emission due to the impact of the accreting matter on the stellar surface (Ulrich 1976; Mundt 1981); the temperature of the heated matter is determined essentially by the infall speed. All these predictions were disproved by the pre-*EINSTEIN* observations: only one single source detected with ANS and SAS-3 could be associated with a PMS object (den Boggende *et al.* 1978), but at an X-ray luminosity level much lower than the predictions, and with a spectrum harder than that predicted on the basis of the accretion models.

The *EINSTEIN* Observatory detected several hundred sources with typical exposure time of 10^3 s. The majority of the PMS stars have been detected in the Orion nebula (Ku and Chanan 1979; Ku *et al.* 1982), in the Taurus-Auriga complex (Gahm 1980; Feigelson and DeCampli 1981; Walter and Kuhi 1981), in the ρ Oph (Montmerle *et al.* 1983), in Chamaleon cloud (Feigelson and Kriss 1981) and in S Mon (NGC 2264) complex (Simon *et al.* 1985). The X-ray luminosity levels range from 10^{29} to 10^{31} erg s^{-1}, i.e., thousands of times more vigorous than that of the corresponding main sequence stars. Essentially all the sources are characterized by extreme variability of the emission (cf. Montmerle *et al.* 1983), and the level of X-ray emission is correlated with the stellar optical magnitude but not with other classical indicator of stellar PMS activity (such as the intensity in H_α); furthermore, the X-ray spectra of PMS stars are intrinsically harder than those of normal main sequence stars and show some cut-off at low energy due to the absorption of the matter in the star-forming region (cf. the extensive review of Feigelson 1984).

New material has been presented at this colloquium on the basis of ongoing work. For example, Caillault (1987) has analyzed 19 IPC and HRI *EINSTEIN* fields covering the central

2° x 2° of the Orion region, and reports more than 200 distinct X-ray sources, 24 of them having no known optical counterpart at $M_V > 16^{mt}$, and 69 out 200 X-ray sources showing evidence for variability. Walter (1987) (cf. also Walter 1986) has undertaken a search for X-ray sources identified with T Tauri stars in Taurus, Ophiucus, and Corona Australis, surveying ~ 45 square degrees which are very crowded with X-ray sources, and has detected a total of 206 X-ray sources, 85 of which have known optical counterparts. In this latter survey, only 15 out of the 45 T Tauri stars present in the combined field-of-view have been detected. Moreover, the optical study of 56 objects reveals that 32 are "naked" T Tauri stars, i.e., stars coeval with the T Tauri, but differing mainly in the lack of a circumstellar envelope.

The X-ray observation of PMS stars raise three major questions, namely: a) the origin of the X-ray emission, which is 10^3 times stronger than for most MS stars; b) the origin of the observed variability; and c) the time-dependent relation between X-ray emission levels and stellar parameters (such as angular momentum, structure of convective interior etc.) as star evolution proceeds.

The first question can be rephrased in terms of the capability of the solar analogy to explain the observed emission; that is, are there quasi-steady activity centers responsible for the observed emission (as happens on the sun) or is the X-ray emission instead due to a superposition of continual flaring (a possibility directly relevant to the second question as well); the present observational status does not allow us to discriminate between these two alternatives, and more high quality spectral and temporal data are needed to answer the question. The third question must also remain unresolved for the present: it requires more extensive surveys in a variety of star formation regions in order to acquire unbiased data on larger samples and in order to study the possible parameter correlations within these samples. This is a program for the future.

8. CONCLUSIONS

We can summarize the results discussed above as follows:

For late spectral type stars:

- Evidence points to activity connected to dynamo action (i.e., coupling of rotation and convection with ambient magnetic field);
- Shallow convection zone stars show a steep decline in activity;
- Fully convective stars, i.e., dwarf M later than M5, show an apparent decrease in X-ray detection;
- The level of X-ray luminosity scales as Ω^2 for all the field stars and the Hyades stars; however, this phenomenological relation cannot be reconciled with the emission levels of the Pleiades K stars.
- The level of X-ray emission depends on stellar age, younger stars being more intense emitters.

For pre-main sequence stars:

- The lack of direct correlation between T-Tauri with strong emission lines and X-ray PMS suggest a different phase for wind phenomena and X-ray phenomena;
- The luminosity range, the variability and the spectral signatures point in the direction of magnetic field-related phenomena for the X-ray phase.

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