THEORY OF STELLAR CORONAE: AN INTERPRETATION OF X-RAY EMISSION FROM NON-DEGENERATE STELLAR SOURCES

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ABSTRACT

I present arguments to demonstrate that the acoustic wave heating theory of stellar coronae is inadequate to explain Einstein observations of stellar coronae as well as previous ultraviolet and X-ray observations of the Sun and other stars. I outline the various lines of evidence that imply that magnetic fields, stellar rotation rates, and to some extent convection zone parameters are the important quantities in determining coronal heating and thus X-ray emission. These general results and the recent Einstein Observatory stellar observations suggest a speculative scenario of stellar coronae consisting of the following elements: Coronae in O-type stars are heated by the interaction of turbulent stellar winds with slowly decaying primordial magnetic fields or by radiative instabilities in the flow. The apparent absence of coronae in Ap stars, which have large but stable magnetic fields, is due to the absence of temporal changes in very stable atmospheres for which even weak convection is suppressed by the strong field. Weak X-ray emission in some normal A-type stars may be due to the beginnings of dynamo action, which is likely the dominant field regeneration process in cooler stars. In F- and later-type dwarfs, dynamo processes, which increase with stellar rotation velocity and convection zone depth, continually replenish surface magnetic fields. These in turn heat the corona through several possible mechanisms. The distinction between dMe and dM stars is probably a result of larger rotational velocities in the former, since these stars are very likely fully convective. For BY Draconis and RS CVn-type systems, which typically are close binaries, binarity is probably only important to the extent that tidal synchronism forces rapid rotation. K- and M-type giants and supergiants are very likely deficient in coronal material because in such stars strong chromospheric winds provide a cooling channel alternative to the conventional hot corona. This notion is reinforced by the "hybrid" character of early G supergiants, which provide an intermediate case. These stars show variable emission lines from hot plasma as well as strong chromospheric winds. The coexisting phenomena suggest the presence of two very distinct outer atmospheric structures, perhaps hot plasma entrained in closed magnetic loops and cool outflowing material in open field regions analogous to solar coronal holes.

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I. INTRODUCTION

The study of stellar coronae is an excellent example of a field in which observations have generally led and dictated theoretical developments. In this review I will summarize how the recent Einstein Observatory observations, beautifully presented in the previous paper (Vaiana 1980), together with stellar ultraviolet (cf. review by Linsky 1980) and solar visual and X-ray observations have precipitated a major change in our understanding of stellar coronae. For example, until very recently acoustic wave dissipation was almost universally accepted as the dominant coronal heating mechanism, however in light of the new UV and soft X-ray measurements, this mechanism is now regarded as unimportant. In what follows, I will summarize what the important parameters in a new theory of coronal heating are likely to be, and then present a speculative scenario to qualitatively describe the different types of coronae that apparently exist in the HR diagram.

II. THE INITIAL PICTURE OF THE SOLAR CORONA

The discovery of visible emission lines of highly ionized iron and calcium, and high temperature radio emission from the Sun in the 1940's led to the first models of a spherically symmetric, million degree corona in hydrostatic equilibrium. Subsequently, Parker (1958) predicted the existence of a supersonic wind, and satellite observations led to estimates of mass loss in the range $10^{-13}$ to $10^{-14}$ $M_\odot$ yr$^{-1}$.

Following the initial suggestions of Biermann (1946) and Schwarzschild (1948), a near consensus developed that the solar corona is heated by acoustic waves generated by turbulent motions in the hydrogen convection zone immediately below the visible photosphere. According to the theory, acoustic waves propagate upward from the deep photosphere and steepen into shocks in the outer atmosphere as a consequence of the rapid decrease in density with height (cf. the reviews of Stein and Leibacher 1974, 1980). The role of the photosphere in this picture is to filter out the short period waves by radiative damping but to permit waves with periods larger than 300 s to shock and dissipate their mechanical energy as heat. The acoustic theory was generally accepted until very recently because of considerable corroborative empirical evidence. The existence of convective cells (granulation), photospheric motions, and the 300-second oscillatory pattern confirmed the existence of a turbulent medium in which acoustic waves can be generated. In addition, time series of solar Ca II K line and other line spectra presented by Liu (1974) and by Cram (1978) provided vivid evidence for the upward propagation of heating pulses into the low chromosphere.

Ulmschneider (1979) has reviewed the development of theoretical solar models computed on the basis of the acoustic wave theory. Kuperus (1965, 1969), Ulmschneider (1967), and de Loore (1970), among others, have extended the theory to the coronae of late-type stars. These authors have typically assumed the mixing length theory of convection, the Lighthill (1952) theory for acoustic wave generation, monochromatic acoustic waves, and grey opacity
stellar atmospheres to compute coronal models as functions of stellar effective temperature and gravity. Such models (cf. Mewe 1979) generally predict bright X-ray emission in F dwarfs, weak emission in G-K dwarfs, essentially no emission in O-A and M dwarfs, and a rapid increase in X-ray surface flux with increasing stellar luminosity (decreasing stellar gravity).

III. PROBLEMS WITH THE ACOUSTIC WAVE HEATING THEORY FOR THE SOLAR CORONA

Gough (1976), among others, has emphasized the inherent inaccuracies of the acoustic wave heating theory that arise simply because the flux production is proportional to $v_{\text{conv}}^3$, where $v_{\text{conv}}$ is the convective bulk velocity deep in the photosphere. Since $v_{\text{conv}}$ cannot be measured directly and theoretical values computed on the basis of the mixing length theory are questionable, derived values of the initial acoustic flux at the base of the solar photosphere are highly uncertain. Furthermore, at least 90% of the acoustic energy flux generated in the convective zone is dissipated by radiative damping in the photosphere itself, and only long period waves escape without appreciable attenuation (Stein and Leibacher 1980). Consequently, the actual acoustic flux available to heat the corona is doubly uncertain. Finally, the acoustic wave spectrum is not known accurately.

An important goal of the OSO-8 ultraviolet spectrometer experiments was to measure the acoustic wave flux and heating rates in the solar chromosphere and transition region (the geometrically thin interface between the chromosphere and corona). Athay and White (1978,1979) have used their measurements of C IV line widths and power spectra to infer an acoustic flux $\lesssim 10^4$ ergs cm$^{-2}$ s$^{-1}$ passing through the transition region, a factor of 30 less than what is needed to balance measured coronal radiative, conductive, and wind energy losses. More recently, Bruner (1979) has revised the estimate of acoustic flux passing through the transition region to a value $< 10^{-3}$ of that needed to heat the corona.

The preceding arguments provide strong evidence against the acoustic wave heating theory, but there are also several compelling arguments in favor of competing mechanisms -- namely, magnetic heating processes. For example, a major result of the high resolution S-054 X-ray imaging experiment on Skylab was the clear identification of strong X-ray emission with extended loop structures, presumably defined by the coronal magnetic field (cf. Vaiana and Rosner 1978), and the confirmation of the previous result (cf. Withbroe and Noyes 1977) that areas of weak, open magnetic field geometry are regions of low X-ray surface brightness (the so-called coronal holes). Significantly, the coronal holes are the origin of high speed solar wind streams. In fact, Pneuman (1973) and others have shown that in coronal holes the wind is the dominant coronal cooling mechanism, whereas in closed loops radiation and conduction are the dominant cooling mechanisms (cf. Withbroe and Noyes 1977). Thus the magnetic field geometry appears to dictate the plasma cooling mechanism in the solar corona.
Presumably the magnetic field configurations and strength also control the coronal heating rate. There is no proof for this conclusion yet, but there is strong circumstantial evidence, including: (1) the correlation of large scale photospheric magnetic fields with bright X-ray emission from overlying coronal active regions, (2) the loop-like structure of bright coronal X-ray emission just described, (3) the empirical correlation of magnetic field flux with X-ray emission (Golub et al. 1980a,b), and (4) the empirical correlation of photospheric magnetic field strength and chromospheric emission line flux in the supergranulation network (Skumanich et al. 1975). The nature of the magnetic heating mechanism is as yet unclear. It may involve the dissipation of MHD waves as originally proposed by Osterbrock (1961) and recently discussed by Ionson (1978), and others (cf. Wentzel 1980 for a review). Alternatively, heating may result from the dissipation of electrical currents which result from nonpotential magnetic field configurations in the corona which, in turn, are induced by photospheric velocity patterns that stress the loop footpoints. A third alternative is steady field annihilation also driven by the twisting of field lines that results from convective motions in the photosphere. Which of these processes is the dominant coronal heating mechanism and the detailed manner in which photospheric motions are converted to coronal heating are major questions for solar physicists in the 1980's.

IV. PROBLEMS WITH THE ACOUSTIC WAVE HEATING THEORY FOR STELLAR CORONAE

If acoustic wave dissipation fails to explain the heating of the solar corona, where comparisons with observations are most detailed, then the theory must be regarded as highly questionable for stellar coronae in general. There are, however, at least two additional arguments against the acoustic theory in the stellar context.

First, the theory makes a clear prediction concerning the dependence of the acoustic wave flux on stellar surface gravity that can be tested against observations (cf. Linsky 1980). For stars of similar effective temperature, the effect of lowering the gravity is to decrease the densities deep in the photosphere. Since the transport of convective energy is proportional to \( \rho v^2_{\text{conv}} \), the decrease in \( \rho \) with decreasing gravity causes an increase in \( v^2_{\text{conv}} \) (for late-type stars most of the flux near the top of the convection zone is carried by convection rather than radiation, consequently \( \rho v^2_{\text{conv}} \) is roughly invariant among stars of similar effective temperature). As a result, the acoustic flux must increase with decreasing gravity. Stein and Leibacher (1980) show that the acoustic flux should be proportional to \( g^{-1} \), and acoustic fluxes computed by Renzini et al. (1977) and those computed by Ulmschneider et al. (1977) including photospheric radiative damping losses show roughly the \( g^{-1} \) dependence. Linsky and Ayres (1978) and Basri and Linsky (1979) have searched for an increase in chromospheric radiative loss rates with increasing luminosity (decreasing gravity) by measuring Mg II resonance line surface fluxes in some 60 stars. They find no dependence on gravity, contrary to the \( \gtrsim 3 \) order of magnitude increase from dwarfs to supergiants predicted by the theory. More recently, Stencil et al. (1980)
have reexamined this question with a larger stellar sample including additional high luminosity stars, and they find at most a factor of 2 increase in the Mg II surface flux between giants and supergiants. While the inference of chromospheric radiative loss rates (and thus heating rates) from Mg II surface fluxes is somewhat uncertain (cf. Ulmschneider 1979, Linsky 1980), it appears that the acoustic wave theory has difficulty heating stellar chromospheres, much less coronae.

A more direct test of the acoustic wave theory of stellar coronae might be to search for a luminosity dependence of the X-ray surface flux for stars of similar spectral type. This test is currently under way as a part of the Einstein/CFA stellar survey (Vaiana et al. 1980). The survey to date is very incomplete in late-type supergiants and giants, but preliminary results suggest a sharp decrease in the $L_X/L_V$ ratio from dwarfs to supergiants at least among M and late K-type stars, consistent with the IUE results of Linsky and Haisch (1979) which show a substantial decrease in transition region line fluxes in the K giants compared with K dwarfs. This test is not conclusive, however, because chromospheric winds in the cool giants may supplant coronae as the dominant cooling mechanism for the outer atmosphere (e.g. Haisch et al. 1980).

A second argument against the acoustic wave theory is the observation that Mg II line fluxes range over an order of magnitude for stars of similar spectral type and luminosity class (Basri and Linsky 1979), while X-ray fluxes range over nearly three orders of magnitude (Vaiana 1980). These large variations in chromospheric and coronal radiative loss rates are found for stars with presumably very similar convective -- and hence also acoustic -- energy fluxes at the bases of their photospheres. It is difficult to reconcile the acoustic wave theory with such a wide range of heating rates, although purely acoustic heating may explain the lowest heating rates and magnetoacoustic heating may explain the larger heating rates.

Finally, the unexpected Einstein discovery that O and B type stars are prodigious X-ray emitters with fluxes up to $10^{33}$ ergs s$^{-1}$ (e.g. Vaiana 1980, Cassinelli et al. 1979) cannot be explained by the acoustic theory, since OB stars are generally thought to be too hot to have any significant convective energy transport in their outer layers.

V. WHAT MIGHT THE IMPORTANT STELLAR PARAMETERS BE?

Before I propose a possible broad picture for stellar coronae, it is important to consider what solar and stellar observations suggest might be the important parameters controlling the structure and energy balance of coronae.

a) Magnetic Fields

In the past decade a major revolution has occurred in our understanding of solar magnetic field structure. Hale's early investigations presented a picture of the Sun with a weak general magnetic field of order 1 G and strong
magnetic fields only in sunspots. However, high resolution magnetographs and spectral polarimetry have since revealed that the global weak field is composed of small-scale (sub arcsec) features (the flux tubes) having kilogauss field strengths. Consequently, virtually all solar fields occur in regions of high field strengths, but the fields have a small filling factor. Why the Sun has such a "curious" magnetic field structure is an important question for theoretical investigation. It is likely that a wide range of stars also have similar "curious" magnetic field structures.

Strong, albeit local, magnetic fields can alter in fundamental ways the energy balance in the overlying chromosphere and corona. For example, the spatial correspondence of strong photospheric magnetic fields (clumps of flux tubes) with overlying bright chromospheric emission and downflows in the supergranulation network (e.g. Skumanich et al. 1975) imply that the magnetic field plays important roles in supplying or channeling nonradiative heating, defining the plasma geometry, and controlling velocity fields in the chromosphere.

Krieger et al. (1971) first showed a general correlation of strong X-ray emission with magnetic flux in the underlying photosphere. Subsequently many investigators pointed out that the solar corona contains two basic structures: open field regions called coronal holes and closed flux tubes. Rosner et al. (1978) have discussed scaling relations between the temperature, pressure, and length of coronal flux tubes. Golub et al. (1980a,b) have shown further that the gas pressures, and hence also the total thermal energy content, in flux tubes are correlated with the total magnetic flux in the underlying photosphere, and that these correlations are consistent with semiempirical scaling laws. Consequently, the magnetic field determines both the geometry and the energy balance of coronal structures.

Until recently there was no direct evidence for magnetic fields in late-type stars other than the Sun. Kelch et al. (1979) did show that chromospheric models of G-M dwarfs with enhanced Ca II K line surface fluxes for their spectral types are similar to solar plage models. Consequently, such stars, specifically ξ Boo A (G8 V), 70 Oph A (K0 V), ε Eri (K2 V), and ΕΕ Vir (K7 Ve), very likely are covered with structures comparable in chromospheric emission and perhaps also field strength to solar plages. Another important piece of indirect evidence is provided by star spots whose presence has been deduced photometrically in BY Draconis stars (cf. Kunkel 1975) and in RS CVn-type binary systems (cf. Eaton and Hall 1979). If the starspots are analoguous to sunspots, they would indicate the presence of large-scale concentrations of strong magnetic fields.

Boesgaard (1974) presented marginal detections of magnetic fields in three stars using standard magnetograph techniques and photographic detection of the spectra. It is difficult to detect magnetic fields in stars using polarizing optics owing to global cancellation of opposite polarity fields for unresolved sources unless the field has a simple geometry (as in Ap stars). Anderson et al. (1976), however, presented evidence for a 40 kG longitudinal field in a starspot on BY Draconis based on Zeeman spectrograms.
taken when a large spot was on the stellar limb. A more promising technique, recently proposed by Robinson (1980), involves the direct measurement of Zeeman triplet patterns in unpolarized high resolution spectra by a comparison of the Fourier deconvolution of lines having different Lande g factors. This technique will yield meaningful results only if the magnetic fields have roughly similar strengths over the surface of a star as appears to be true for the Sun. Robinson et al. (1980) have used this technique to measure fields of $2.6 \pm 0.4$ kG covering roughly 30% of $\xi$ Boo A and fields of $1.9 \pm 0.4$ kG covering perhaps 10% of the surface of 70 Oph A. The Sac Peak program of stellar magnetic field measurements is being continued actively.

These first direct and indirect studies of magnetic fields in late-type stars are consistent with the following picture: (1) stellar magnetic fields are spatially concentrated (cf. Zwaan 1977) and of roughly constant field strength, (2) stars with large chromospheric emission line surface fluxes have considerably larger magnetic field filling factors and perhaps a modest increase in field strength compared with the Sun, (3) starspots (or spot groups) can be much larger in geometrical extent and cover much greater fractions of the stellar surface than in the solar case, and (4) the magnetic field very likely controls both the geometry and energy balance of late-type stellar coronae. The direct correlation of magnetic field strength or flux with coronal X-ray emission has now been made for the Sun and will presumably be made for stars when the data become available. It is important to point out, however, that the star for which a large field filling factor has been inferred, namely $\xi$ Boo A, has an X-ray luminosity $L_x \approx 2 \times 10^{29}$ ergs s$^{-1}$ (Walter et al. 1978) some 30 times the quiet Sun, but comparable to the Sun entirely covered by plages (Vaiana and Rosner 1978).

b) Rotation

During the 1960's, a number of authors found a statistical correlation of decreasing Ca II K line strength with increasing age for solar-type stars. Significantly, such stars also spin down as they grow older owing to the loss of angular momentum by weak coronal winds. This work is summarized by Wilson (1966), and by Linsky (1977), among others. In particular, Skumanich (1972) proposed that both the stellar rotational velocity and Ca II emission strengths decrease with age proportional to $t^{-1/2}$, suggesting a causal relation between rotational velocity and chromospheric heating.

It is now possible to determine such correlations more quantitatively owing to the development of sensitive methods for measuring rotational velocities and quantitative means for deriving chromospheric radiative loss rates from emission line strengths. For example, the photometric periods of spotted stars such as the BY Draconis class yield accurate estimates of rotational velocities independent of uncertain inclinations ($\sin i$). Using such data, Bopp (1980) and Carrasco et al. (1980) comment that as a class the dMe stars, which have larger chromospheric radiative loss rates and therefore larger heating rates than dM stars (Kelch et al. 1979), are also more rapidly rotating. Rapid rotation could be either a consequence of youth or tidally forced synchronism in short-period ($P \lesssim 20^d$) binary systems
Young and Koniges (1978) have shown that RS CVn-type binaries with periods less than 20 days have extremely bright Ca II emission lines and Basri and Linsky (1979) have shown that such systems are bright in Mg II as well. Young and Koniges propose that the enhanced chromospheric emission in the close binaries is due to amplification of the acoustic or mechanical wave energy transport driven by tidal coupling.

An alternative explanation is that rapid rotation itself is the underlying cause of enhanced chromospheric heating rather than tidal coupling per se or some other aspect of binarity. For example, Bopp (1980) argues that EQ Vir (dK7e) is a rapid rotator with all the photometric symptoms of spottedness and strong chromospheric emission line behavior of binary BY Draconis stars, but EQ Vir shows no evidence for a close companion. Ayres and Linsky (1980) make a similar argument by demonstrating that the rapidly rotating secondary star in the widely separated, nonsynchronous Capella system is the dominant source of chromospheric and transition region emission, while the slow rotating primary is a comparatively weak emission source.

Fourier deconvolution of high signal-to-noise line profiles has led to recent measurements of stellar rotation velocities with precision heretofore unattainable. Smith (1979) has reviewed recent developments in this field. The detailed comparison between rotational velocity, chromospheric emission and X-ray luminosity for late-type stars using a good statistical sample of stars has not yet been done, but Ayres and Linsky (1980) find a good correlation between X-ray luminosity and rotational velocity for a small sample of late-type stars observed by HEAO-1, and Vaiana (1980) finds a similar preliminary correlation using Einstein observations. It is probably not coincidental that the early G dwarf with the highest measured rotational velocity in Smith's (1979) list, π1 UMa, has the brightest Ca II K line surface flux of a G dwarf in the Linsky et al. (1979) survey and the highest X-ray luminosity of a G star in the Vaiana et al. (1980) survey with Einstein.

While the connection between coronal X-ray emission and stellar rotation has not yet been established conclusively, there is ample direct and indirect evidence that it is very real. Furthermore, the likely mechanism for this connection in F and cooler stars is almost certainly dynamo action (Parker 1958), which continually regenerates magnetic fields deep in the stellar convection zone.

c) Convection Zone Parameters

Since O- and B-type stars, which lack appreciable convection zones, have coronae with X-ray luminosities up to $10^7$ times larger than the quiet Sun, the existence of a convection zone must not be a prerequisite for the existence of a corona. However, a striking result of the Einstein stellar survey is the rapid increase in typical values of $L_x/L_y$ from O- to M-type stars (Vaiana 1980). The increase in $L_x/L_y$ ratios is far faster than the decrease in $L_y/L_{bol}$ with decreasing effective temperature, consequently there must be real increase in $L_x/L_{bol}$ with decreasing effective temperature. Since there is no known statistical correlation of stellar rotational velocity

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with effective temperature for stars later than spectral type G, I conclude that some aspect of the stellar convection zone plays an important role in determining coronal properties of cool stars.

d) Coronal Base Pressure and Gravity

Hearn (1975) proposed that the properties of a stellar corona can be computed by minimizing the total energy loss due to radiation, conduction, and the stellar wind. This so-called minimum flux corona concept was initially applied to a plane-parallel, hydrostatic corona with no magnetic fields. Hearn (1977) subsequently generalized the minimum flux concept to include the effect of inclined magnetic fields on conductive cooling of the corona. In the absence of magnetic fields the minimum flux corona hypothesis predicts that increased coronal temperature produces both increased X-ray emission and stellar wind losses. However, such a correlation between X-ray emission and stellar wind loss is the opposite of what is seen on the Sun (see §III).

The minimum flux corona hypothesis is highly controversial. Vaiana and Rosner (1978), Antiochos and Underwood (1978), among others, have criticized the theory on thermal stability and other grounds, and Hearn (1980) has confronted his critics. It is not the intent of this paper to join the controversy other than to point out that the minimum flux corona hypothesis does not address what I consider to be the most important question, namely, how coronae are heated and what stellar parameters determine the coronal heating rates. Instead, a coronal base pressure is assumed as a lower boundary condition, but the base pressure must be a direct result of the heating rate. Thus the minimum flux corona hypothesis provides little guidance at this time for developing a broad picture of stellar coronae.

VI. A SPECULATIVE PICTURE OF STELLAR CORONAE

While systematic surveys of stellar coronae in different regions of the HR diagram and as functions of such parameters as rotation, gravity, age, and chromospheric properties are incomplete, enough preliminary data are available and have been presented (Vaiana 1980) to begin to piece together a speculative picture of stellar coronae. In doing so I am guided by the principle that magnetic fields define the basic geometry and control the energy balance of stellar coronae as they clearly do for the Sun (see §III). Magnetic fields can either be slowly decaying remnants from the protostellar collapse or be regenerated by dynamo processes. In either case the fields are probably stochastic, as they are for the most part in the solar case, consequently stellar coronae should be temporally variable and spatially inhomogeneous.

Many of the speculations that follow are simple extrapolations of trends seen in the solar and stellar data. Rosner and Vaiana (1979) have independently arrived at similar conclusions. Finally, I should clearly state that what follows is highly speculative and in some cases not corroborated in any way by existing data.

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a) O- and B-Type Stars

The O-type Einstein sources have X-ray luminosities in the range \( \log L_X = 32-34 \) and surface flux ratios in the range \( \log L_X/L_Y = -5 \) to \( -3 \). The B-type stars detected tend to have somewhat smaller values of \( L_X \) and \( L_X/L_Y \). Since these stars have short evolutionary time scales, they all must be young and it seems reasonable to assume that they possess remnant magnetic fields that have not yet decayed. I assume that dynamo processes cannot operate in such stars owing to the absence of appreciable surface convection zones.

The OB stars generally have strong winds, especially the most luminous O- and Of-type stars (cf. Cassinelli 1979). A critical aspect of these winds is that they are not steady. For example, Conti and Niemela (1976) have found long-term changes in the H\alpha profiles of \( \zeta \) Pup (O4If) and York et al. (1977) have found changes in the O VI absorption components of three O stars on time scales of hours. These and more recent data suggest turbulent flows. Such flows can twist and stretch embedded magnetic fields into configurations that are far from potential. The stressed fields may then dissipate their stored energy by mechanisms similar to those responsible for heating the solar corona. An alternative mechanism, not requiring magnetic fields, has been proposed by Lucy and White (1980). They note that winds driven by radiation pressure in lines are unstable (cf. references in their paper), and that nonradiative heating occurs in bow shocks between accelerated cool blobs that plough through the ambient material, which is not radiatively driven due to shadowing by the blobs. Castor (1980) is investigating the likely geometry of shock waves that are produced in this flow. If either of these scenarios is correct, then the brightest hot-star X-ray sources should be those with the most turbulent wind flows. Consequently, the most luminous O stars, which have the greatest mass loss rates and likely also the most turbulent flows, should be the strongest X-ray sources.

b) A and Ap Stars

Those A-type stars which have been detected by Einstein exhibit a very wide range of \( \log L_X (26-31) \) and \( \log L_X/L_Y (-8 \) to \( -3) \). The most interesting A stars from the perspective of coronae are the Ap stars. These stars are thought to possess kilogauss fields on the basis of direct measurements or by inference. In particular, the Ap stars often exhibit abundance anomalies which are commonly interpreted as the result of diffusion in an extremely stably stratified atmosphere in which convective motions have been suppressed by strong fields with a simple dipole geometry.

In a search of 18 B5-A7 stars with HEAO-1, Cash et al. (1979) detected one normal B star (\( \pi \) Cet) and one classical Ap star (\( \phi \) Her). The remaining stars were not detected even though many are closer and optically brighter than the stars detected. Snow and Cash (1980) have continued this program by studying five bright Ap and Am stars with Einstein. They determined three upper limits (\( \log L_X < 28 \)) and two detections, but both are binary systems and the unresolved companions may be the X-ray sources.
The interesting question is why stars with kilogauss fields are weak X-ray sources if magnetic field strength appears to be intimately associated with coronae and strong X-ray emission, at least for solar-type stars. I think the answer is that magnetic fields per se do not do the heating; rather the heating results from either MHD wave processes or the relaxation of stressed (nonpotential) fields perhaps by particle acceleration, current dissipation, or magnetic field annihilation. All of these processes require turbulent motions in addition to magnetic fields. The detection of kilogauss fields by Babcock-type magnetographs implies simple, stable field configurations in the Ap stars. It is possible that there are two distinct classes of field configurations for A-type stars: either strong dipolar fields that suppress turbulent motions and thereby suppress coronal emission, or weaker fields that are disordered and somewhat turbulent owing to weak convective motions. Sirius, Vega, and the Einstein A-star sources may be of the latter type.

c) F-Type Dwarfs

F-type dwarfs are characterized by \( \log L_X = 28.5 - 30.5 \) and \( \log L_X/L_V = -5 \) to \(-3\). Thus the X-ray emission is \( 10^1 - 10^3 \) times that of the quiet Sun and comparable to or somewhat brighter than solar plages. I assume that the typically large values of \( L_X \) are a consequence of the onset of dynamo-regenerated magnetic fields near spectral type F0, while the wide range of \( L_X \) is due to the range in rotational velocity, that in turn depends on age as described above.

The theory of stellar dynamos is far from understood, and there is no consensus yet as to which type of dynamo process operates in the Sun. Despite this important uncertainty, a critical parameter determining the kind of differential rotation expected in a stellar convection zone, and thus the efficiency of dynamo field regeneration, is the ratio of the convective turnover time to the stellar rotation period (Gilman 1980). Since the convective turnover time should be roughly proportional to the convection zone depth (\( d_{\text{conv}} \)), the rate of creation of magnetic flux should depend functionally on the product \( v_{\text{rot}}d_{\text{conv}} \).

In Figure 1, I schematically plot the increase in \( d_{\text{conv}} \) toward cooler stars and the dependence of rotational velocity on spectral type for young and old stars. If turbulent magnetic fields are responsible for coronal heating and the field regeneration rate depends functionally on \( v_{\text{rot}}d_{\text{conv}} \), then \( L_X/L_V \) should depend on spectral type and stellar age as shown schematically in Figure 1. In particular, there should be a rapid increase in \( L_X/L_V \) in the early F stars and \( L_X/L_V \) should depend on \( v_{\text{rot}} \) and thus age for single stars of the same spectral type. The \( L_X/L_V \) versus age prediction can be tested by observing clusters of different ages. In fact, Stern et al. (1979) have reported that F stars in the young Hyades cluster have relatively large \( L_X/L_V \) values compared with F stars in the solar neighborhood. Finally Vaisanen et al. (1980) find that the largest \( L_X/L_V \) ratio for F stars is about \( 10^{-3} \), implying that \( 10^{-3} \) is the maximum efficiency for converting convective flux to magnetic fields by dynamo processes in such stars.
Figure 1. A schematic representation of parameters relevant to stellar coronae for main sequence stars. Included are systematic trends of stellar rotational velocities ($v_R$) for young and old stars, the ratio of convection zone depth to stellar radius ($d_c/R$), and expected X-ray-to-visual luminosity ratios ($L_X/L_V$) for old and young stars. A rough division into regimes of turbulent flows, stable photospheres, and significant convective zones is indicated.
d) G and K Dwarfs

G- and K-type dwarfs have X-ray luminosities in the range $10^{27}$ to $10^{30}$ ergs s$^{-1}$ and $\log L_X/L_V$ in the range $-6$ to $-2$. The median X-ray luminosities are an order of magnitude smaller than for the F stars, presumably because the mean rotational velocities of field G- and K-type stars are smaller than field F-type stars. As previously noted, $\pi^1$ UMa is a very rapid rotator for its spectral type (G0 V) and is the G dwarf with the largest $L_X$ so far detected.

e) dM and dMe Stars

The coolest dwarf stars also exhibit a wide range in $L_X$ ($\log L_X = 27$ to $30$) and in $L_X/L_V$ ($\log L_X/L_V = -3$ to $0$). Since M dwarfs are cool, only a small fraction of the bolometric luminosity appears in the visual band. Thus values of $\log L_X/L_{BOL}$ probably lie in the range $-4$ to $-1$, but these ratios are still far larger than for any other stellar types. One plausible reason is that these stars are the only dwarfs with convection zones that extend most or all of the way down to the stellar core. Thus if $L_X/L_{BOL}$ depends functionally on the product $v_{rot} d_{conv}$, then EQ Vir (dK5e) and BY Dra (dM0e) should have far larger $L_X/L_{BOL}$ ratios than $\pi^1$ UMa (G0 V), since all three stars have similar $v_{rot}$ (cf. Smith 1979) but EQ Vir and BY Dra have much deeper convection zones. Also the type of dynamo and its efficiency in regenerating magnetic flux may be different for stars with deep convection zones compared to stars with shallow zones (Gilman 1980).

Although detailed calculations are not yet available, I presume that M dwarfs all have deep convection zones with comparable values of $d_{conv}$. Thus the wide range in $L_X/L_{BOL}$ should be due mainly to differences in $v_{rot}$, which depends on stellar age (cf. Carrasco et al. 1980). M dwarfs are generally divided into two groups: dM stars with no emission lines in the visible except Ca II, and dMe stars which show emission in the Balmer and other lines. If, as I presume, rotational velocity is the single key parameter determining the X-ray emission of M dwarfs, then dM stars should be slower rotators than the dMe stars and the dM stars should occupy the low range of $L_X/L_{BOL}$ in the M star distribution. Kelch et al. (1979) have found that the chromospheric radiative loss rate (and thus nonradiative heating rate) for 61 Cyg B (a dM0 star) is much smaller than for EQ Vir (dK7e), a result consistent with lower field regeneration rates in dM stars.

f) Close Binary Systems

Walter et al. (1980a) find that X-ray luminosities for RS CVn-type binaries typically lie in the range $\log L_X = 30.3$ to $31.3$ and $\log L_X/L_{BOL} = -5$ to $-2.5$. These X-ray luminosities are large, but they are similar to the brightest of the G-K dwarf single stars (Walter et al. 1980b, Vaiana et al. 1980), and thus the mechanism for heating the coronae of RS CVn-type systems is probably similar to that operating in single stars. As previously noted, synchronism of rotation and orbital period is expected for RS CVn-type binaries with periods less than about 20 days. Thus the KO IV active stars
in such systems are probably strong X-ray emitters as a result of tidally induced rapid rotation, whereas single stars with comparable X-ray luminosities are rapid rotators as a result of youth.

Simon and Linsky (1980) have computed chromospheric models for the KO IV stars in two representative RS CVn systems, HR 1099 and UX Ari. Pressures at the top of the chromospheres in these stars lie in the range 0.2-1 dynes cm⁻² and are consistent with density diagnostic line ratios for lines formed near 5 × 10⁴ K. Rosner et al. (1978) have derived an empirical scaling law for closed flux tubes in the solar corona, \( T_C = 1.4 \times 10^3 \left( \frac{P_C L}{L} \right)^{1/3} \), where \( T_C \), \( P_C \), and \( L \) are the coronal temperature, pressure, and flux tube length, respectively. Assuming \( T_C = 10^7 \) K (Walter et al. 1978) and coronal pressures equal to those derived for the top of the chromosphere, \( L = 2-8 \) times the KO IV star radius. Since the semimajor axis of the UX Ari system is 16 K star radii, these data suggest that coronal flux tubes from the K-star fill a significant portion of the volume of the system.

Short period RS CVn systems have been observed to flare at radio, optical, and ultraviolet wavelengths for periods of hours to almost two weeks. During one flare on UX Ari, Simon et al. (1980) observed with IUE a factor of six enhancement in ultraviolet emission line fluxes and asymmetries in the Mg II lines indicating flows of material from the KO IV star to the G5 V star in the system. They interpret these data as resulting from the interaction of large flux tubes of both stars, field reconnection, and the temporary magnetic connection of the two stars via a single flux tube that permits flow of material from one star to the other. While this scenario is indeed speculative, it is based on the reasonable deduction that these stars have large closed field configurations which can have lengths comparable to the stellar separations.

**g) G-M Giants and Supergiants**

Except for G- and K-type giant components of long period RS CVn-type systems like Capella (e.g. Holt et al. 1979), G-M-type single giants and supergiants have not yet been detected as X-ray sources. I expect that G-type single giants and supergiants will eventually be detected, but the cooler luminous stars probably have no hot coronae at all or perhaps have only small regions in their atmospheres hot enough to emit X-rays. The upper limit on the X-ray surface flux of \( \alpha \) Sco (MIIb+B), for example, is \( 10^{-4} \) that of a coronal hole (Vaiana 1980).

The apparent absence of detectable coronae in such stars can perhaps be explained simply using Parker's wind theory. When the critical point lies at the base of a thermally-driven wind, the coronal temperature is maximized and is related to the stellar mass and radius by the equation

\[
T_C = 5.5 \times 10^6 \frac{K}{M} \left( \frac{R_*}{R} \right) \]

For assumed masses of order unity, \( \alpha \) Boo (K2 III) would have \( T_C = 2 \times 10^5 \) K.
and α Ori (M2 Iab) would have $T_c = 1 \times 10^4$ K. Thus one would not expect to see X-ray emission from such stars unless the masses are much larger than solar or closed flux tubes can survive disruption by the large stellar winds in some regions of these stars.

Stencil (1978) and Stencel and Mullan (1980) have shown that asymmetries in the Ca II and Mg II resonance line profiles are qualitatively different on either side of a roughly vertical line in the HR diagram near spectral type K2 III. They interpreted the change in asymmetry as due to the rapid onset of large winds as a star evolves toward cooler effective temperatures across the dividing line. On theoretical grounds, Mullan (1978) inferred that there should be a rapid increase in stellar winds on a line in the HR diagram that he called the supersonic transition locus (STL). This line is in roughly the same location on the HR diagram as the Ca II and Mg II asymmetry lines. Subsequently, Linsky and Haisch (1979) found from IUE observations that along a line in the HR diagram in a similar location to the STL and asymmetry lines, there is a rather abrupt change from stars with transition region emission lines ($T > 20,000$ K) to the left side of the line to stars with no or extremely weak transition emission lines on the right side of the dividing line. The sharpness of this dividing line may be less than originally thought (Dupree and Hartmann 1980). Thus there appears to be a good empirical correlation of bright transition region lines with weak winds and weak transition region emission with strong winds.

There are several probable consequences of this empirical correlation and these dividing lines in the HR diagram:

1. The existence of a transition region strongly implies the presence of a hot corona. The apparent absence of coronae in single stars among giants and supergiants cooler than about spectral type K2 III is consistent with this picture.

2. The apparent absence of coronae to the right of the dividing line implies that the winds are sufficiently strong to disrupt quickly any closed magnetic loop structures that are stable in stars to the left of the dividing line.

3. The energy balance in the outer atmospheres of stars on either side of the dividing lines is probably very different, although the input of non-radiative energy could be similar. To the left of the dividing lines the nonradiative energy input to the corona is probably dissipated as X-ray emission and thermal conduction to the transition region. To the right, the energy input is probably converted into the expansion of the stellar wind.

4. For stars to the right of the dividing lines the winds cannot be Parker-type flows because the material is so cool. Also, except for M-type supergiants, there is no measured infrared excess or other evidence for dust, so that radiation pressure on dust cannot accelerate the wind. Instead, Haisch et al. (1980) suggest that the winds are accelerated by the momentum deposition of Alfvén waves and $\mathcal{L}_\alpha$ radiation pressure. Hartmann and
MacGregor (1980) have investigated winds driven by the momentum and energy deposition of acoustic and Alfvén waves.

The early G supergiants, of which α Aqr (G2 Ib) and β Aqr (G0 Ib) are prototypes, are interesting in that they have bright transition region emission lines and strong winds (their Ca II and Mg II lines exhibit absorption components blue-shifted up to ~125 km s\(^{-1}\) [Dupree and Hartmann 1980, Hartmann et al. 1980]). Thus the outer atmospheres of these stars are hybrid in character. In addition, Dupree and Baliunas (1979) report that both the wind velocity and emission line fluxes in α Aqr are variable. One possible explanation for the hybrid character of the outer atmospheres of these stars is that they may consist of closed loops and open field structures similar to solar coronal holes. The closed loops contain the hot, X-ray emitting material while the coronal holes produce the supersonic wind. The supergiant wind is much cooler and has far greater mass loss than the high-speed streams from solar coronal holes probably as a result of the three orders of magnitude smaller stellar gravity.

VII. FINAL COMMENTS

During the next few years I would like to see major progress in addressing the following uncompleted tasks:

(1) First, we need a complete survey of X-ray emission from stars throughout the HR diagram. This work is fortunately far along and Vaiana et al. (1980) will soon publish the results of the first stellar survey with Einstein.

(2) Most of the observations to date have been single detections with no repeated observations to test for time variability. One anticipates variability owing to rotational modulation and evolution of loops, coronal holes, and active regions, as well as to flares and stellar cycles. Since a great deal of observing time is needed to search for variability on many time scales in a reasonable sample of stars, a dedicated X-ray and ultraviolet observatory is probably required.

(3) To date we have very little information on coronal temperatures, densities, and flares. To measure these critical quantities we need a high resolution X-ray spectroscopy experiment with sufficient sensitivity to observe a large number of stars.

(4) Finally we need a concerted effort to develop a theory of stellar coronae with high predictive power. In particular, we need further studies of dynamo processes, mechanisms for converting turbulent magnetic fields into heat, and acceleration mechanisms for stellar winds.

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REFERENCES

Biermann, L. 1946, Naturwiss., 33, 118.
Bopp, B. W. 1980, in Highlights of Astronomy, 5, in press.


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Vaiana, G. S. 1980, this volume.