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X-ray Emission from Stars*

By

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I. INTRODUCTION

From the point of view of stellar structure and evolution, a star's life is a fairly quiescent affair but for its birth and death. Yet during its long period of relative dormancy, the stellar surface is dominated by (often violent) activity; that, at least, is the Sun's lesson, if we are to believe in the Sun as a prototypical star. This surface activity apparently reflects a departure from the orderly process of outward thermal energy transport from the energy-producing nuclear burning core to the radiating exterior. We will discuss the processes leading to stellar surface activity, using as a focus the new EINSTEIN Observatory results on stellar X-ray emission: because of the fortunate circumstance that stars throughout the H-R diagram turn out to emit X-rays, this emission serves as a useful diagnostic for this activity.

Before commencing, we note that the problem of stellar surface activity is sufficiently broad and complex in and of itself that it is easy to overlook its roles 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), is directly responsible for mass and angular momentum loss during main sequence life (thus affecting the course of stellar evolution), and may play a significant role in despinning during the formative T Tauri phase of stellar evolution. From the galactic point of view, stellar surface activity is responsible for mass input to the interstellar medium (ISM) via stellar winds (thus affecting both the mass balance and the elemental abundances of the ISM), contributes to the galactic component of the soft X-ray background by virtue of X-ray emission from stellar coronae 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 (thus aiding 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;

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a wide range of plasma phenomena are 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 X-ray emission) has opened up new opportunities for studying these plasma processes.

II. Background

The standard observational theoretical perspective on stellar surface activity in its various forms is much discussed in the literature, most recently and extensively in the reviews of Linsky (1977), Conti (1978), Cassinelli (1979), Mewe (1979), and Ulmschneider (1979); these contain extensive relevant bibliographies. A summary of the particular theoretical problems relevant to our discussion can also be found in the review by Rosner and Vaiana (1980). I would like to first briefly summarize the various pre-EINSTEIN observational results which suggested that the canonical theory of stellar surface activity was in need of revision.

A. *Stellar X-ray Observations*

Standard coronal theory based upon acoustic wave heating predicts significant stellar X-ray emission levels in the spectral type range from early F to late G (cf. Mewe 1979). These expectations for essentially solar-like stars were to some extent confirmed by observations of X-ray emission from Capella (Catura, Acton & Johnson 1975; Mewe *et al.* 1975) and the α Cen system (Nugent and Garmire 1978); the identity of the dominant emitter in these binary systems could, however, not be resolved observationally (standard theory predicting, for example the dominance of the G dwarf in the α Cen system). In contrast, the extensive observations of X-ray emission from RS CVn stars (cf. Walter *et al.* 1980) could not be easily reconciled with available theory. These stars' inferred surface X-ray fluxes are orders of magnitude larger than the Sun's, associated with inferred plasma temperatures substantially higher than the Sun's active corona, yet their effective surface gravity is much lower than the Sun's. These stars' coronae must be confined non-gravitationally (Walter *et al.* 1980; Holt *et al.* 1979; Swank *et al.* 1979). A rather different problem arose from observations of X-ray emission from A stars (Topka *et al.* 1977, 1979; den Boggende *et al.* 1978; Cash, Snow & Charles 1979), especially the single A0 V star Vega. Standard theory cannot account for Vega's X-ray luminosity, which lies at essentially solar levels (Topka *et al.* 1979).

B. *Stellar UV Observations*

A large number of stars have been studied spectroscopically with Copernicus, BUSS and IUE, and line emission due to ionization states associated in the solar case with the transition region lying between the chromosphere and corona have been observed. Major results include:

(i) Observations of lines of O VI and N V from early-type stars have suggested that plasma at temperatures above the stellar effective temperature is present in the early-type stellar envelopes (Snow and Morton 1976; cf. review of Cassinelli 1979).

(ii) Observations of transition region lines from late-type dwarfs to giants and supergiants suggest a correlation between effective gravity and transition region extent, e.g. a transition from solar-like coronal conditions dominated by closed structures in dwarfs to a wind-dominated open atmosphere in evolved stars of similar spectral type (Linsky and Haisch 1979; Böhm-Vitenze and Dettmann 1980; Hartmann, Dupree & Raymond 1980).

(iii) Transition region line emission from late-type dwarfs appears to be relatively independent of stellar effective temperature, contrary to expectations from standard coronal theory (Hartmann *et al.* 1979).

(iv) Some evidence exists for a correlation between UV line emission levels and stellar rotation rate for late-type stars (Ayres & Linsky 1980), suggesting that convective activity levels are not the sole determinant of coronal activity.

C. *Stellar Ca II H & K Line Emission*

Ca II H and K emission, which is believed to be a good indicator of stellar surface activity (Wilson 1966), is a prominent feature of stars of spectral type ~ F5 and later. Because solar Ca II emission is strongly correlated with surface magnetic fields (Sheeley 1967), the observed stellar emission is thought to be also indicative of solar-like stellar magnetic field activity (cf. Skumanich 1972). Blanco *et al.* (1974) have shown that Ca II line emission levels, however, do not scale as expected on the basis of acoustic heating theory along the main sequence: the relatively active stars they investigated showed substantially higher emission levels than standard acoustic coronal theory predicts. Related difficulties regarding Mg II surface emission fluxes (showing an apparent absence of a dependence on stellar gravity) have been encountered by Linsky and Ayres (1978) and Basri and Linsky (1979).

D. *Solar Coronal Observations*

The recent revolution in high resolution solar observations has substantially changed our perspective on the "coronal problem". Reviews can be found in Withbroe and Noyes (1977), Vaiana and Rosner (1978), Wentzel (1978), as well as the several Skylab and OSO Workshop proceedings. The principal results relevant to our discussion are:

(i) *The solar corona is structured.* Solar X-ray emission dominantly derives from well-defined structures ("loops") whose geometric integrity is provided by coronal magnetic fields. There is no evidence for a significant contribution to the total solar coronal X-ray luminosity from volumes other than "loop" structures. Regions in which the magnetic field is "open" to the interplanetary medium ("coronal holes") show very low levels of X-ray surface flux and contribute negligibly to the integrated coronal radiative emission. Similarly, the solar mass loss is spatially extremely inhomogeneous but, in contrast to the X-ray flux, dominantly derives from regions of "open" magnetic field lines. Thus, strong winds (≡ "high speed wind streams") emanate not from regions of coronal activity (as defined by the surface X-ray flux), but rather from regions of minimal activity (coronal holes). Coronal activity and mass loss are hence *spatially anti-correlated* and, further are *temporally* anti-correlated on time scales short compared to the solar cycle period. There is as yet insufficient data to judge whether mass loss and coronal activity are temporally correlated on time scales longer than the solar cycle period.

(ii) *Coronal heating is extremely inhomogeneous.* Soft X-ray and EUV observations provide incontrovertible evidence that coronal activity levels ($\sim$ intensity of observed emission) correlate with surface magnetic fields. In addition to the morphological association, quantitative studies show that the temperature of closed coronal structures scales roughly as $(pL)^{1/3}$ [p the coronal plasma pressure and L the scale length of the magnetically confined coronal structure], and that p is positively correlated with the mean surface magnetic field $\langle B \rangle$ (Golub *et al.* 1980a). If one, in addition, recalls that thermal conduction is strongly anisotropic under coronal conditions ($\kappa_{\parallel} \gg \kappa_{\perp}$, where $\kappa_{\parallel}$ and $\kappa_{\perp}$ are the thermal conductivities along and across the local magnetic field, respectively), it is evident that local plasma heating must be extremely inhomogeneous (as reflected by the observed structuring), and further more there is a strong implication that this heating process is sensitive to the surface magnetic fields. In contrast there is little evidence for a correlation between local coronal emission levels and local surface (photospheric) turbulence levels. This view had not been universally accepted but recent OSO-8 observations, designed to test for acoustic wave propagation, have in fact placed constraints upon the acoustic flux which fall *below* levels necessary to heat the corona (*viz.* Athay and White 1979).

III. The Einstein Stellar Observations

At the present time the preliminary phase of the EINSTEIN stellar survey has been completed; the ubiquity of stellar X-ray emission has been established, and detailed analysis and extensive further observational programs are under way. In the following, we (i) briefly summarize the key results of the preliminary surveys and (ii) report an update on the most recent observations of interest to the general astronomical community. The results reported here reflect observations both from the EINSTEIN/Center for Astrophysics (CfA) Stellar Survey observing program and collaborating guest observers (Vaiana *et al.* 1981) as well as from independent observing programs of other EINSTEIN Consortium members and guest observers which have been kindly provided.

A. *Results from Preliminary EINSTEIN Stellar Surveys*

The EINSTEIN observations have given us the first opportunity to directly examine coronal emission from a large sample of "normal" stars. In consequence, it appears that there is no category of stars to be called "X-ray stars". That is, the data are consistent with the hypothesis that all stars are X-ray sources at some

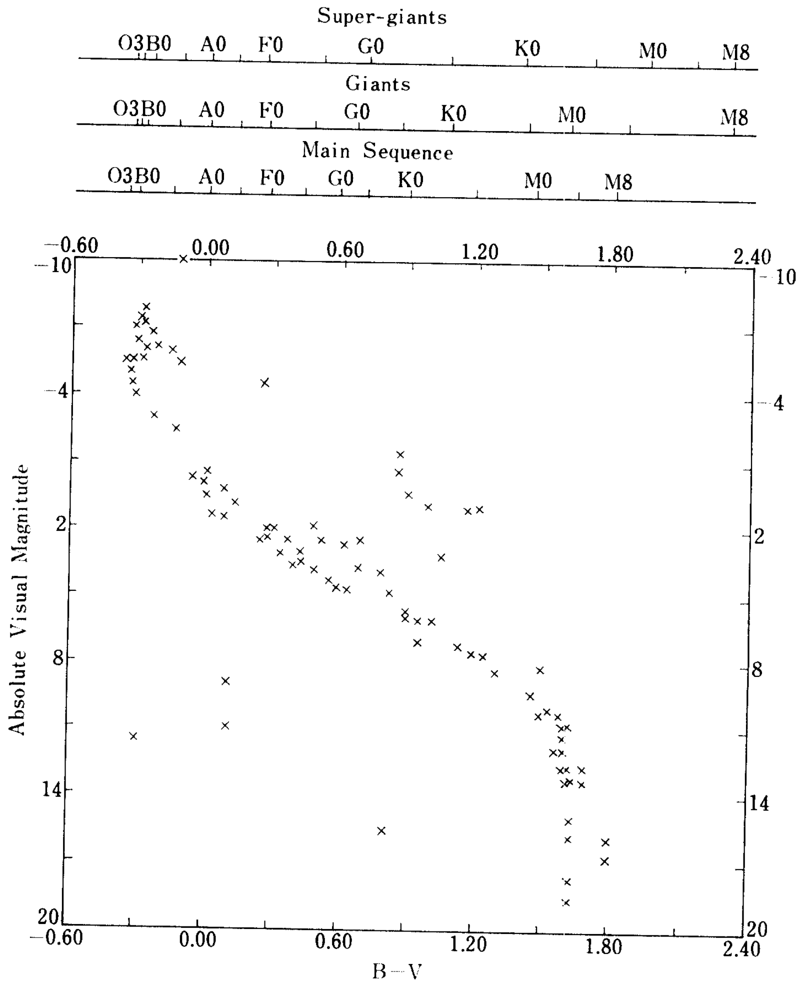


FIG. 1. H-R diagram showing the location of stars detected as soft X-ray sources by the EINSTEIN Observatory/Center for Astrophysics Stellar survey; only optically well-characterized stars are shown. We have now detected virtually all types of stars, including stars along the entire main sequence, giants, supergiants, pre-main sequence stars, and white dwarfs (from Vaiana *et al.* 1980).

level, so that the two categories "stars" and "stellar X-ray sources" may be essentially coextensive.

Most EINSTEIN stellar surveys (Consortium as well as guest observer) consist of pointed observations of pre-selected, optically well-characterized stars. The EINSTEIN/CfA Stellar Survey combines such observations with:

(1) serendipitous detection of stars in fields observed for other purposes;

(2) systematic searches for detection of (or upper limit for) X-ray emission from stars down to visual magnitude V=8.5 at medium sensitivity;

(3) identification of stellar X-ray sources in the deep survey fields observed for $\sim 10^5$ seconds. Considering the CfA observations alone, one can see from Figure 1 that X-ray emission occurs from stars virtually throughout the H-R diagram.

Typical EINSTEIN stellar observations involve exposure times of $\sim 10^3$–10^4

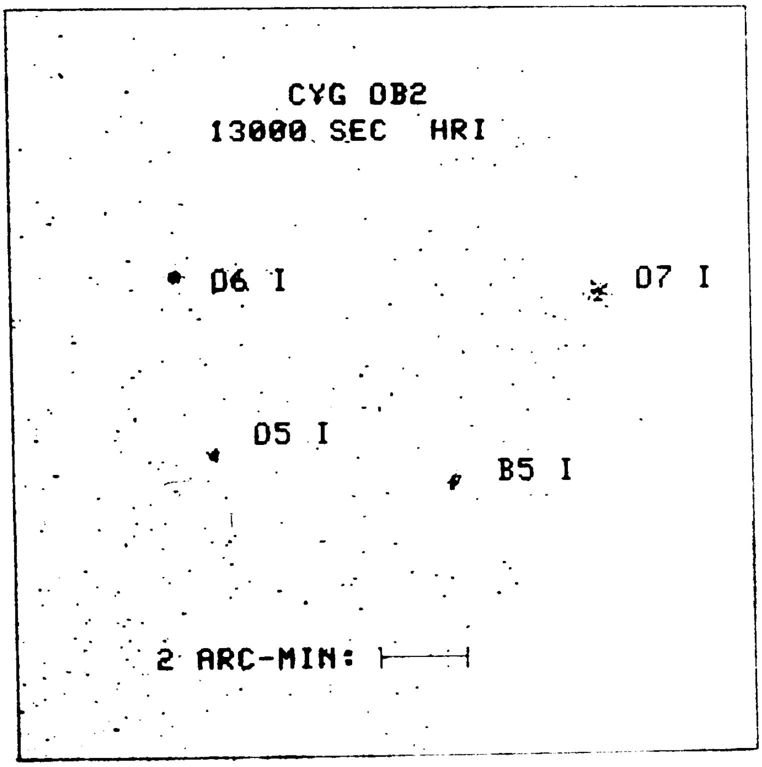


FIG. 2. One of the earliest EINSTEIN Observatory pointings was at the well-known X-ray source Cygnus X-3; one unexpected result was the discovery of X-ray emission from OB stars (Harnden *et al.* 1979), as shown in this figure. These stars, part of the Cygnus OB 2 association, are fairly strong stellar soft X-ray emitters, with luminosities ranging from above 10^{32} to above 10^{33} erg s^{-1}.

seconds, which yield a point source sensitivity of $\sim 10^{-12.5}$ to $\sim 10^{-13.0}$ erg s^{-1} cm^{-2} in the 0.2 to 3 keV passband. Some examples of our detections are shown in Figures 2–10. Among the first images returned from EINSTEIN were observations of OB star associations in Cygnus and η Carina (Fig. 2; Harnden *et al.* 1979a; Seward *et al.* 1979); these data, as well as later observations of other OB associations and single early-type stars (Cassinelli *et al.* 1979; Harnden *et al.* 1979b; Stewart *et al.* 1979; Long and White 1980), have shown that early-type stars are vigorous X-ray sources. Continuing along the main sequence, we see an image of Vega (A0 V), for which both a detection and an upper bound have been obtained (Fig. 3); an image of HR 1436 (F4 V), a single dF star (Fig. 4); an image of π^1 UMa, a classic single G dwarf (G0 V) known as an active chromosphere star (Fig. 5); an image of the α Cen system (G2 V+K5 V), showing a High Resolution Imager (HRI) picture which resolves the two binary components and shows the K dwarf to be slightly brighter (contrary to standard coronal theory; Fig. 6); an image of the supposedly relatively inactive M dwarf Proxima Centauri, which was seen to flare during the EINSTEIN observation and shows that M dwarfs have both quiescent and transient X-ray emission components (Haisch *et al.* 1980; Fig. 7); an image of the late-type supergiant Canopus (F0 I) showing that X-ray

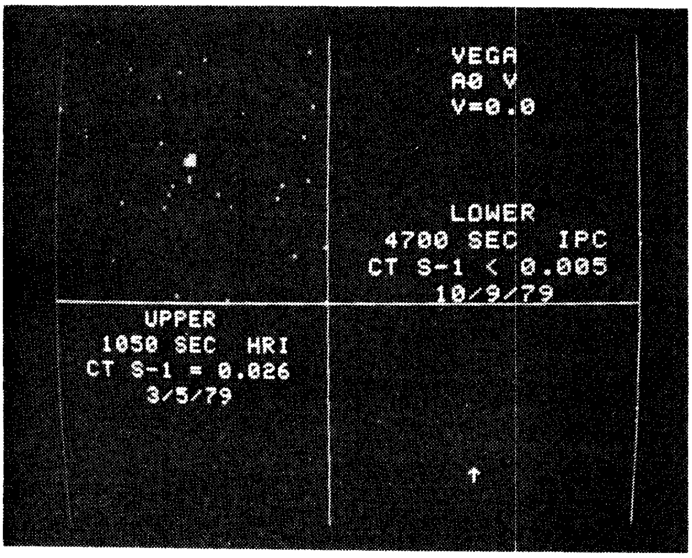


FIG. 3. Vega (A0 V) has been observed with both EINSTEIN imaging focal plane instruments. It was detected in an HRI pointing (Vaiana *et al.* 1980), but only an upper bound has been obtained from the IPC pointing; the upper bound is approximately a factor of three below the HRI detection level, strongly suggesting variability.

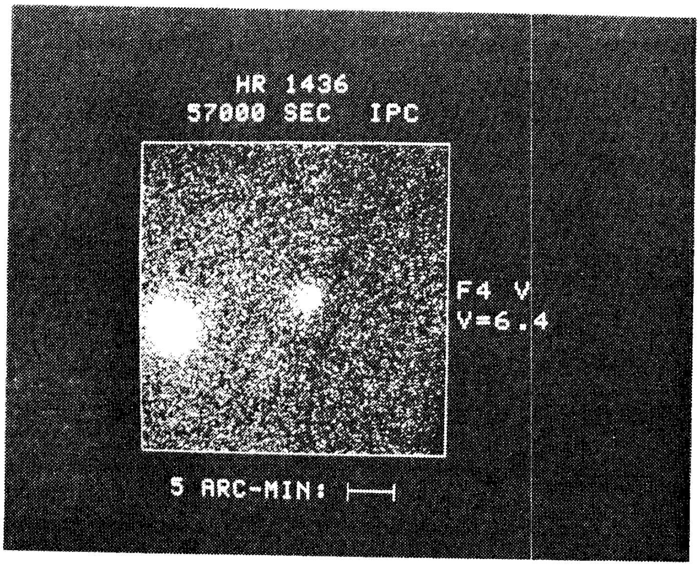


FIG. 4. HR 1436, the fainter of the two X-ray sources shown, is a fairly typical main sequence F star (F4 V), with an X-ray luminosity of $\sim 10^{29}$ erg s^{-1}.

emission from late-type stars is not confined to the main sequence (Fig. 8); an image of β Lep, a late-type giant (G5 III; Fig. 9); and finally, an HRI image of the Orion Trapezium region, showing not only the Trapezium stars in emission, but also a number of pre-main sequence stars (from CfA survey; see also the first IPC observation by Ku and Chanan 1979, and later extensive observations by

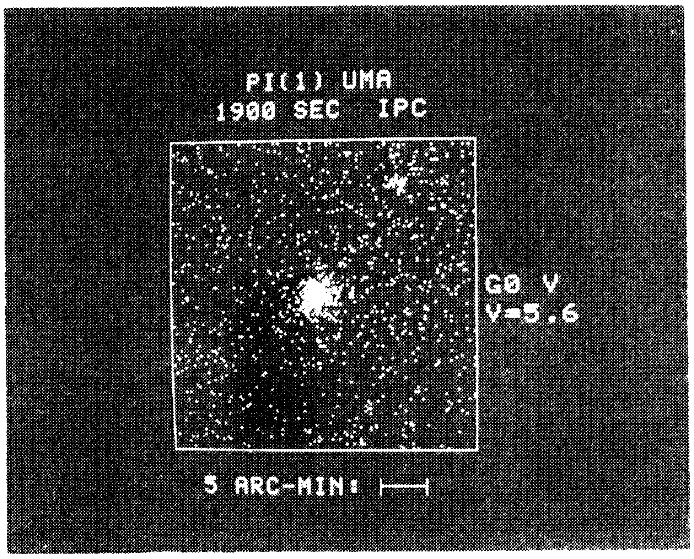


FIG. 5. π¹ UMa (G0 V) is a well-known active emission-line dwarf, presumably a relatively young main-sequence star; the EINSTEIN IPC image shows it to be a fairly strong stellar X-ray source with an X-ray luminosity of ~$10^{[illegible]}$ erg s^{-1} (Vaiana et al. 1980).

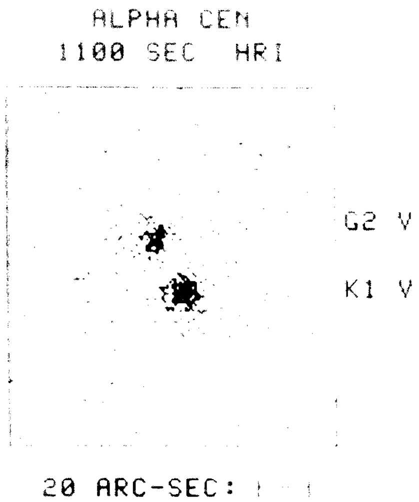


FIGURE 6

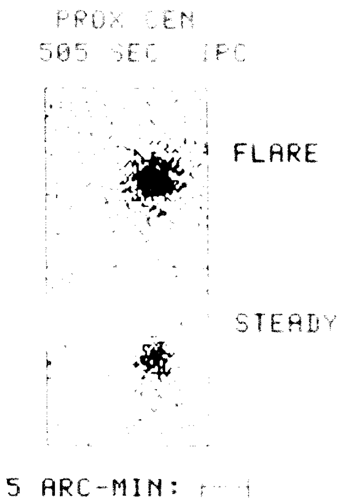


FIGURE 7

FIG. 6. The *α* Cen system, sonsisting of a G and a K dwarf, was known to be an X-ray source from the observations of Nugent & Garmire (1978). Although unresolved in the IPC image shown here, the system can be resolved by the HRI, as demonstrated in the insert. Contrary to predictions of standard acoustic coronal heating theory, it is the K dwarf (K5 V) which is the stronger X-ray source rather than the G dwarf (G2 V); because these stars are presumably coeval, evolutionary differences cannot for this result within the context of acoustic heating theory (Golub *et al.* 1980b).

FIG. 7. The nearest star, Prox Cen has been seen as both a steady and a transient X-ray source by EINSTEIN (Haisch *et al.* 1980a). The flare observed by Haisch *et al.* appears to be associated with plasma whose temperature and emission measure are similar to those of solar flares.

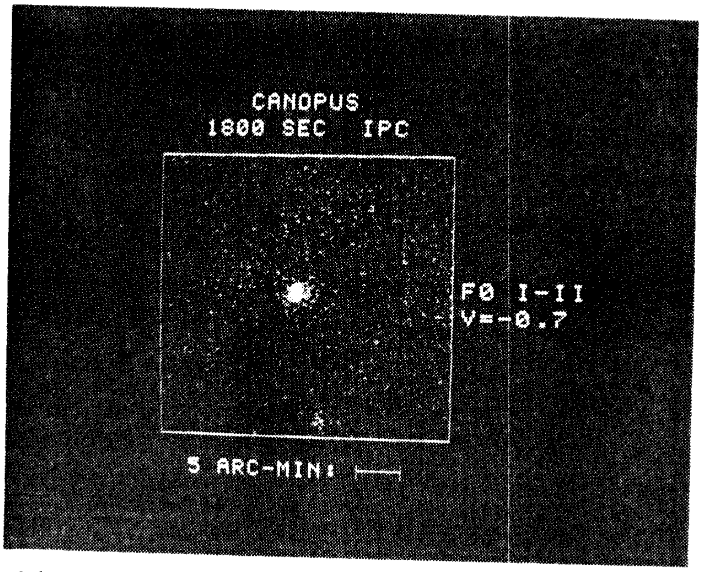


FIG. 8. The first late-type supergiant observed as an X-ray source by EINSTEIN, Canopus (F0 I) is a fairly strong stellar X-ray source ($L_x \sim 10^{30}$ erg s^{-1}): its mean surface X-ray flux is, however, quite low when compared to that of main sequence stars of similar spectral type.

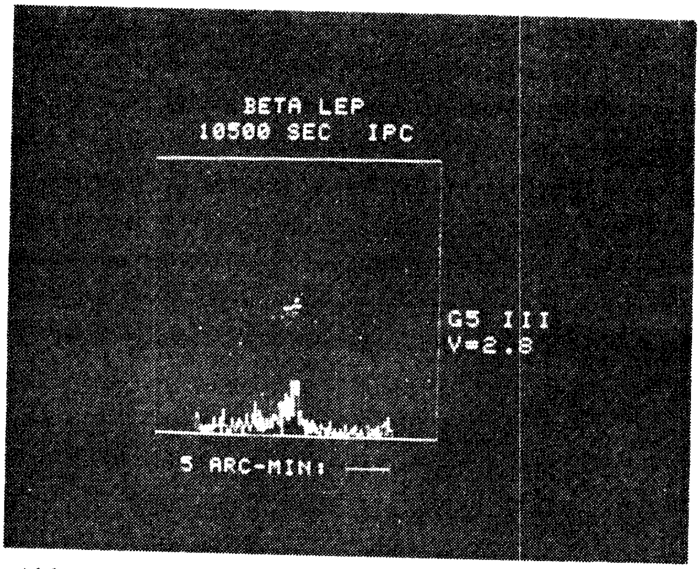


FIG. 9. Although the majority of G giants appear to be week X-ray emitters, a small fraction is found at levels of 10^{29}—10^{30} erg s^{-1}; typical of this more active class is β Lep (G5 III), which has been detected at a level of 2×10^{29} erg s^{-1}.

Chanan *et al.* 1979; Fig. 10). To summarize the principal conclusions (Vaiana *et al.* 1980):

(i) Virtually all types of stars (main-sequence, giants, supergiants, pre-main sequence) are X-ray sources; only white dwarfs have not been established as a class of X-ray sources (but the possibility that they are cannot be excluded).

(ii) Along the main sequence, the median X-ray luminosity L_x varies dramati-

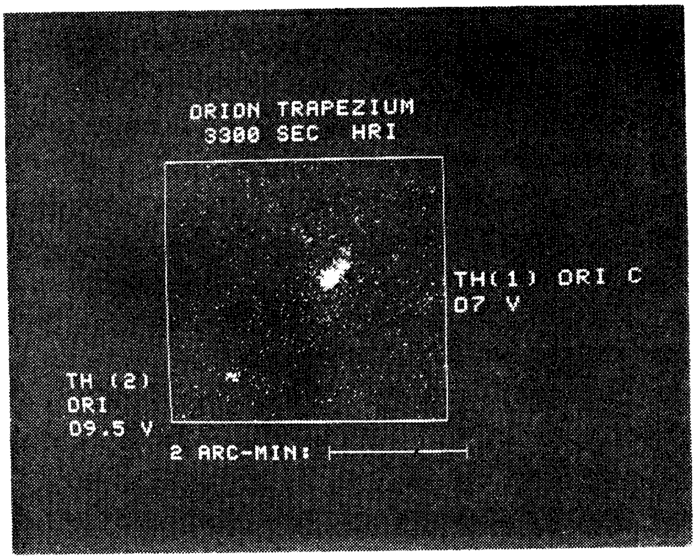


Fig. 10 An early EINSTEIN target was the Orion Trapezium, shown here in a CfA HRI image. This image also shows [illegible] additional sources, which were first discovered by Chanan & Ku (1979) in an IPC observation and were tentatively identified with pre-main sequence stars in the Orion complex; the high spatial resolution of the HRI image shown makes the identification definitive.

cally from ~ 10^{32}–10^{33} erg s^{-1} at early O to less than $10^{[illegible]}$ erg s^{-1} at late A, rises somewhat at F, and drops to ~ 10^{27}–10^{28} erg s^{-1} at G and beyond to M (Fig. 11a); for late-type dwarfs, there is a considerable scatter of ~ 10^{3} in observed luminosity.

(iii) Evolved stars show a monotonic decrease in X-ray luminosity in going from O to late spectral types, with the sole (and important) exception of the RS CVn stars, which appear to lie at the upper range of observed luminosities of main-sequence stars of comparable spectral type (Fig. 11b).

(iv) The inferred median X-ray surface fluxes f_x for main-sequence stars (Fig. 12) and evolved stars (Fig. 13) show a similarly systematic behavior with spectral type as the median X-ray luminosity. An interesting aspect of these surface fluxes is that their values correspond to the range of observed solar X-ray surface fluxes, with the sole exception of M spectral type giants and supergiants, whose present upper bounds on f_x (averaged over the stellar surface) lie several orders of magnitude below the observd X-ray surface flux of solar coronal holes (Maxson and Vaiana 1977).

B. *Update of EINSTEIN Stellar Survey Program*

More detailed analysis of EINSTEIN stellar data and follow up observations have recently provided major new results in several research areas; summarizing these (in several cases, preliminary) results briefly:

(i) *X-ray emission and stellar rotation.* We have correlated the stellar X-ray luminosity L_x with rotation rate (*i.e.*, $v \sin i$) for all EINSTEIN stars for which rotation data are available in the literature. The X-ray results used here are taken

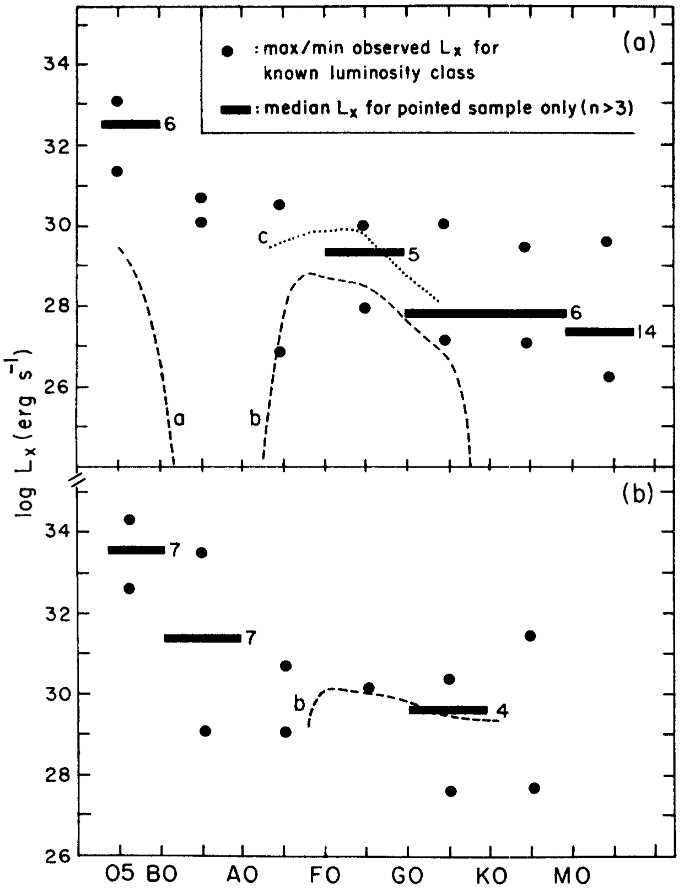


FIG. 11. Variation in X-ray luminosity L_x *vs.* spectral type for the optically well-classified sample of EINSTEIN-CfA survey and collaborating guest observer stars: (a) main sequence, (b) giants and supergiants. We indicate, by means of circles, the maximum and minimum values of L_x found in this optically classified sample (which is by no means statistically complete) and, by means of horizontal bars, the median value of L_x for the subset of Pointed-survey stars. The median has been calculated only if this subsample contains more than three stars for a given spectral type; we indicate, by a small numeral adjacent to each bar, the number of stars which entered into the median computation.
For comparison we also plot several theoretical predictions of X-ray emission levels, all based upon acoustic coronal heating (*a* and b: from Mewe 1979; c: from Landini & Monsignori-Fossi 1973; see Vaiana *et al.* 1980 for discussion of passbands). Our primary intention here is to emphasize the gross discrepancies between such theories and observation of the present (statistically incomplete) sample at early and late spectral types.

from the published data of the EINSTEIN CfA and Columbia stellar surveys and from data provided by EINSTEIN guest observers J. Cassinelli; J. Linsky, T. Ayres, and collaborators; and S. Bowyer, F. Walter, and collaborators. The principal results are shown in Figure 14 which is a scatter plot of L_x *vs.* $v \sin i$ (from Pallavicini *et al.* 1980a); Pallavicini *et al.* conclude that:

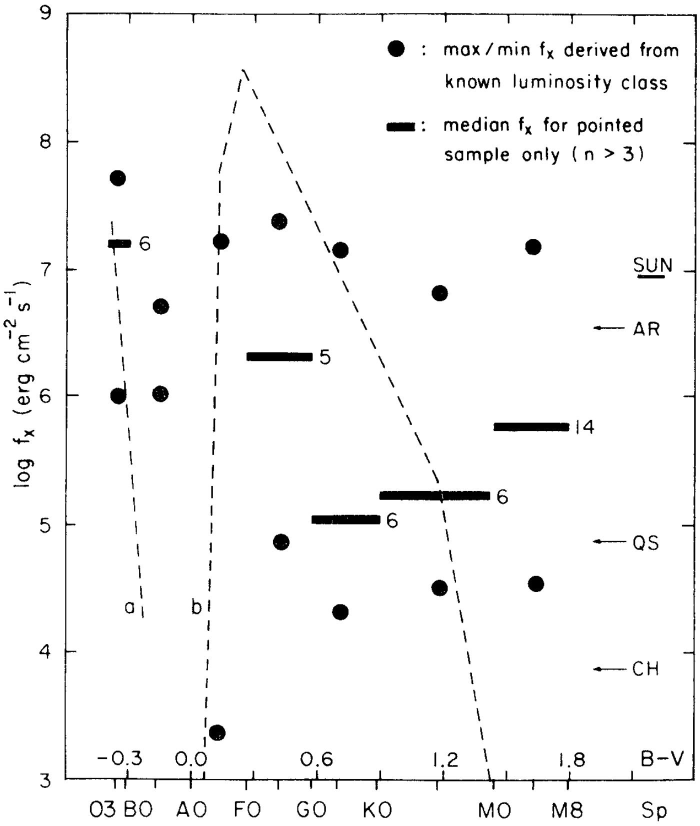


FIG. 12. Variation of derived X-ray surface flux f_x *vs*. spectral type for main-sequence stars observed by the EINSTEIN Observatory. Circles indicate the maximum and minimum observed f_x for main-sequence stars in the optically well-classified sample; bars indicate the median f_x for the Pointed sample of main-sequence stars only (calculated only if this sample contained more than three stars; this number is indicated next to each bar).

For comparison we plot the variation in total available acoustic surface flux f_a as a function of spectral type predicted by: (a) Hearn (1972, 1973) and (b) Renzini *et al.* (1977); more recent calculations by Ulmschneider and collaborators suggest flux levels at very late spectral types may have been severely underestimated by Renzini *et al.* (Ulmschneider, private communication), but such revisions do not appear to eliminate the discrepancies between theory and observations. We note that f_a places a very strict upper bound f_x if acoustic heating dominates (because such heating must also account for chromospheric, *etc.* losses, which are not shown here); as discussed by Vaiana *et al.* (1980), the vastly different qualitative variation of f_a and f_x appears to exclude acoustic heating as a viable universal coronal heating mechanism.

As a guidepost we have also indicated in the right-hand margin the typical values of soft X-ray surface flux for various solar features (AR=active region, QS=Quiet Sun, CH=coronal hole) taken from Vaiana & Rosner (1978); we note that the range of observed stellar surface fluxes corresponds fairly well to that of the inhomogeneous solar corona.

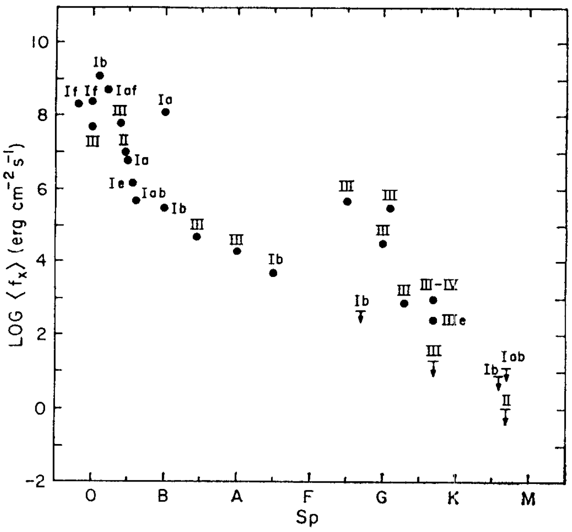


FIG. 13. Variation of derived X-ray surface flux f_x and upper bound *vs*. spectral type for giants and supergiants observed by the EINSTEIN Observatory. Surface flux has been derived by using spectroscopic parallax and theoretical stellar radius values (Allen, 1973) for each star. Note that there is a consistent pattern in going from early to late-type evolved stars. The decrease in surface flux appears to be monotonic and smooth, with no sign of sudden changes as a function of spectral type, except for the fraction of exceptional G giants (cf. Fig. 9 and text).

(a) No strong correlation between L_x and rotation rate is apparent for the ensemble of early-type stars examined;*

(b) There is a correlation between L_x and rotation rate for stars of type F8 and later, which becomes more evident if one separates stars into distinct spectral types. The correlation obeys a scaling law of form:

$$L_x \sim 10^{27} (v \sin i)^2 \quad \text{erg s}^{-1}, \tag{3.1}$$

with v in units of km s^{-1}, and applies to *all luminosity classes* with relatively little scatter.

(c) The above strong dependence of L_x upon $v \sin i$ is not evident for F stars and for the RS CVn stars; both groups show substantially weaker (if any) dependence of L_x upon $v \sin i$. However, we note that, *as a class*, both types of stars obey the general correlation between X-ray emission levels and rotation rate shown by late-type stars. We conjecture that, at least in the case of dwarf F stars, the onset of vigorous convection, and

* Examination of OB supergiant data alone shows some correlation between L_x and $v \sin i$. We believe, however, that this correlation is a selection effect, and reflects a correlation between L_{bol} and $v \sin i$ for the sample examined; the latter correlation, together with the approximate constancy of L_x/L_{bol} (see (ii) following), appears to account for the observed relative behavior of L_x and $v \sin i$.

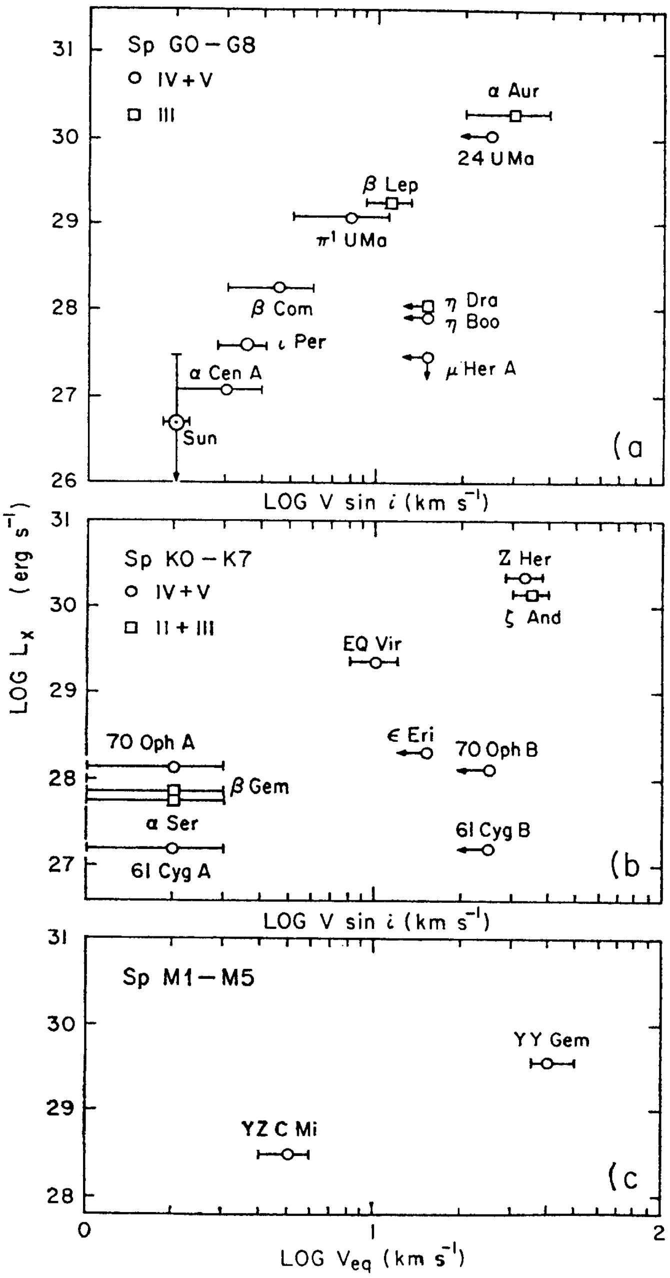


FIG. 14. X-ray luminosity *vs.* rotational velocity ($v \sin i$) for stars of various spectral types and luminosity classes detected by the EINSTEIN Observatory in rotational data are from a variety of published sources: values used in the plot are weighted averages of the available measurements, all reduced to the Slettebak-Kraft scale. Stars for which only upper limits on $v \sin i$ are known have not been plotted but have been considered in interpreting the data.

the consequent modulation of coronal heating (which is not understood!), masks the kind of rotational dependence of X-ray emission observed for the remaining late main-sequence stars.

As discussed by Rosner and Vaiana (1980; see also Linsky 1980), the strong rotational dependence of stellar X-ray emission argues against simple coronal acoustic heating theories, and for a coupling mechanism between rotation and coronal heating (as if provided by magnetic field-related coronal heating processes).

(ii) *X-ray emission and Ca II H & K line emission in late-type stars.* Early optical work suggested that Ca II H & K emission may be a good indicator of stellar chromospheric activity in late-type stars (Wilson 1966; Skumanich 1972), and demonstrated a statistical correlation between the strength of emission and stellar rotation rate and age (Skumanich 1972; Blanco *et al.* 1974). In light of the correlation between X-ray emission and stellar rotation discussed in (i) above, as well as the correlation between solar magnetic fields and Ca II activity (Sheeley 1967) and X-ray emission (Golub *et al.* 1980a), one would expect a correlation between Ca II emission strength and X-ray luminosity as well (Mewe and Zwaan 1980). We have examined this observational problem, using EINSTEIN/CfA X-ray data for stars for which Ca II K line surface fluxes calibrated in absolute units are available in the literature, with the results shown in Figure 15. For a given spectral type there is a good correlation between X-ray and Ca II K line

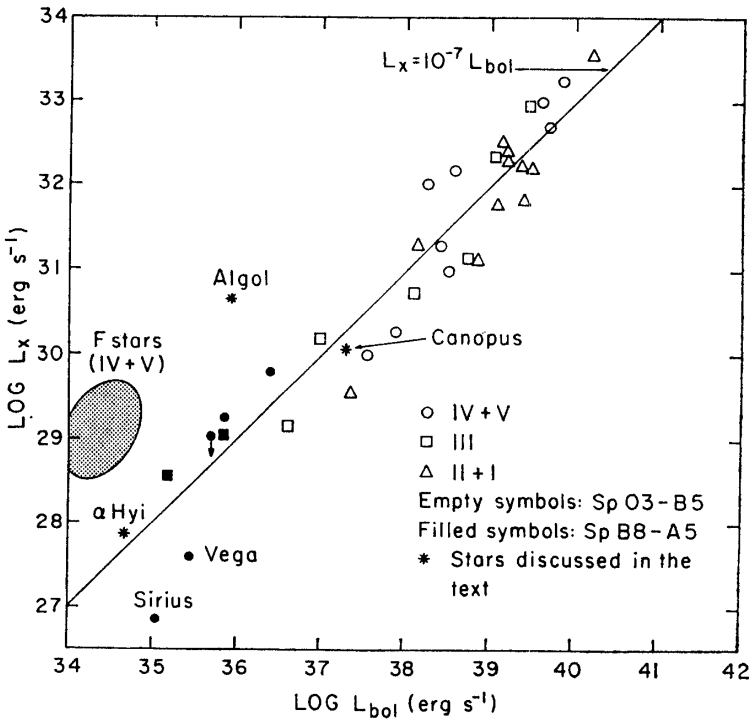


FIG. 15. X-ray luminosity *vs.* bolometric luminosity for stars of spectral type from O3 to A5, and of all luminosity classes. X-ray data are from the EINSTEIN Observatory. The straight line corresponds to the relationship $L_x = 10^{-7} L_{bol}$. Upper limits have not been plotted, but appear by and large consistent with the trend shown.

fluxes, thus confirming and extending a similar result reported by Mewe and Zwaan (1980). We are presently using these data, together with provisional plasma temperature determinations (based upon IPC data) to construct coronal models for late-type stars. Our preliminary results indicate that: (a) differences in activity level for stars of similar spectral type result primarily from differences in average coronal base pressure; (b) differences in X-ray surface flux between late-type stars of different spectral type, but comparable activity level within their respective spectral type, result primarily from differences in the fractional stellar surface covered by high pressure "loop" structures (*i.e.* the "active region" coronal component).

(iii) *X-ray emission from early-type stars.* In addition to the original serendipitous CfA observations of OB stars in Cygnus OB2 and η Car (Harnden *et al.* 1979a; Seward *et al.* 1979) and their follow-up observations (Harnden *et al.* 1979b), extensive surveys of early-type stars are being conducted by both Consortium and guest observer groups. These include CfA observations of galactic OB associations accessible to EINSTEIN, detailed studies of the Orion region by the Columbia group and collaborating guest observers (Chanan *et al.* 1979); pointed observations of nearby early-type stars by CfA, Columbia, and guest observers J. Cassinelli, T. Snow and W. Cash, and R. Thomas and collaborators; and spectroscopic studies using the Solid State Spectrometer (S^3) and the Objective Grating Spectrometer (OGS) by the Goddard and CfA groups (the latter in collaboration with the Utrecht observers). Two principal empirical results stand out:

(a) *X-ray emission and bolometric luminosity are correlated.* Using published X-ray data of the CfA stellar survey (Vaiana *et al.* 1980) and the Columbia survey of Long and White (1980), as well as X-ray data kindly provided by collaborating guest observers J. Cassinelli, T. Snow and W. Cash, and R. Thomas and collaborators, Pallavicini *et al.* 1981 find that the X-ray luminosity L_x and bolometric luminosity L_{bol} are correlated within the spectral-type range O3 to A5. The detected stars obey, to within a factor of 3, a scaling law of the form

$$L_x \sim 10^{-7} L_{bol}. \tag{3.2}$$

This result (shown in Fig. 16) appears, to first approximation, to be independent of luminosity class. However, inclusion of upper bounds on detection levels suggests a weak luminosity class effect (supergiants showing a tendency for a lower L_x/L_{bol} ratio than main-sequence stars of comparable bolometric luminosity). Scaling similar to Eq. (3.2) was found by Rosner *et al.* (1979), Harnden *et al.* (1979a, b), Long and White (1979), and Cassinelli *et al.* (1979), but on the basis of sparser data. In the present case there are sufficient data so that the observed scatter about eq. (3.2) constrains the likely level X-ray variability of individual sources (*i.e.* fluctuations in total luminosity in excess of factors of three must be relatively rare).

(b) *X-ray emission may be uncorrelated with stellar wind mass loss.* We

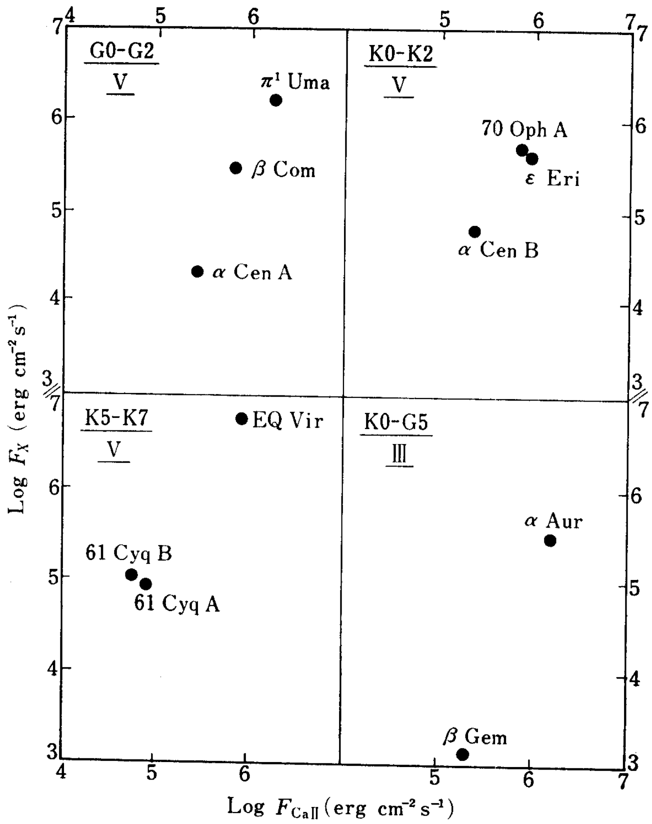


FIG. 16. X-ray surface fluxes *vs.* Ca II K line surface fluxes for main-sequence stars and giants of various spectral types. Stars of similar spectral type have been grouped together in the same panel. Ca II K line data are from Kelch *et al.* (1978), Kelch *et al.* (1979), and Linsky *et al.* (1979). X-ray data are from EINSTEIN Observatory. Although the data are as yet somewhat sparse, there is a clear tendency for the X-ray and Ca II surface fluxes to be correlatted for stars of similar spectral type (Pallavicini *et al.* 1980b).

have analyzed (Fig. 17a, b) the correlation of X-ray emission levels available stellar wind parameters for early-type stars, using the recent determinations and compilations of mass loss rate M by Lamers (1980), of terminal wind speed v_∞ by Snow and Morton (1976) and, for stars for which Lamers (1980) did not give mass loss rates, the values for M from Hutchings (1976), Barlow and Cohen (1977), and Conti and Garmany (1980). The available data show little, if any, correlation between X-ray luminosity and terminal wind speed (Fig. 17b). Because for the sample of stars considered here, mass loss rate and bolometric luminosity do appear to be correlated it may be that the lack of observed correlation between L_x and M is simply due to the statistical scatter in the data. However, consider the three stars ζ Pup (O4If), 9 Sgr (O4 V(f), and τ Sco (B0 V) (using the results of Cassinelli *et al.* 1980 and and of R. Thomas and collaborators): ζ Pub and τ Sco have virtually the

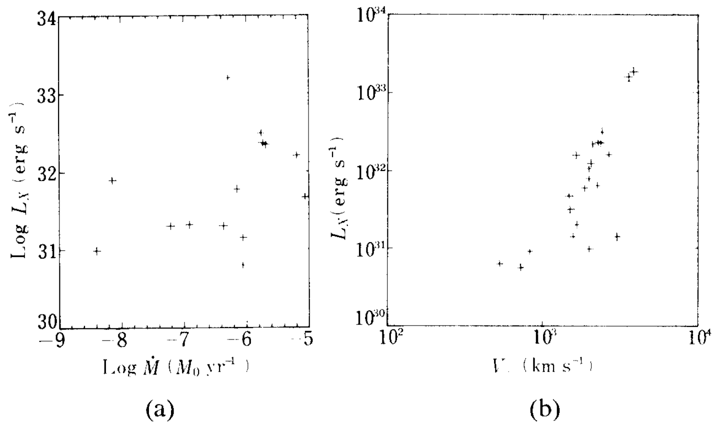


FIG. 17. (a) Scatter diagram of X-ray luminosity and stellar mass loss rate for early-type stars. The X-ray data are from published results of Harnden *et al.* (1979), Seward *et al.* (1979), Long & White (1980), Vaiana *et al.* (1980), as well as from Cassinelli *et al.* (1980) and EINSTEIN guest observations by R. Thomas and collaborators. The mass loss rates are generally from Lamers (1980). For a few stars for which X-ray data are available, Lamers (1980) dose not give mass loss rates; in these cases mass loss rates published elsewhere (see text) are used instead. The scatter diagram does not show a clear correlation between X-ray luminosity and stellar mass loss rate.
(b) Scatter diagram of X-ray luminosity and stellar wind terminal wind speed for early-type stars. The X-ray data are as given in Fig. 17a; the terminal wind speed data are from the compilation of Snow & Morton (1976). A slight correlation of X-ray luminosity and terminal wind speed is seen.

same X-ray luminosity (within a factor of two), but differ in mass loss rate by almost two orders of magnitude (Lamers 1980), and differ in bolometric luminosity by a factor of ~ 40. In contrast, ζ Pup and 9 Sgr have a very similar bolometric luminosity ($\Delta M_{bol} \sim 0.15$), spectral type, and mass loss rate (Lamers 1980), yet the X-ray luminosity of ζ Pub is a factor of ~ 25 below that of 9 Sgr. The suggestion that additional physical parameters not yet accounted for must play a significant role in fixing X-ray emission levels seems unavoidable.

(iv) *X-ray emission from pre-main sequence stars.* The recognition that pre-main sequence stars may be X-ray sources is due to the early IPC observation of the Orion nebula by Ku and Chanan (1979). Definitive identification of many of the sources in Orion with the Orion nebular variables (a class of pre-main sequence stars) followed as a result of HRI observations by Chanan *et al.* (1979) and Vaiana *et al.* (1980). Extensive observing programs for pre-main sequence objects are now being carried out by the Columbia group and a substantial number of EINSTEIN guest observers, including G. Gahm and K. Fredga, L. Kuhi and F. Walter and W. DeCampli in collaboration with E. Feigelson at MIT. In addition, guest observers studying molecular cloud regions have also serendipitously discovered pre-main sequence X-ray sources (for example, Montmerle and colla-

	BINARY	NOT BINARY
SEEN	9	2
NOT SEEN	2	10

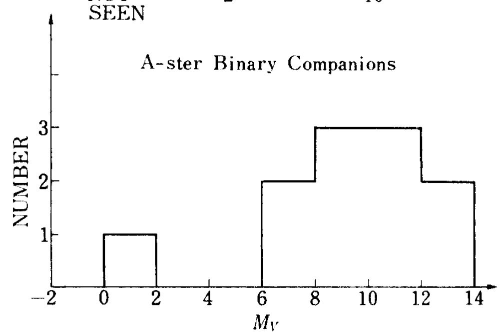


FIG. 18. Observations of A main-sequence stars with the EINSTEIN Observatory show a strong correlation between X-ray emission levels and stellar multiplicity (a); this effect holds for normal as well as peculiar (Ap and Am) A stars. If one considers the binary systems alone, the distribution of secondary absolute visual magnitude (b) strongly suggests the presence of a late-type (dK or later) companion; because EINSTEIN observations of young late-type stars show them to be strong ($L_x \gtrsim 10^{29}$ erg s^{-1}) sources, and because the late-type secondaries in these binaries are presumably relatively young, it is likely that the dominant X-ray emitter in these systems is the optically fainter late-type star. Data are from pointings of the CfA stellar surveys and from Guest Observer programs of Snow and Cash.

borators have found at least one T Tauri X-ray source in the ρ Oph cloud; Montmerle, private communication). It now appears that such stars form a new class of low-luminosity galactic X-ray sources, with X-ray luminosity levels at the upper end of the X-ray luminosity function for main-sequence stars of comparable spectral type ($L_x \gtrsim 10^{30}$ erg s^{-1}). Because these stars are rapidly evolving, it is of considerable interest to determine the evolutionary behavior of the observed X-ray emission (at least one EINSTEIN guest observer program is focussing on this particular issue; Kuhi and Walter, private communication) and to extend these observations of evolutionary behavior to young main-sequence stars [as is being done by Stern *et al.* (1980) for the Hyades, and by the Columbia group for the Pleiades].

(v) *A stars as X-ray sources.* In the preliminary report of the EINSTEIN/CfA stellar survey, we indicated that the X-ray emission behavior of main sequence A stars was somewhat unusual: the dA population generally segregated into two groups, one of which was associated with X-ray luminosities (or upper bounds) at 10^{27} erg s^{-1} or less, the other with luminosities of 10^{28} erg s^{-1} or higher. In a collaborative program with T. Snow and W. Cash, a large number of dwarf A stars have been examined with EINSTEIN. The result of the CfA and Snow and Cash observing programs is given in Figure 18: of 11 known binaries whose primary is of spectral type A, *all* have been detected; of 18 single stars (or stars for which no binary component is given in the literature), only 4 were detected. A further striking result is that the observed binaries largely have late-type, low mass secondaries and that such secondaries are known from independent CfA EINSTEIN observations to be capable of attaining intrinsic X-ray luminosities comparable to those seen from these binaries. An obvious solution to the above dA luminosity peculiarity immediately suggests itself: assume that dA stars are intrinsically weak X-ray emitters ($L_x \lesssim 10^{27}$ erg s^{-1}); for dA stars in binary systems with late-type secondaries, EINSTEIN data on late-type dwarfs suggests that the system X-ray luminosity would then be dominated by the secondary (as the median L_x for spectral types later than F0 lies above 10^{27} erg s^{-1}). In particular, we know from EINSTEIN observations that relatively young (and rapidly rotating) late-type dwarfs are strong X-ray emitters, with $L_x \gtrsim 10^{28}$ erg s^{-1}. But in the binaries under consideration, the late-type secondary is certain to be young relative to its normal evolutionary sequence, given its presence in a binary dominated by a dA primary (n.b. the contraction time of late-type dwarfs onto the main sequence can be comparable to the main sequence lifetime of dA stars). We thus obtain the following picture: single A dwarfs ought to be seen at relatively low X-ray emission levels, and A dwarf binaries with later spectral-type companions ought to be consistently seen at X-ray emission levels comparable to those of the active (and young) late-type dwarf stars. This is observed.

IV. *Conclusions: Looking Toward the Future*

The above discussions attempted to minimally mix interpretation with the observations and to allow the data to speak for themselves. To anyone even cursorily familiar with stellar atmospheres, these results ought to be quite surprising, at least in contrast with expectations based on standard stellar coronal theory. The remaining discussion will focus on the implications of these observations, not only for stellar atmospheres, but also in the larger context of astrophysical "activity".

The ubiquity of X-ray emission throughout the H-R diagram immediately raises the problem of accounting for the presence of the responsible hot plasma. Several distinct experimental and theoretical issues are involved:

(i) What is the basic process which produces hot plasma overlying the stellar surface? Is there more than one such process which is plausible?

(ii) What are the appropriate plasma diagnostics for probing the energy supply and loss mechanisms? Are these diagnostics presently available, or can they be envisaged for future instrumentation? What observational questions cannot be presently asked because of instrumental constraints?

(iii) Do the stellar observations lend any insight into plasma processes in other astrophysical systems (or vice versa)?

(iv) How do the stellar observations impact our notions of stellar structure and evolution, and the role of stellar dynamics in galactic structure?

Some of these issues have been discussed previously (cf. Rosner and Vaiana 1980, Linsky 1980, Rosner 1980); we would like to focus on three general problems with which our group at Harvard has been contending. They have been chosen not because the problems posed have been solved (they have not), but rather because they give a good indication of the scope of future research opened up by the EINSTEIN observations of stellar X-ray emission.

A. *X-ray Emission and Stellar Evolution*

The ubiquity of stellar X-ray emission raises the question whether such emission may be used as a diagnostic for processes affecting stellar evolution. Certainly this is the case for late-type main sequence stars, for which X-ray emission signals the presence of stellar coronae (which leads to stellar mass and angular momentum loss). In order to gain access to the more general problem, we have plotted the variation of stellar X-ray emission along the evolutionary track of a star in the H-R diagram, using a 1 $M_\odot$ star as an example (Fig. 19). It is evident that hot circumstellar plasma is present essentially throughout a star's life. One key question is whether the mechanism for heating this plasma is always the same, or varies with the star's evolutionary stage; a closely related question is whether these dynamical processes signalled by X-ray emission play important roles in the star's evolution in general (*i.e.*, not only on the main sequence).

Now, a good case can be made that, at least for late-type main-sequence stars, these plasma-heating processes are largely governed by stellar magnetic fields rather than by the dissipation of convective turbulence generated acoustic flux (cf. Fig. 11; Rosner and Vaiana 1980; Linsky 1980; Rosner, 1980; Vaiana *et al.* 1980). Such arguments in fact strongly reenforce the general picture developed by Biermann (1946), Schwarzschild (1948), Schatzman (1962), Kraft (1967) and later workers (see Kippenhahn 1973 for a detailed overview) that stellar magnetic fields, in conjunction with mass outflow from a corona, lead to stellar despinning

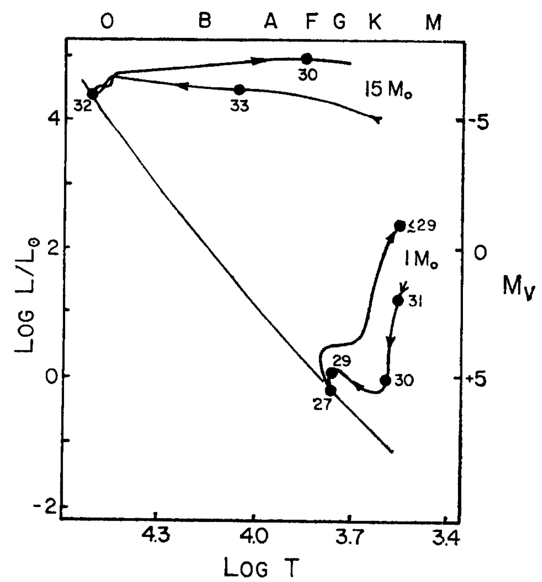
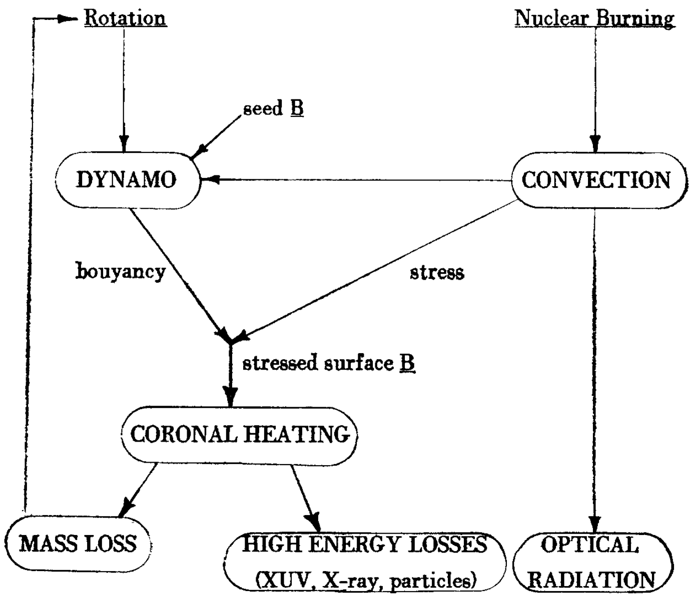


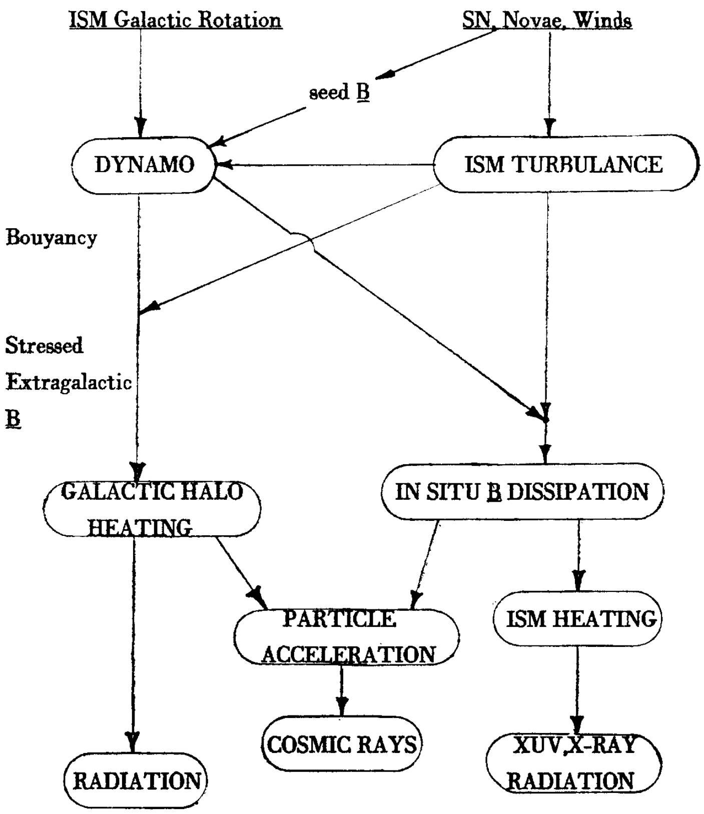
FIG. 19. We indicate schematically the likely temporal evolution of stellar X-ray emission along the evolutionary tracks of a 1 $M_\odot$ and a $\sim$15 $M_\odot$ star in the H-R diagram. The values used for the levels of X-ray emission indicated are derived from the analysis of stellar X-ray observations carried out as part of the EINSTEIN/CfA stellar survey.

STELLAR CORONAE

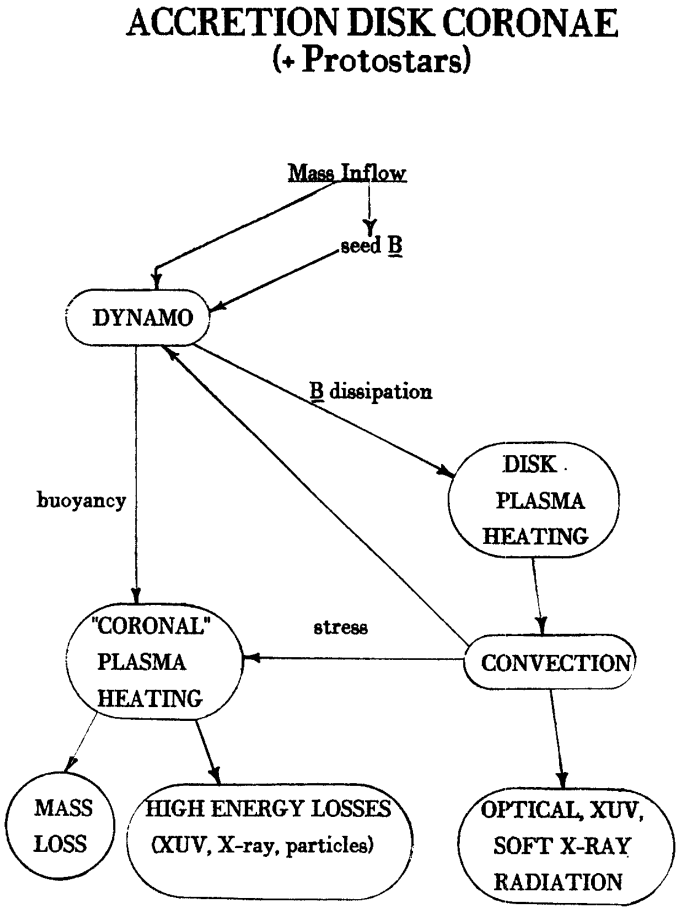


(a)

GALACTIC CORONAE



(b)



(c)

FIG. 20. The processes leading to X-ray emission from late-type stars may be related to processes underlying X-ray emission from other astrophysical systems. We suggest that the common element is the presence of magnetic fields in turbulent flow fields; the schemes shown here indicate how magnetic field-modulated plasma heating may occur in: (a) stars; (b) the interstellar medium, and (c) accreting systems.

on the main sequence. The EINSTEIN results now argue for an extension of this picture to at least pre-main sequence stars. For example, Feigelson and DeCampli (1980) have shown that the X-ray emission from T Tauri stars very likely occurs near the stellar surface and is not produced in the wind as a whole. The extremely turbulent state of the pre-main sequence stellar envelope and the likelihood of (dynamo) amplification of primordial magnetic flux in such stars then suggests stellar coronae as the responsible agent for the observed X-ray emission. Characteristic of such magnetically heated coronae is the dominance of radiative emission from magnetically confined structures (cf. Vaiana and Rosner 1978 and reference therein); in that case one would not expect any direct correlation between coronal emission and emission from out (or in) flowing matter (which occurs in geometrically distinct regions). In fact, Feigelson and DeCampli report that "the level of X-ray emission appears uncorrelated with the strength of the optical emission lines produced in the wind or envelope" of the stars in their sample.

The picture sketched here has some immediate implications. For one thing, late-type stars show a good correlation between X-ray emission levels and rotation rate (Pallavicini *et al.* 1980a). We would therefore expect pre-main sequence stars (which are rapidly rotating) to lie at the top of the stellar X-ray luminosity function for a given evolutionary track. Present data in fact support this expectation (cf. Fig. 19). Secondly, the dynamics of primordial ("seed") magnetic fields in pre-main sequence stars which eventually descend to the late-type portion of the main sequence ought not be very different from that occurring in very massive pre-main sequence stars. That is, flux trapping during contraction and field amplification by turbulent "surface" layers ought to occur in both cases regardless of stellar mass. Thus, having observed T Tauri stars as X-ray sources, one should expect tc see X-ray emission from very young early-type stars (a study of possible age dependence of X-ray emission levels is one of our objectives in the CfA OB association studies), and one would expect an anti-correlation between X-ray emission levels and stellar age along a given evolutionary track (the data are as yet insufficient to test this prediction). Interestingly enough, the above difficulty of correlating X-ray emission and wind characteristics also holds for early-type stars (see §III.B above). We believe this is a reflection of relative decoupling of flow acceleration and dominant plasma heating (because they occur in spatially well-separated volumes), as occurs in the Sun.

B. *X-ray Emission in the Larger Context of "Activity" in Astrophysics*

One of the striking recent results of X-ray astronomy is the recognition that hot ($T > 10^6$ K) plasma is pervasive, being associated with high luminosity galactic X-ray sources, interstellar medium, clusters, galaxies, galactic clusters, as well as the stars we have been discussing. Because in many instances the emission shows substantial evidence for structuring within the emitting region, some of which is presumably due to the effects of ambient magnetic fields, it seems reasonable to ask whether there is some commonality in the processes that lead to the presence and maintenance of the hot plasma under such a wide variety of conditions. One the formation and maintenance of hot, low-β plasma in the proximity of rotating possibility which we have been actively pursuing is based on a general model for self-gravitating systems; the essential elements of the model are (Rosner and Vaiana 1980):

(i) The observed correlation between the presence of hot plasma and magnetic field is attributed to a cause-and-effect relation, *viz.* the magnetic fields are held to be the agent for directly heating the tenuous hot plasma.

(ii) Dissipating magnetic fields require a production mechanism (*i.e.* one must account for the continual presence and regeneration of magnetic fields). Such field generation (a "dynamo") can operate only in a $\beta \sim 0(1)$ environment. We identify this generator with the rotating self-gravitating system (the "high-β plasmoid").

(iii) Both the process leading to field regeneration and amplification within the high-β plasmoid, and the process leading to field stressing (and eventual heating) in the proximate low-β plasma, require sources of free energy. In the model proposed here, the overall sequence of processes (from dynamo action to eventual "coronal" heating) is regarded as an alternative channel by which the high-β plasmoid can transport energy from its interior outwards. More specifically:

(a) In stars, magnetic fields in the outer convection zone divert some fraction of the outward energy flux (produced by nuclear burning and carried by thermal convection). Instead of being liberated at the stellar photosphere, some (possibly substantial) fraction of the total stellar luminosity is therefore radiated by a magnetically heated tenuous extended atmosphere (Rosner and Vaiana 1980).

(b) In accretion disks about massive compact objects, magnetic fields within the disk tap a large fraction (possibly all) of the gravitational energy liberated by inward-falling matter. In this case, fields act as the thermalizer of the available free energy by either directly heating the disk interior (cf. Lightman, Shapiro & Rees 1978 and references therein) or indirectly heating the disk by generating an extremely hot surrounding "disk corona" (Galeev, Rosner and Vaiana 1979).

(c) In rotating clusters or galaxies, magnetic fields tap both the rotational energy of the gaseous component, as well as the turbulent energy resident in the large-scale random motions of the interstellar medium. In this case, the field does not only thermalize the available free energy in large-scale motions, but also injects significant amounts of energy into suprathermal particles (because at the low densities typical of the interstellar medium, microscopic plasma heating processes such as tearing tend to produce large numbers of runaway particles).

This general model is schematically depicted in Figure 20. Part of our interest in stellar X-ray emission arises from the fact stars and their coronae may serve as a laboratory for exploring such magnetic-field dominated activity.

C. *Toward Future Observations*

Although it now seems evident that the study of stellar X-ray emission is, and will long continue to be, extremely fruitful, it is not obvious that the proper observational material will in fact be available. At the termination of the EINSTEIN Observatory flight, we expect that somewhat in excess of $\sim 10^3$ stars will have been surveyed. For the vast majority of these stars, we will have available flux measurements and very low-resolution ($E/\Delta E \sim 1$) spectra of variable quality (strongly dependent upon source strength). Medium-resolution ($E/\Delta E \sim 50$–100) spectra will be available for an extremely small number of stars (very likely substantially less than 50). Thus the EINSTEIN data will answer questions of existence and activity level of emission, but will not enable much progress in detailed model building of stellar coronae.

What is lacking is self-evident: at minimum, high-sensitivity, medium to high resolution ($E/\Delta E \sim 50$–200) spectral data for stars throughout the H-R diagram so that simple multi-temperature coronal (or other) models can be constructed; at best, extremely high-sensitivity, high-resolution ($E/\Delta E \gtrsim 500$) spectral data for large numbers of stars, so that both differential emission measure analyses and Doppler measurements (of line shifts or broadening, depending upon resolution) can be carried out. The latter data will eventually be obtained from AXAF, which in all probability will have the requisite instrumental capability. In the interim, there are no firm plans for a mission capable of carrying out even the relatively modest spectroscopic stellar X-ray observations. Some suggestions have, however, been brought forth, principally by our group at Harvard. These include an imaging X-ray telescope capable of dispersive spectroscopy using an objective greating spectrometer (which we have dubbed STCOEX = Stellar Coronal X-ray Explorer). In view of the exciting prospects facing future stellar X-ray astronomy, we can only hope that these plans (or ones like them) can be realized.

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