STELLAR CORONAE

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INTRODUCTION

The standard theory of stellar coronae requires the presence of vigorous surface convection. In consequence, the expectation of such a theory is that stellar x-ray emission -- if due to a corona -- should be limited to a subset of stars (principally those of main sequence spectral types F and G), and therefore should be relatively rare. This theory also makes detailed predictions about coronal heating, which are subject to test if spatially resolved coronal data are available. We are now in a position to subject the standard coronal scenarios to observational scrutiny on both counts: Skylab and later observations have supplied us with spatially resolved data of the solar corona, while the succession of high-energy x-ray astronomy satellites, culminating with EINSTEIN, now gives us a long-awaited glimpse of stellar x-ray emission throughout the H-R diagram.

I will maintain that these new data imply that coronal x-ray emission dominantly derives from plasma structure confined by stellar surface magnetic fields;that coronal heating is likely to be non-acoustic in character and involves the confining magnetic fields; that stellar x-ray emission is not well correlated with the level of surface convection activity. These results of course cast serious doubt upon the viability of the standard theory of stellar coronal formation. In the following, I will try to very briefly summarize the solar and stellar data, to present the context in which they were initially obtained, and very briefly sketch the new coronal picture we are pursuing. The results presented here are excerpted from lectures presented by R. Rosner and myself recently at Erice, Italy (viz. Vaiana 1979) and from the preliminary results of the EINSTEIN Stellar Survey (Vaiana et al. 1979). The latter, part of a larger effort in x-ray astronomy led by R. Giacconi, involves the work of many people, including F.R. Harnden, L. Golub, P. Gorenstein, R. Rosner, F. Seward, K. Topka at CFA, as well as a number of EINSTEIN guest investigators.

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"CANONICAL" THEORY OF STELLAR CORONAE

The conventional theory of stellar coronal formation pioneered by Biermann (1946) and Schwarzschild (1948) is inextricably tied to the presence and vigor of stellar outer convection zones, and plays a major role in present notions of stellar mass and angular momentum loss. Following Schatzman's (1962) seminal paper on this subject, the following "standard" scenario has been developed by a large number of workers (including Wilson 1966, Kraft 1967, and Skumanich 1972) for single stars:

a. During pre-main sequence evolution, stars lose the bulk of their angular momentum (possibly including during the Hayashi phase).

b. Further despinning on the main sequence depends upon the presence of an outer convection zone. If the latter is present then:

(i) An extended, hot outer atmosphere and associated stellar wind is generated via the heating of surface layers by shocked acoustic modes generated by convective turbulence;

(ii) A convectively driven (Babcock/Parker) magnetic dynamo is operative, leading to surface magnetic fields;

(iii) Plasma flows from the hot coronal atmosphere interact with the surface magnetic fields. Corotation enforced by the coronal magnetic field takes place up to the Alfven radius R_A [defined by $v_{alfven}(R_A) = U$, where U is the coronal wind speed]; beyond $R = R_A$, the coronal plasma effectively decouples from the stellar atmosphere. The effective "lever arm" for angular momentum loss is hence R_A, rather than the stellar radius R_*; because $R_A >> R_*$ (at least in the Sun's case), the combined effect of stellar wind and surface magnetic fields leads to far more rapid despinning than would occur in the absence of surface magnetic fields [e.g. $J = (R_A/R_*)^2 J(B = 0)$].

A crucial aspect of this scenario is that coronal formation (with its associated x-ray emission) and surface magnetic fields are only accidentally related -- via their common origin in turbulent surface convection -- but are both necessary elements in understanding stellar spindown on the main sequence. Thus, calculations of stellar interiors suggest the appearance of significant outer convection zones for stars later than ∿F0-5. In consequence, calculations of atmospheric heating by acoustic waves (based upon the Lighthill theory of sound generation in turbulent flows) lead to predictions of the acoustic flux intensity shown in Figure 1 (from Mewe 1979), with a peak in mechanical flux at around F0-F5. Independently, MHD dynamo theory leads to the expectation that magnetic dynamo activity also occurs at the onset of convection. These theories thus predict significant x-ray emission and despinning for F and later stars. On a substantially more qualitative level, dynamo models relate the level of magnetic activity to the star's rotation; the further expectation is hence that magnetic activity (as indicated, for example, by Ca II emission) decreases as a given star despins.

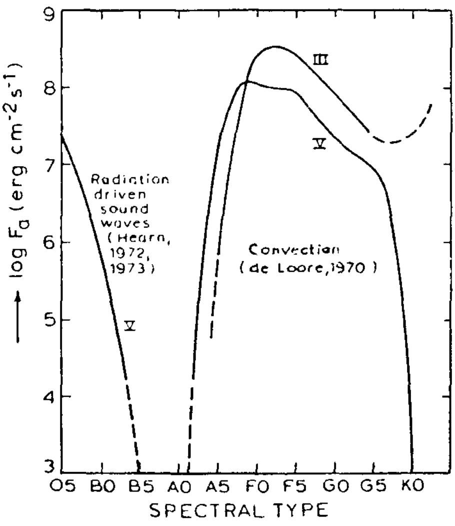

Fig. 1. Available surface acoustic flux f_a (erg cm^{-2} s^{-1}) as a function of spectral type for main sequence stars and giants (from Mewe 1979).

To summarize, the principal predictions of the "standard" scenario of direct interest to the observations to be discussed are:

(a) The level of coronal emission should follow the level of acoustic flux generation (Fig. 1) and hence be independent of the stellar rotation rate for a given level of convective "vigor". In particular, coronal emission should be relatively negligible for stars earlier than ∿ A2 and later than ∿ K0, peak at around F2-F5, and be relatively constant with age as long as the star remains on the main sequence.

(b) Mass loss (via wind) varies with coronal activity level.

Finally, a brief caveat: Before the advent of EINSTEIN observations, considerable controversy surrounded the question whether very early-type (OB) stars should have coronae (possibly due to shock heating via radiatively-driven sound waves, Hearn 1975). Although we now know the answer (they very likely do; Harnden *et al.* 1979), and although the underlying physics is still unclear, what is clear is that classical acoustic heating is entirely inadequate, and that radiatively driven acoustic heating might require unreasonable high efficiency to account for the x-ray coronal emission.

WHAT THE SUN HAS TO TELL US

Reviews of the observational and theoretical impact of recent solar coronal observations can be found in Withbroe and Noyes 1977, Vaiana and Rosner 1978, and Wentzel 1978 as well as in the reviews in the present context, the results of significance are:

1. Is mass loss related to coronal activity level? The solar wind is extremely inhomogeneous. Strong winds (≡ "high speed wind streams") emanate not from regions of activity, but rather from regions of lowest activity ("coronal holes"). This anticorrelation extends into the temporal domain as well: e.g., high equatorial mass loss rates are not in phase with activity level. Thus, there is no present observational basis for assuming high mass loss rates to be associated with high stellar coronal activity levels.

2. Is coronal heating due to dissipation of acoustic modes? Coronal activity levels correlate with surface magnetic fields, i.e. one finds that coronal structures (apparently confined by surface magnetic fields) follow rough scaling laws having the form (viz. Rosner, Tucker and Vaiana, 1978; Golub et al. 1979)

$$p \sim \langle B \rangle^{3/2}; \qquad T \sim 10^3 \, (pL)^{1/3}$$

where p is the coronal plasma pressure, $\langle B \rangle$ the mean local surface field strength, T the coronal temperature, and L the scale length of the magnetic coronal structures. The observations therefore suggest that the heating process leading to hot magnetically confined coronal plasma is related to the surface magnetic fields. Finally, theoretical analysis shows that:

(i) Acoustic modes may have difficulty reproducing many of the basic observational characteristics: total coronal intensity, spatial inhomogeneity, evolutionary behavior of activity centers;

(ii) Several models of magnetic field-related heating mechanisms have been proposed to provide natural explanations for the observed behavior [including dissipation of coronal fields via current-driven instabilities (Tucker 1973, Rosner et al. 1978) and damping of magnetic surface waves (Ionson, 1978), Alfven modes (Hollweg 1979), and magneto-acoustic modes (Habbal et al. 1979)]. Present data are insufficient to distinguish between these mechanisms as yet. In all cases the basic idea is to relate coronal heating to the stressing of coronal magnetic fields by surface turbulence and to retrieve the scaling laws obeyed by observed coronal structures (Galeev et al. 1979), as well as the correlation between structure pressure and local mean photospheric magnetic field (Golub et al. 1979). In this view, coronal formation requires stellar surface fields as well as surface turbulence, with magnetic fields providing both the means of plasma confinement and plasma heating. The coexistence of coronae and surface magnetic fields required for stellar despinning on the main sequence is, according to this hypothesis, no longer accidental, but is instead intrinsic.

STELLAR CORONAL OBSERVATIONS FROM EINSTEIN

Before the advent of the EINSTEIN Observatory, data were already at hand suggesting that the problematics of standard solar coronal theory extended to the more general stellar domain (see reviews by Gorenstein & Tucker 1976, Linsky 1977, Vaiana & Rosner 1978, and Mewe 1979). Focussing upon x-rays, these puzzling results were, briefly:

(a) Certain classes of stars had been found to be very strong emitters, too strong to be accounted for by standard coronal theory, as for example, RS CVn stars. The latter have surface x-ray fluxes orders of magnitudes larger than the Sun's associated with plasma whose temperature is substantially higher than the Sun's corona, yet have effective surface gravities much lower than the Sun's; clearly, these coronae must be confined. For more details on these stars, see review by Walter et al. 1979.

(b) At least one single A0 V star (Vega) had been found to have a corona (Topka et al. 1979); standard theory fails to account for this.

(c) A number of stars throughout the H-R diagram had been looked at with Copernicus and IUE, and UV line emission due to ionization states associated in the solar case with the transition region between the chromosphere and corona had been observed. Particularly striking have been observations of O VI and other transition region line emission from early-type stars (cf. Snow and Morton 1976), suggesting that these stars also may possess coronae; the possible correlation between UV emission and stellar rotation rate for late-type stars reported by Ayres, Linsky and coworkers, suggesting that convective activity levels alone are not the sole determinant of coronal activity; and indications from the UV that the transition region structures of late-type dwarfs are relatively independent of the stellar effective temperature (Hartmann et al. 1979).

These tantalizing hints have received dramatic confirmation in the EINSTEIN stellar data, which have also raised a number of additional new observational challenges to theories of coronal formation. In the following, our principal conclusions, presented in more detail in the reports of the preliminary EINSTEIN Survey results (cf. Vaiana 1979, and Vaiana et al. 1979) are summarized.

The EINSTEIN/CFA stellar survey combines results from: (1) pointed observations aimed at optically well-characterized stars; (2) serendipitous detection of stars in fields observed for other purposes; (3) systematic search for detection of (or upper limit for) x-ray emission from stars down to visual magnitude V = 8.5 at some medium sensitivity; (4) identification of stellar x-ray sources in the deep survey fields observed for some 10^5 seconds. *This survey has now demonstrated that x-ray emission is associated with stars throughout the H-R diagram* (Fig. 2).

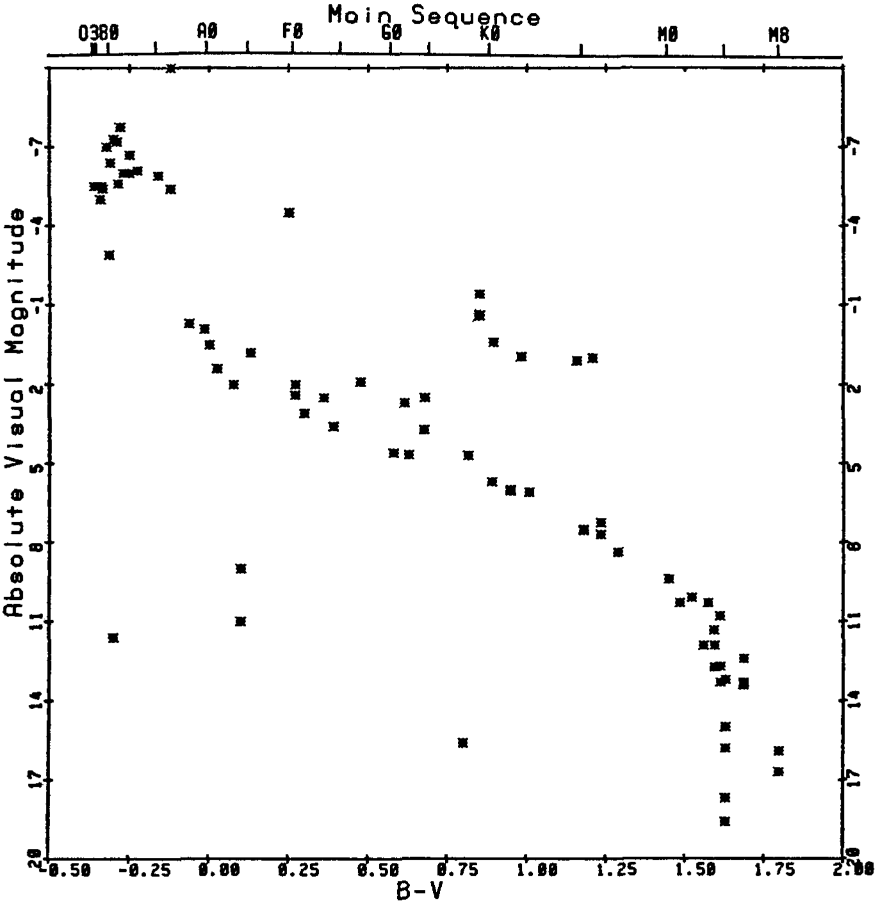

Fig. 2. H-R diagram of stars which have been detected as x-ray sources by EINSTEIN (Pointed Survey only)

Our typical sensitivity for most fields in the 0.2 to 3 keV passband ranges from 10^{-13} to 10^{-12} erg s^{-1} cm^{-2}. This means that we can probe for 10^{28} erg s^{-1} coronae to some 100 pc, and down to 10^{26} erg s^{-1} coronae for the closest objects. For most of our sources, the count rate in the IPC instrument goes from a few times 10^{-3} to 1 ct s^{-1} for the closest and the brightest objects (such as Sirius B).

Piecing together the statistical information contained in a sample of 60 IPC fields (for serendipitous stars to a limiting V of 8.5) and in the deep survey with the results obtained in the sample of specifically pointed observations allows us to reach the following preliminary conclusions:

(i) Early O stars have an associated x-ray emission level of $L_X \sim 10^{34-33}$ erg s^{-1}, essentially for all luminosity classes.

(ii) For the main sequence, in going from O to A, the ratio L_X/L_V drops from 10^{-4} to 10^{-6}, and a similar trend exists for all other luminosity classes. Continuing to later-type stars, virtually all of the main sequence F stars have a large $L_X/L_V \sim 10^{-4.5}$ ($L_X \sim 10^{29}$ erg s^{-1}), with a rapid onset at late A and a sharp drop again at early G. This drop brings the emission of the main sequence stars to solar coronal values of 10^{26-27} erg s^{-1}, with typical $L_X/L_V \sim 10^{-5.5}$ at $\sim$ G1, with evidence for a significant spread in L_X/L_V. The most striking result is the sustained increase in L_X/L_V for main sequence stars later than G0, through K and M stars. For example, we have observed coronal emission from CN Leo, a late DMe, at 10^{27} erg s^{-1}, comparable to that of our own Sun and containing $\sim$10% of the energy being emitted by the star in the V passband. This is consistent with other dMe stars observed by several EINSTEIN guest investigators, including Haisch and Linsky, and R.H. Johnson.

(iii) The giants and supergiants experience a monotonic decrease in L_X/L_V from O to M, with $L_X/L_V \lesssim 10^{-6}$ reached for late G giants. However, some as yet not well-determined fraction [$\sim$ (10%)] of early G giants are relatively strong emitters, with $L_X/L_V \sim 10^{-4.5}$.

The preliminary results for main sequence stars (which are based upon upper limits as well as detections) are partially illustrated in Fig. 3, where we plot L_X/L_V vs. spectral type for main sequence stars. The conflict between these results and predictions of conventional theories of coronal formation is particularly striking if one compares the available (theoretically-derived) surface flux of acoustic waves for main-sequence stars with the mean stellar x-ray surface flux derived from our observations (Fig. 4). The key difficulties seem to be the large x-ray surface fluxes for: 1) main-sequence spectral types later than K0 and 2) early-type stars of all luminosity classes. In the first case, coronal emission levels exceed the levels attainable by acoustic heating by many orders of magnitude; in the latter case the efficiency of thermalizing hypothetical acoustic modes must be of the order of unity. *The suggestion is therefore very strong that coronal heating cannot be due to damping of acoustic modes, at least not as commonly envisaged. What then is heating the coronae we are observing?*

Our suggestion, presented in detail elsewhere (Rosner 1979 and Vaiana 1979), is that *stellar magnetic fields play the key role in determining the level of coronal emission, and that the modulation of the surface magnetic flux level (by variation of the interior structure of the stellar convection zone and by stellar rotation) and the level of stressing of surface magnetic fields (by surface turbulence) essentially determine the variation of mean coronal activity in the H-R diagram;* this scenario is schematized in Fig. 5. The elements in this scenario are thus the assumption that the Sun is indeed representative (not on the quantitative, but rather on the qualitative level) and the theoretical assumption that magnetic fields provide the means of channeling free energy resident in the stellar surface layers to the extended atmosphere, and thermalizing the energy there locally so as to produce a corona.

The unique consequences of this coronal formation scenario are thus:

(a) that surface magnetic fields are prerequisites for significant coronal formation;

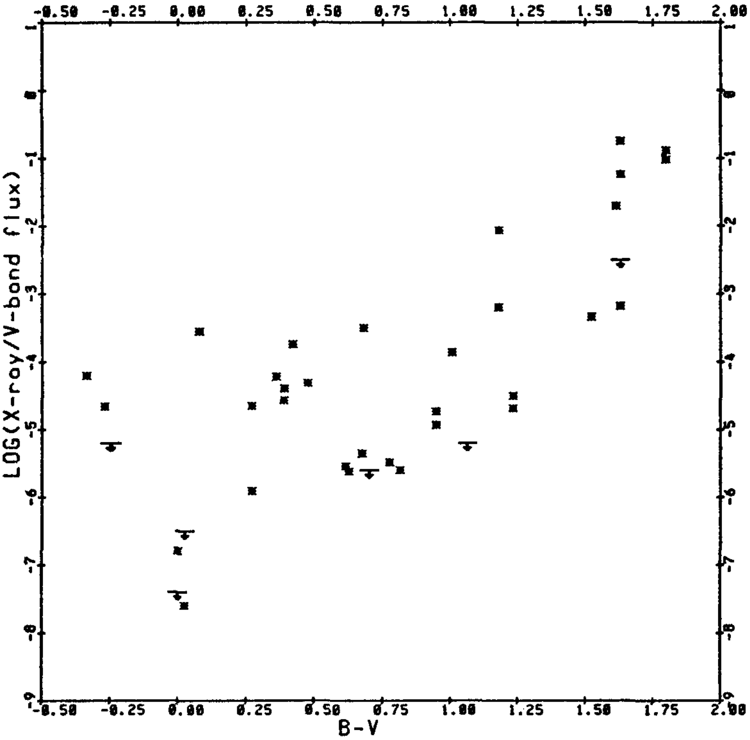

Fig. 3. L_x/L_v vs. spectral type for main-sequence stars observed by EINSTEIN.

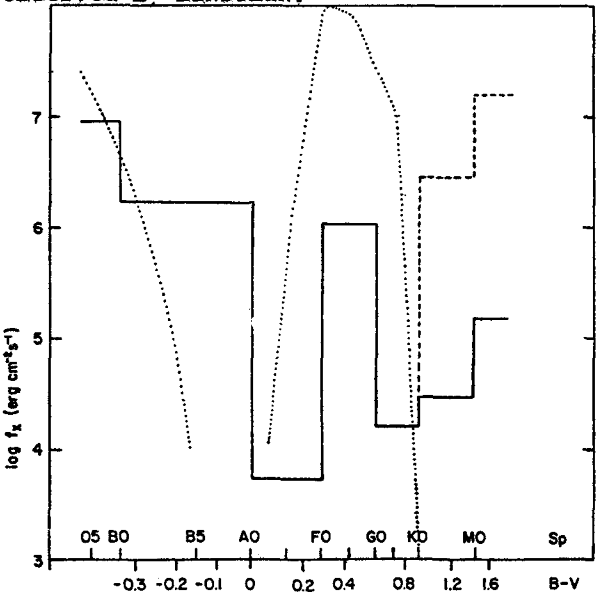

Fig. 4. Surface x-ray flux (solid & dashed) and available surface acoustic flux (dotted) vs. spectral type along main sequence.

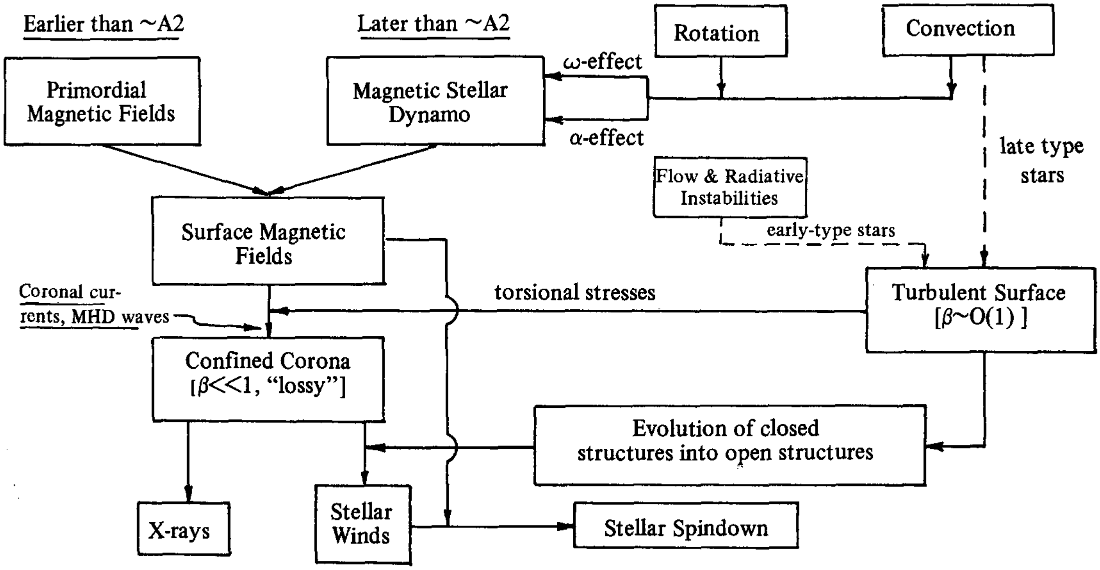

Fig. 5. Schematic formation process of stellar coronae.

(b) that coronal activity levels are not simply related to the vigor of surface turbulence, but rather necessarily involve additional stellar parameters, including the stellar rotation rate;

(c) that coronal structure -- open or closed -- reflects the star's magnetic topology; the magnetic field is thus an important determinant of the nature of coronal energy loss, radiative (primarily in closed structures) and kinetic (primarily in open structures).

In this view, stellar coronae are no longer just the dumping ground for excess stellar free energy; they are instead seen as a multitude of astrophysical plasma laboratories which on their own explore the interaction between turbulent flows and magnetic fields.

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