X-rays at Sharp Focus: Chandra Science Symposium
*ASP Conference Series, Vol. **VOLUME**, 2002*
eds. S. Vrtilek, E. M. Schlegel, L. Kuhi

CRAZY CORONAL ABUNDANCES

JEFFREY L. LINSKY

JILA/University of Colorado and NIST, Boulder CO 80309-0440 USA

Abstract. Closed magnetic structures in the solar corona show abundances very different from the photosphere. Elements with first ionization potentials less than 10 eV are typically overabundant by a factor of four. Analyses of Chandra and XMM-Newton spectra of active stars show an inverse FIP bias in which the low FIP elements are underabundant and some high FIP elements are overabundant. I summarize the new data for the inverse FIP bias and propose an explanation for solar FIP and active star inverse FIP biases.

The devil is ALWAYS in the details.

1. The Importance of Stellar X-ray Spectroscopy

Welcome to the first scientific meeting devoted to the new field stellar x-ray spectroscopy. With the successful launch of the Chandra X-ray Observatory and the XMM-Newton satellite, we can now study stellar coronae with a new and very powerful set of tools. Just as optical spectroscopy more than a century ago provided the data for astrophysics to infer the physical properties of the gas in stellar photospheres, X-ray spectroscopy provides the information needed to infer the physical properties of stellar coronae. Beginning in the 1960s, X-ray spectroscopy of the solar corona has provided measurements of plasma temperatures, densities, chemical compositions, dynamics, and structure of the corona of the nearest inactive star. Before Chandra and XMM-Newton, stellar coronae could only be studied with a resolution of about 150 eV, which is inadequate to resolve individual emission lines and to separate emission lines from the continuum. High resolution spectroscopy of only two coronal emission lines are feasible outside of the X-ray region – the Fe XXI 1354 Å line observable by the GHRS and STIS instruments on HST with 3 km/s resolution, and the Fe XVIII 975 Å line observable with FUSE with 20 km/s resolution. Now Chandra and XMM-Newton we can study several hundred X-ray emission to infer the physical properties of the hot plasma in stellar coronae to compare with what we have learned about the solar corona.

2. Some Fundamental Questions about Stellar Coronae

Before I proceed to a discussion of what we are learning about stellar coronal abundances, it is important to mention some of the major objectives of stellar X-ray astronomy.

2.1. What types of stars show evidence for coronae?

Observing programs with the Einstein and ROSAT observatories, especially the ROSAT All Sky Survey demonstated that coronae are ubiquitous on essentially all dwarf stars of spectral type F, G, K, and M, giants of spectral type F through early-K, and spectroscopic binaries containing a late-type companion. In addition, O and early-B type stars are also X-ray emitters although by shocks in their radiatively unstable winds rather than the conversion of magnetic energy into heat.

- B3-A5 stars
- "Coronal graveyard stars" – K and M giants
- Brown dwarfs

Binarity: How does the presence of a nearby companion star determine the properties of a stellar corona?

Geometry: What are the important structures in a corona? How extended are coronae? Are the structures magnetically confined?

X-ray Luminosity: How does L_X correlate with $v\sin i$, P_{rot}, age, and other physical parameters? When and why does saturation occur? What is supersaturation? How small can L_X and F_X be?

Physical properties: What are typical emission measure distributions and thermal–density structures in coronae?

Nonthermal plasma: Do hard X-rays imply nonthermal or very hot electrons? Why are gyrosynchrotron radio and thermal bremsstrahlung X-ray emission correlated?

Ionization: How valid is the assumption of ionization equilibrium during quiescence and flaring? How important are radiative processes?

Flares: What is a self-consistent physical model for a flares that has predictive power?

Dynamics: What flows occur in stellar coronae? Does only the coolest coronal plasma expand as a wind? Is the hot plasma always confined?

Magnetic fields: What roles do magnetic fields play in stellar coronae? Do magnetic fields play a role in hot star coronae/winds?

Energy source: What mechanism(s) provide energy (thermal, kinetic, nonthermal particles) into a corona? What physical mechanisms determines the maximum temperature of a corona?

Abundances: Is the inverse FIP effect real? Why are low FIP metal abundances depleted, and why do they rise to photospheric values during flares?

3. Crazy Coronal Abundances

The chemical composition of an astrophysical plasma is a critically important property because it provides information on the evolution of the object studied and its energy budget. For the hot plasmas in stellar coronae, the radiative loss rate depends critically on the chemical abundance. Analysis of the X-ray spectra obtained by Chandra and XMM-Newton for the first time permit us to derive accurate chemical abundances in stellar coronae. I will summarize this work to date, with two basic questions in mind: **Do stellar coronal abundances differ from the abundances of the star as measured in the photosphere? Since this is often the case, what physical processes are responsible for these different abundances?**

3.1. Solar coronal abundances

First consider the case of the solar corona, whose abundances have been measured from analysis of X-ray spectra and *in situ* measurements of the solar wind plasma for more than 30 years. In their excellent review, Feldman & Laming (2000) showed that abundances in the solar corona depend on (1) the magnetic field structure in which the plasma is located, (2) how long the plasma has been in this structure, and (3) the first ionization potential (FIP) of the element. Elements with FIP < 10 eV (e.g., Mg, Si, and Fe) generally behave differently from elements with FIP > 10 eV (e.g., O, S, Ne, and Ar). The term "FIP bias" or "FIP effect" refers to the enhancement of the low FIP ions relative to their photospheric values.

The solar wind consists of two dominant components. The high-speed wind with typical velocities $v \approx 750$ km/s originates in coronal holes (coronal structures near the solar poles that are characterized by open magnetic fields, relatively low temperatures and low X-ray emission fluxes). *In situ* measurements of the high speed wind by the Ulysses and previous sattelites show that the abundances of high-FIP and low-FIP ions are photospheric. The slow-speed wind with typical velocity $v \approx 400$ km/s originates in quiet regions at low latitudes on the Sun in which the magnetic field is a mixture of closed and open field structures. Abundances of low-FIP ions are generally enhanced by a factor of 4–5 (FIP bias = 4–5), while the abundances of the high-FIP ions are photospheric. Clearly the magnetic field structure plays a role in determining the coronal chemical abundances.

Analyses of X-ray and extreme-ultraviolet spectra obtained with the SUMER and CDS instruments on SoHO, P78-1, Skylab, and other satellites provides the following picture of solar coronal abundances.

New, rapidly-heated plasma: Newly emerging or flare "evaporated" plasma from below initially has photospheric abundances.

Time behavior of plasma in coronal loops: FIP bias increases from initial value of 1.0 linearly with time. The FIP bias reaches about 4 in 2 days and a maximum value of about 15 seen in very old loops.

Coronal hole plasma: Photospheric abundances like the fast-speed wind.

High in the corona: In large magnetic structures (i.e., streamers) at $\geq 1.2R_{\odot}$, emission lines of Fe are a factor of 3 weaker than other low-FIP ions. Probably due to gravitational settling of the heavier ion (Fe).

3.2. Difficulties in measuring stellar coronal abundances

Accurate measurements of stellar coronal abundances from EUV and X-ray spectra must surmount a number of difficult problems. Here is a partial list:

1. The flux emitted by a hot plasma in a given emission line is proportional to the element abundance, atomic parameters (e.g., collisional excitation rate), the ionization equilibrium as a function of temperature and density, and the emission measure distribution over the range of temperature at which the relevant ion is abundant. Uncertanties in any of these quantities translate into errors in the abundance inferred from the emission line flux.

2. The ionization equilibrium is generally calculated assuming steady-state Collisional Ionization Equilibrium (CIE) in which the included processes are collisional ionization and excitation from the ground state and radiative and dielectronic recombination. Thus ionization from and recombination to excited states are not included and photoionization is not included. The steady state assumption is probably valid, except possibly during flares when the time scales for the important processes may be very short and we may see a recombining plasma far out of equilibrium. Since densities may not be accurately known, the dielectronic recombination and various collisional rates may not be known accruately.

3. Some ions are abundant over a wide range of temperatures and have high temperature tails. The Li-like and Na-like ions are good examples. For these ions one must know the emission measure distribution over a wide range of temperature as the emission lines can be formed at temperatures far from that of peak ion abundance.

4. While a major effort has gone into calculating atomic parameters for the important ions seen in stellar coronae, for example by the Opacity Project, there are a great many lines for which no data or only low quality data are available.

5. Abundances of an element are credible only when at least one ion is formed at temperatures where the emission measure distribution is well known.

In addition to these generic problems, analysis of low resolution spectra from EUVE and X-ray fluxes from ASCA which have CCD resolution (typically 150 eV) provide additional challenges for infering coronal abundances:

1. High spectral resolution and S/N are required to measure strengths of weak lines and to identify blends. Analysis of lower resolution data can only yield accurate abundances when all lines contributing to the blends are known and their atomic data and ionization equilibria well understood. This is not presently the case.

2. Abundances relative to H require an accurate measurement of the continuum, which is produced mainly by hydrogen free-free emission. Except for very hot plasmas where the continuum dominates the emission, high resolution is needed to separate the continuum from the emission lines.

3.3. Summary of the pre-Chandra and Pre-XMM results on abundances

Given the low spectral resolution of the data upon which these abundance analyses are based, the derived results should be considered indicative rather than definitive. The most credible results are for the low-FIP element iron, for which there are many bright emission lines that often dominate the spectrum.

Procyon (inactive F5 IV-V) star: Analysis of EUVE spectra of coronal emission lines show photospheric abundances.

Nearby solar-like stars: α Cen AB (G2 V + K1 V), ϵ Eri (K2 V), and ξ Boo A (G8 V) show a solar-like FIP bias. (e.g., Drake & Kashyap ((2001).

AB Dor (young K2 IV-V): Analysis of EUVE and ASCA data show both low-FIP and high-FIP metals depleted by factor of 2–3 relative to stellar photosphere. (Mewe et al (1996).

Capella (F9 III + G6 III): EUVE spectra show no evidence for a FIP bias either positive or negative.

II Peg (K2 IV + ?): Analysis of EUVE and ASCA data for this single-lines RS CVn-type system shows metal abundances about 0.3 solar photosphere, but [Fe/H] = 0.1 times solar photosphere (3 times smaller than stellar photosphere). During a flare the Fe abundance increases a factor of 3! (Mewe *et al.* (1997).

UX Ari (G5 V + K0 IV): Analysis of EUVE and ASCA data for this RS CVn-type system shows Fe, Mg, Si abundances 0.2–0.4 times solar photosphere, but during a flare the low-FIP and high-FIP abundances increase by a factor of 3. (Güdel *et al.* (1999).

σ^2 **CrB (F5 V + G0 V):** Analysis of EUVE and ASCA data for this RS CVn-type system show:

- Before the flare, the low-FIP and high-FIP abundances are about 1/4 that of the solar photosphere.
- During the flare rise, the abundances of the low-FIP elements (Mg, Si, Fe) jump a factor of 4.
- During the decay phase of the flare, the low-FIP abundances drop to quiescent values after about 1 day.

Despite the difficulty of infering accurate abundances from low resolution data, these initial results show a trend in which the inactive solar-like stars show the FIP bias seen in closed field regions in the solar corona, the most active stars (the RS CVn-type systems and AB Dor) show a reverse FIP bias in which the low FIP elements are enhanced relative to the solar photosphere, and the intermediate activity star Capella shows no FIP bias. In addition, during flares the low-FIP element abundances jump to near photospheric values and then decay to their pre-flare values as the flare subsides. Are these preliminary trends supported by the new high resolution data from Chandra and XMM-Newton? What happens to the high FIP ions?

3.4. Stellar coronal abundances obtained from analyses of Chandra and XMM-Newton spectra

The X-ray luminous ($\log L_X = 31.4$) RS CVn-type binary system HR1099, consisting of K1 IV and a G5 IV star in a 2.8 day orbit, has been observed by Chandra and XMM-Newton. Drake *et al.* (2001) analyzed the 136 ks spectrum of HR1099 obtained with the High Energy Transmission Grating (HETG) and ACIS-S detector on Chandra using the PINTofALE IDL software suite. They assumed an optically thin, coronal plasma in CIE to derive the emission measure distribution, EM(T), from fluxes of Fe XVI–XXV emission lines formed over the range $\log T = 6.5$–7.7). Abundances relative to iron, [X/Fe], can be derived from the ratio of observed/predicted fluxes for lines of element X using the EM(T) derived from ions of iron. Since Ar XVII, S XV, Mg XI, Si XIII, Ne IX–X, and O VIII are formed in the same temperature range as Fe XVI–XXV, abundances of these elements relative to iron are determined by this analysis. The continuum is due to bf and ff transitions of H, therefore the ratio of the predicted/observed continuum for the derived EM(T) leads to abundances relative to hydrogen. They derive the following logarithmic abundance ratios:

- [Fe/H] = –0.51 (0.3 ± 0.05 of solar abundance).
- [O/Fe] and [Mg/Fe] mildly enhanced.
- [Ne/Fe] = 0.99 ± 0.11 (FIP = 21.6 eV).
- [Ar/Fe] = 1.39 ± 0.15 (FIP = 15.8 eV).

Brinkman *et al.* (2001) also derived coronal abundances for HR1099 by analyzing a 570 ks spectrum of the 5–35 Å region with the Reflection Grating Spectrometer (RGS) on XMM-Newton. They also found an inverse FIP effect with [Fe/H] = 0.25 times that of the solar photosphere. They also found that the high FIP element neon abundance is 3.8 times that in the solar photosphere. It is interesting that a high abundance for Ne is seen in some solar flares and HR 1099 likely flares at some level all the time. One problem with their analysis is that C and N ions used to obtain the abundances of these elements are formed at temperatures outside of the range where EM(T) is determined from the observed ions of Fe. Also the stated error bars for the abundances of all of the elements are the same even though the abundances of some elements are based on only one line while others are based on many lines from different ionization stages. Nevertheless, the two coronal abundance analyses for HR 1099 are in good agreement with an inverse FIP bias for the low FIP elements and an overabundance of the high FIP elements Ne and Ar.

II Peg is another X-ray luminous ($\log L_X = 30.8$) RS CVn-type binary system, although in this case the companion to the observed K2 V-IV star in a 6.7

day orbit is unknown. Huenemoerder *et al.* (2001) analyzed a 45 ks observation with Chandra's HETG also assuming steady state CIE and optical thin X-ray emission lines. The observation includes both quiescent and flare times. The analysis technique is similar to that used for analyzing the HR 1099 data in which they compute the differential emission measure (DEM) from emission lines (mostly Fe) and the continuum. The DEM peaks at $\log T = 7.2$ for quiescent times and $\log T = 7.7$ during the flare. The abundances (outside of the flare) relative to solar photosphere are definitely inverse FIP. They find that Fe/H is 0.10 times that of the solar photosphere and Ne/H is 2.2 times that of the solar photosphere abundance.

The young (20–30 Myr) rapidly rotating (0.514 day rotational period) star AB Dor has now been observed by Chandra and XMM. This star is extremely active with X-ray luminosity ($\log L_X = 30.0$), close to the saturated limit ($L_X/L_{\rm bol} \approx 10^{-3}$) observed in the most active stars. Güdel *et al.* (2001) analyzed the XMM-Newton RGS spectrum of this star. He found that the emission measure has peaks at $\log T = 6.6$, 6.9, and 7.3. Therefore a three-temperature plasma is appropriate for the analysis. During a flare emission lines of Fe XXIV and a bright continuum emission appear, indicating the presence of a higher temperature plasma component. Before the flare the coronal abundances of AB Dor show the inverse FIP bias qualitatively similar to that seen in HR 1099 and II Peg. At the beginning of the flare the abundance of Fe increases by a factor of 3 to near solar photospheric abundance and then decreases as the flare decays.

Gagné *et al.* (in preparation) has analyzed a 60 ks Chandra HETG spectrum of AB Dor. They also find that the emission measure peaks at three temperatures ($\log T = 6.7$, 6.9, 7.5) based on the best fit to the emission lines and continuum. The emission lines show no wavelength shifts, showing that the coronal plasma is confined, presumably by magnetic fields, and that the line widths exceed instrumental + thermal width by 50 – 150 km/s. This is likely due to very rapid rotation ($vsini = 89.5$ km/s) and an extended corona (out to $> 3R_\star$). Relative to the solar photosphere, the abundances of the low FIP ions are low (e.g., Fe/H = 0.22 – 0.40) and the abundance of the highest FIP elements are somewhat high (e.g., Ne/H = 1.10 – 1.60).

Finally, we mention the Mewe *et al.* (2001) analysis of Capella's X-ray spectrum obtained with the Chandra's Low Energy Transmission Grating (LETG). Capella is a relatively inactive long period (104 days) RS CVn-type binary system (G1 III + G8 III). Although most of the UV emission is from the G1 III star, both stars contribute equally to the Fe XXI 1354 Å emission (Wood *et al.* 1998). Abundances derived using a 4-temperature EM(T) distribution show that Ne/Fe is close to solar, but the low FIP element ratios to iron (N/Fe, Mg/Fe, and Si/Fe) are about twice solar. Thus Capella appears to show neither a solar-like FIP bias nor an inverse FIP bias. Capella could be a transition case between the inactive Sun with a FIP bias and the active stars with their inverse FIP biases.

Table 1 summarizes the stellar coronal abundances obtained from Chandra and XMM-Newton. In this table the abundances relative to hydrogen are given in logarithmic units compared to the solar photosphere, $[X/H] = \log\,[X/H]_{corona} - \log\,[X/H]_{solarphoto}$. The horizontal line in the table separates the low FIP from the high FIP elements. I call attention to the excellent agreement for the coronal abundances for HR 1099 obtained by Chandra and XMM-Newton. For AB Dor the agreement is not quite as good with the coronal abundances obtained from the analysis of the HETG data about a factor of 1.5–2 larger than those obtained with XMM-Newton. Thus the data obtained by Chandra and XMM-Newton are self-consistent. All three active stars show an inverse FIP Bias and enhanced abundances of the high FIP element neon.

Table 1. Coronal Abundances for Active Stars Observed with Chandra or XMM-Newton

Element	FIP	Log (Abundances) relative to the solar photosphere				
		HR1099 (HETG)	HR 1099 (RGS)	AB Dor (RGS)	AB Dor (HETG)	II Peg (HETG)
[Ni/H]	7.63		–0.48	–0.33		
[Mg/H]	7.64	–0.11	–0.02	–0.57	–0.29	–0.40
[Fe/H]	7.87	–0.51	–0.60	–0.66	–0.43	–1.00
[Si/H]	8.15	–0.23			–0.18	–0.35
[S/H]	10.36	–0.34	–0.35		–0.18	–0.10
[O/H]	13.61	–0.03	0.00	–0.40	–0.15	+0.04
[N/H]	14.53		(+0.15)	–0.28	–0.10	(–0.22)
[Ar/H]	15.78	+0.88		–0.06		(0.00)
[Ne/H]	21.56	+0.48	+0.57	+0.00	+0.15	+0.34

3.5. Summary of stellar coronal abundances

4. A Proposed Explanation for the Observed Crazy Coronal Abundances

How can one explain the FIP bias seen in the Sun and inactive stars and the inverse FIP bias seen in the very active stars? Possible physical mechanisms that could produce the solar FIP bias include diffusion across magnetic field lines, gravitational settlement, thermal difffusion along a strong temperature gradient, ionization by hot electrons, and contamination by cometary dust. In their discussion of these mechanisms von Steiger & Geiss (1989) argue that ion-atom separation across magnetic field lines in the upper chromosphere is a far more plausible explanation. I agree with their arguments and extend them to the inverse FIP bias seen in the active stars. I illustrate the different atom-ion fractionation pictures with three cartoons that show the fundamental proccesses.

First, consider the solar FIP bias. As von Steiger & Geiss (1989) show, separation of low FIP from high FIP elements can only occur in the chromosphere where low FIP elements are mostly ionized and high FIP elements are mostly neutral. Thus the low FIP elements (e.g., Fe) are trapped in magnetic flux tubes and over time move out into the corona with the normal flow patterns that occur in magnetic flux tubes. On the other hand the high FIP elements (e.g., Ne) are mostly neutral and thus leak out of the magnetic flux tubes. Von Steiger & Geiss show that the thickness of the magnetic flux tubes must be very small ($\leq$ 10 km) for this atom-ion separation to work on a sensible time scale compared to ionization and recombination times. Since the fractional area of

Table 2. Summary of Solar and Stellar Coronal Abundances

Coronal Structure	Low-FIP [X/H]	Time variation of low-FIP	High-FIP [X/H]	Magnetic Field
		Solar Corona		
High speed SW	0.0		0.0	open
Slow speed SW	+0.6		0.0	mixed
New coronal plasma	0.0	increases	0.0	closed
Coronal loops	+0.6	$\Rightarrow$+1.7	0.0	closed
Coronal holes	0.0		0.0	open
Fe at $R > R_{\odot}$	+0.6	$\Rightarrow$0.0	0.0	closed
		Pre-Chandra/XMM Results		
Solar-like stars	+0.6		0.0	$f \leq 0.1$
AB Dor	–0.4		–0.4	large f
Capella	0.0		0.0	
II Peg	–0.5		0.0	large f
II Peg (flare)	0.0	decreases	0.0	
UX Ari	–0.5		0.0	large f
UX Ari (flare)	0.0	decreases	0.0	
σ^2 CrB	-0.6			large f
σ^2 CrB (flare)	0.0	decreases		
		Chandra/XMM Results		
HR 1099 (HETG)	–0.5		+0.7	large f
HR 1099 (RGS)	–0.6		+0.6	large f
AB Dor (HETG)	–0.5		+0.1	large f
AB Dor (RGS)	–0.6		0.0	large f
AB Dor (RGS)(flare)	0.0	decreases		
II Peg (HETG)	–1.0		+0.3	large f
Capella (HETG)	0.0		0.0	intermediate

the solar photosphere covered by strong magnetic fields is very small ($f \approx 0.01$), the high FIP elements are not trapped in the flux tubes and are not preferentially transported into the corona along the field lines. Since coronal densities in closed loop structures are high, the loops are bright in X-rays, enhancing the emission from the ionized low-FIP elements that are already overabundant in the flux tubes. Open field regions and the high speed solar wind do not show a FIP bias because in the chromosphere there are not any strong magnetic flux tubes where the atom-ion separation can occur. The solar FIP bias is illustrated schematically in Figure 1.

Second, consider the case of very active stars where strong magnetic fields fill nearly the whole stellar surface. Therefore, high-FIP neutrals leak out of one flux tube into another. Thus there is no mechanism for enhansing the coronal abundance of the low FIP elements relative to the high FIP elements, and the coronal abundances should be similar to the photospheric abundances. Since this is not what we observe, some other mechanism in the active stars is required to produce an inverse FIP bias with enhancement of the high FIP elements. Nobody has seriously considered this question, but I would like to propose a plausible mechanism that should be tested by realistic calculations. The X-ray emission from the active stars may be dominated by a few closed field structures where the heating is very large producing very large emission measures and X-ray flux. If so, then the X-ray and EUV flux shining down on the chromosphere near the flux tube foot points can photoionize the high FIP elements, trapping them in these flux tubes along with the ionized low FIP elements. The effect is to enhance the abundance of the high FIP elements in flux tubes from which most of the X-ray emission originates. This can lead to the appearance of enhanced coronal abundance of the high FIP elements. Whether it also leads to the appearance of decreased abundances of the low FIP elements is unclear. The scenario for active stars is illustrated in Figure 2.

Finally, we consider how flares may alter stellar coronal abundances. In one popular model for solar flares, magnetic field reconnection in the corona produces a beam of high energy electrons that follow the field lines down into the chromosphere and upper photosphere. Other models predict beams of high energy protons or shock waves following the field lines. In any case, the effect is to rapidly heat the cool gas leading to an explosion of highly ionized plasma travelling up the field lines at about 400 km/s for about 30 seconds. Evidence of this has been seen during solar flares in lines of helium-like Ca XIX and there are models that explain this phenomena. The important point is that a large amount of plasma with photspheric abundances can quickly enter a coronal loop that is the brightest source of X-rays from a stellar corona. Thus the deduced coronal abundances will be close to photospheric during the early phases of a flare and then gradually relax to the pre-flare abundances as the flaring loop fades. This is illustrated in Figure 3.

This work is done in collabortion with my colleagues at the University of Colorado including Tom Ayres, Alec Brown, Graham Harper, Greg Herczeg, Rachel Osten, Seth Redfield, Steve Skinner, and Brian Wood. I would also like to thank Marc Gagné at West Chester University for his work on the analysis of Chandra spectra of AB Dor. I would like to thank NASA for support of our work on the Chandra program.

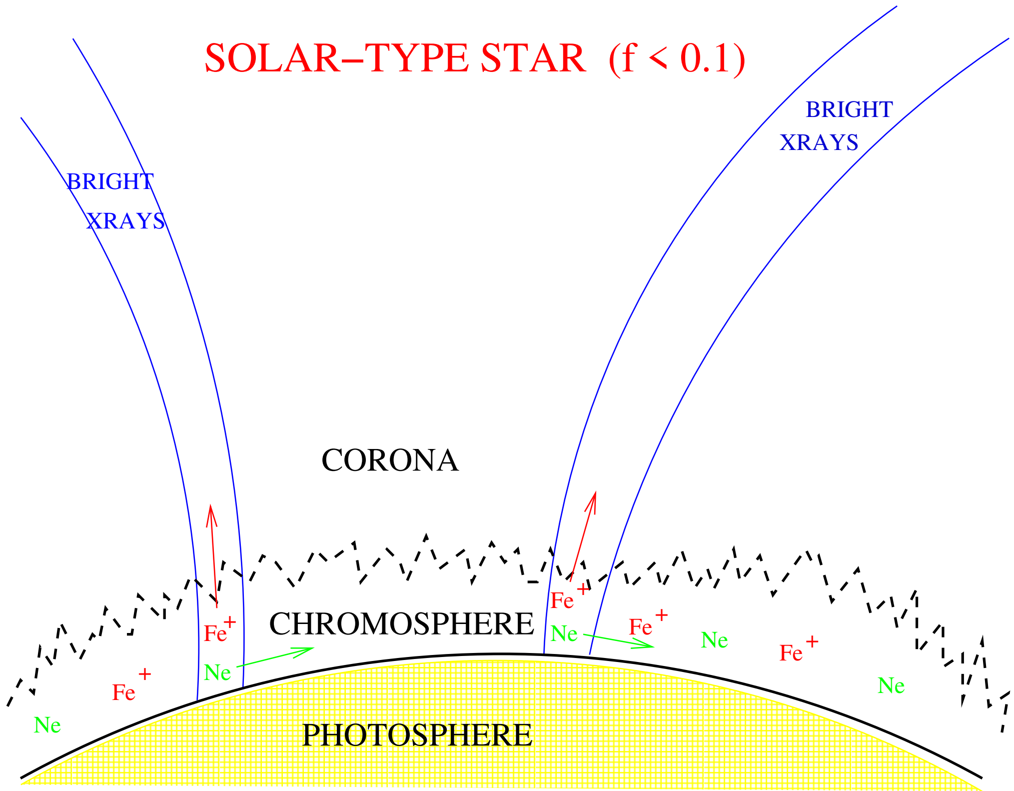

Figure 1. A schematic model for the atmospheres of the Sun and similar stars with magnetic fields covering on a small fraction of their photosphere. Two isolated magnetic flux tubes are shown which have high coronal densities and thus have bright X-ray emission. The low FIP elements are represented by Fe, which is almost completely ionized in the chromosphere. The high FIP elements, which are mostly neutral in the cromosphere, are represented by Ne. Since the Fe^{+} ions are trapped in the field lines, they will readily enter the corona given the pressure gradient and normal flow patters along the field lines. This is illustrated by the arrows attached to Fe^{+}. High FIP elements represented by Ne are neutral in the chromosphere are not trapped and thus do not participate in the flows along the filed lines.

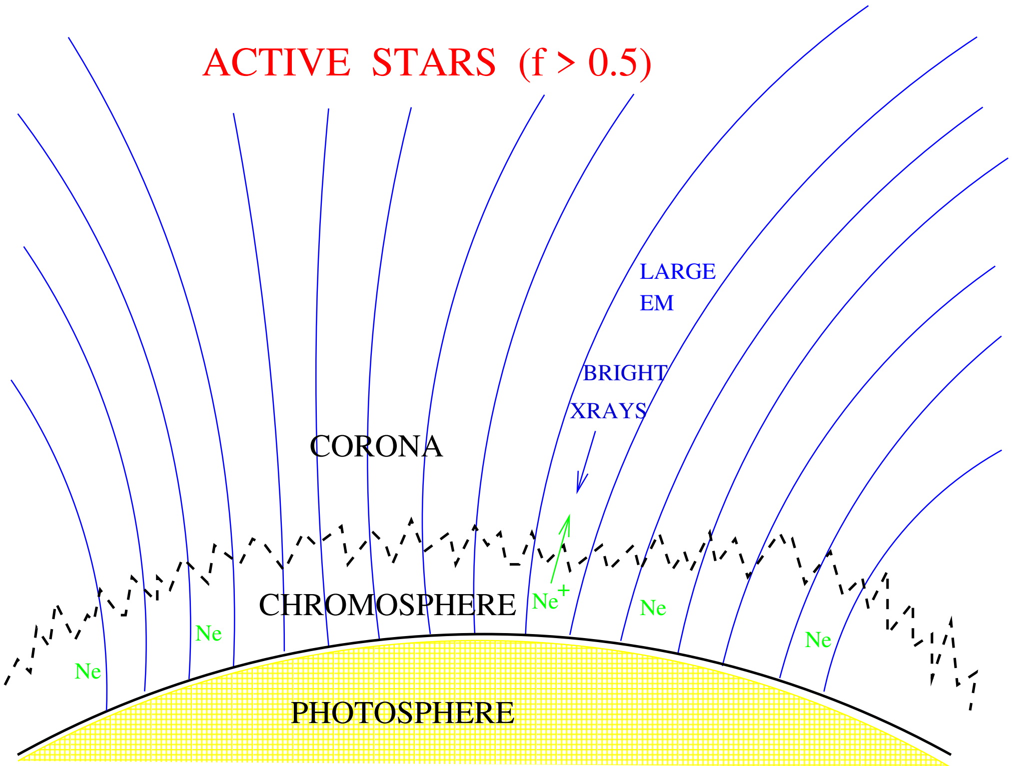

Figure 2. A schematic model for the atmospheres of active stars for which magnetic fields cover a very large fraction of their photospheres. For most of the stellar chromosphere the low FIP elements are ionized (e.g., Fe^+), while the high FIP elements are neutral (e.g., Ne). Most of the X-ray emission from the star, however, may come from the high density plasma in a small number of flux tubes. The bright X-rays and EUV radiation from these flux tubes can photoionize the high FIP elements are their footpoints, in which case Ne^+ and other high FIP ions will be trapped in these flux tubes, leading to enhanced abundances of these elements. Since these flux tubes dominate the total X-ray emission, the high FIP elements will appear to be overabundant in the corona.

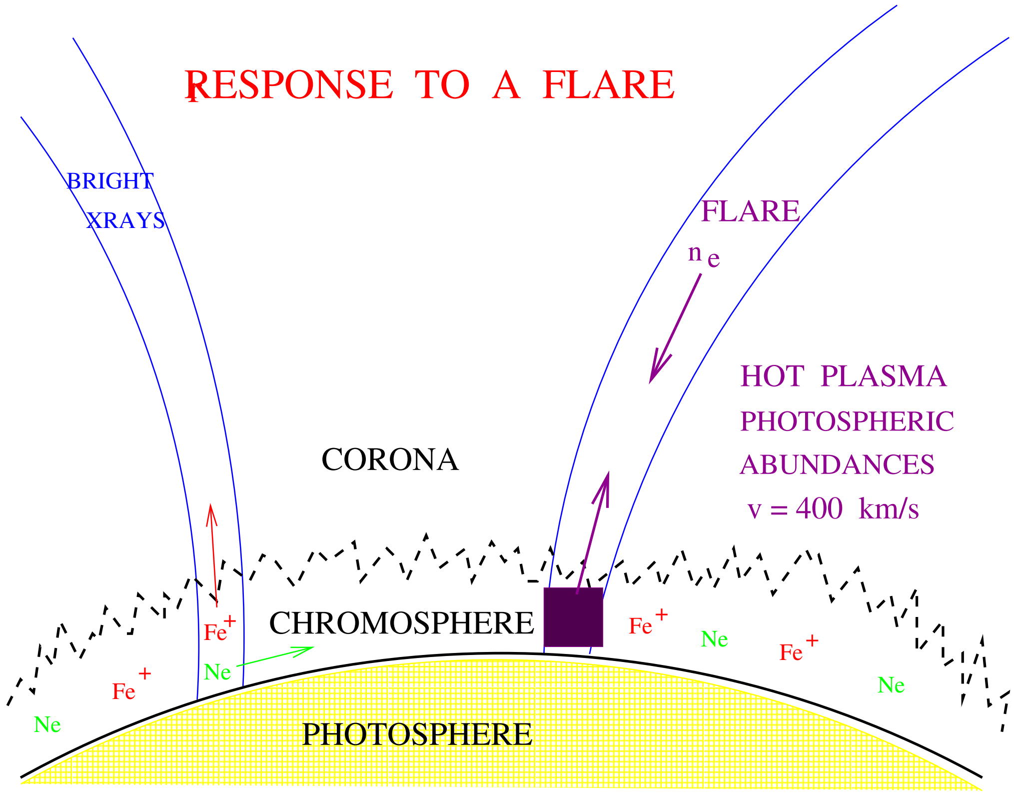

Figure 3. A schematic model for the response of a stellar atmosphere to a flare in the corona. The flare produces a beam of high energy electrons that travel down the field lines and rapidly heat the gas in the chromosphere and photosphere at the loop footpoints. The dark region of the chromosphere and upper photosphere indicates where the rapid heating occurs and the arrow shows the rapid expansion of highly ionized plasma with solar abundances into the flaring loop.

References

Brinkman, A.C., *et al.* 2001, A&A, 365, L324
Feldman & Laming 2000, Physica Scripta, 61, 222
Drake, J.J., & Kashyap, V. 2001, ApJ, 547, 428
Drake, J.J., *et al.* 2001, ApJL, 548, L81
Gagné *et al.* 2001, in preparation
Güdel, M., *et al.* 1999, ApJ, 511, 465
Güdel, M., *et al.* 2001, A&A, 365, L336
Huenemoerder, D.P., Canizares, C.R., & Schulz, N.S. 2001, astro-ph 0106007
Linsky, J.L., Wood, B.E., Brown, A., & Osten, R.A. 1998, ApJ, 492, 767
Mewe *et al.* 1996, A&A, 315, 170
Mewe *et al.* 1997, A&A, 320, 147
Mewe, R., *et al.* 2001, A&A, 368, 888
von Steiger, R. & Geiss, J. 1989, A&A, 225, 222
Branch, D. 1990 in Supernovae, ed. A. Petschek, (NY: Springer-Verlag), 30
Chevalier, R. & Fransson, C. 1994, ApJ, 420, 268
Chugai, N. 1997, Astron Repts, 41, 672
Filippenko, A. V. 1997, ARAA, 35, 309
Jha, S. et al. 1999, IAUC 7329
Kirshner, R. 1990, in Supernovae, ed. A. Petschek, (NY: Springer-Verlag), p59
Nomoto, K. et al. 1996, in Compact Stars in Binaries, ed. J. van Paradijs et al., (Dordrecht: Kluwer Academic Publ.), 119
Pooley, D., et al. 2001, ApJ, in press (astro-ph/0103196).
Sakai, S. et al. 2000, ApJ, 523, 540
Schlegel, Eric M. 2001, ApJ, in press
Schlegel, Eric M. 1995, Rep. Prog. Phys., 58, 1375
Schlegel, Eric M. 1990, MNRAS, 244, 269