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Crazy Coronal Abundances

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Abstract. Closed magnetic structures in the solar corona show enhanced abundances of elements with first ionization potentials (FIP) less than 10 eV. 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. We propose an explanation for both of these abundance anomalies.

1. Introduction

In their excellent review, Feldman & Laming (2000) showed that abundances in the solar corona depend on (1) the magnetic field structure, (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. FIP biases of 4–5 are typically seen in the slow-speed wind and in long-lived coronal loops, but only small FIP biases, if any, are seen in the fast-speed wind and in coronal holes.

ASCA and EUVE provided the first hints of anomalous stellar coronal abundances, although low spectral resolution prevented measurement of individual emission lines or the continuum needed to determine abundances relative to H. Nearby solar-like stars like α Cen AB (G2 V + K1 V), ϵ Eri (K2 V), and ξ Boo A (G8 V) show a solar-like FIP bias, whereas young stars like AB Dor and active RS CVn systems like II Peg, UX Ari, and σ^2 CrB show an inverse FIP bias with underabundant low-FIP elements. The intermediate activity star Capella shows no FIP bias. During flares in several active stars all abundances increased by a factor of 3. Are these preliminary trends supported by the new high resolution data from Chandra and XMM-Newton? What happens to the high FIP ions?

2. Stellar coronal abundances from Chandra and XMM-Newton

The X-ray luminous ($\log L_X = 31.4$) RS CVn-type binary system HR1099, with 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 HETG on Chandra. They assumed an optically thin,

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Table 1. Summary of Coronal Abundances for Active Stars

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

coronal plasma in collisional ionization equilibrium (CIE) to derive the emission measure distribution, EM(T), from Fe XVI–XXV lines formed at $\log T =$ 6.5–7.7). Their derived abundances relative to iron, [X/Fe], are summarized in Table 1. 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 found an inverse FIP effect with Fe/H = 0.25 times that of the solar photosphere. They found that the high FIP element neon abundance is 3.8 times that in the solar photosphere, which is also seen in some solar flares.

II Peg is a X-ray luminous ($\log L_X = 30.8$) RS CVn-type binary system. 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 abundances (outside of the flare) are definitely inverse FIP. They find that Fe/H is 0.10 times and Ne/H is 2.2 times that of the solar photosphere.

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 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 RGS spectrum of this star. Before a 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.* (2001) are analyzing a 60 ks Chandra HETG spectrum of AB Dor. The emission lines have the same Doppler shift as the star, 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^{-1}. This is likely due to very rapid rotation ($vsini = 89.5$ km s^{-1}) and an extended corona. Relative to the solar photosphere, the abundances of the low FIP ions are low and the abundance of the highest FIP elements are somewhat high. Table 1 summarizes the stellar coronal abundances relative to H, which 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. Note the excellent agreement for the coronal abundances for HR 1099 obtained by Chandra and XMM-Newton. All three stars show an inverse FIP bias and enhanced high FIP element Ne abundances.

Mewe *et al.* (2001) analyzed Capella's X-ray spectrum obtained with the Chandra's LETG. Capella is a relatively inactive long period (104 days) RS CVn-type binary system (G1 III + G8 III). Ne/Fe is close to solar abundance ratio, 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.

3. Crazy Coronal Abundances Partially Explained

How can one explain the FIP bias seen in the Sun and other inactive stars and the inverse FIP bias seen in the very active stars as summarized in Table 2? A wide variety of possible physical mechanisms have been proposed that may produce the solar FIP bias (cf. review by Hénoux 1998). These include diffusion across magnetic field lines, gravitational settlement, thermal diffusion along a strong temperature gradient, and contamination by cometary dust. Von Steiger & Geiss (1989) argue that ion-atom separation across magnetic field lines in the upper chromosphere is the most plausible explanation. We agree with their arguments and extend them to the inverse FIP bias seen in active stars.

First, we consider the solar FIP bias. As Geiss (1982) first demonstrated, the 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 up into the corona with the normal flow patterns. 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 (≤ 10 km) for this atom-ion separation to work on a sensible time scale. Since the fractional area of 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 therefore 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. Open field regions and the high speed solar wind do not show a FIP bias because in the chromosphere there are no strong magnetic flux tubes where the atom-ion separation can occur. The solar FIP bias is illustrated schematically in Figure 1.

Now consider very active stars where strong magnetic fields cover nearly the entire stellar surface. When high-FIP neutrals leak out of one flux tube they enter another. Thus atom-ion fractionation across field lines cannot enhance the coronal abundance of the low FIP elements, and the coronal abundances should be photospheric. Since this is not observed, some other mechanism is required to produce an inverse FIP bias with enhancement of the high FIP elements. Nobody has seriously considered this question, but we 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

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 wind	0.0		0.0	open
Slow speed wind	+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

where the heating is very large, producing very large emission measures and X-ray flux. In such superheated loops 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. This enhances the abundance of high FIP elements in those 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 (see Figure 2). Whether it also leads to the appearance of decreased abundances of the low FIP elements is unclear.

Finally, consider how flares may alter stellar coronal abundances. In one popular model (cf. Haisch, Strong, & Rodonò 1991), magnetic field reconnection in the corona produces a beam of high energy electrons that follow the field lines down into the lower atmosphere. Other models predict beams of high energy protons or shock waves. This rapidly heats the cool gas, leading to an explosion of highly ionized plasma travelling up the field lines at about 400 km s^{-1} for about 30 seconds as is seen during solar flares (Antonucci *et al.* 1993). Thus

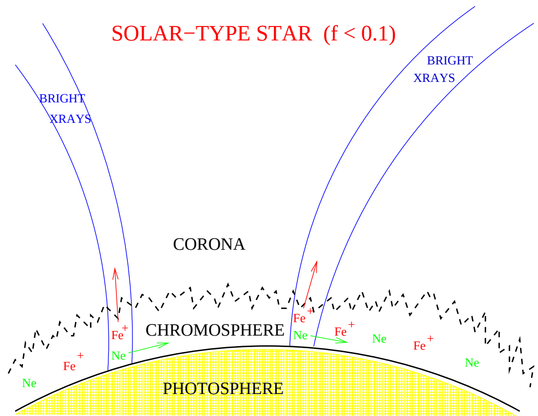

Figure 1. A schematic model for the atmospheres of the Sun and inactive stars with magnetic fields covering only a small fraction of their photospheres. Magnetic flux tubes have high coronal densities and thus bright X-ray emission. The low FIP elements are represented by Fe^+, and the high FIP elements 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 patterns. The high FIP elements are not trapped in the flows along the field lines.

a large amount of plasma with photospheric abundances enters a coronal loop that becomes the brightest source of X-rays. The deduced abundances for the entire corona will be close to their photospheric values early during a flare when the flaring loop dominates the total emission, and the abundances will relax to their pre-flare values as the flaring loop fades (see Figure 3).

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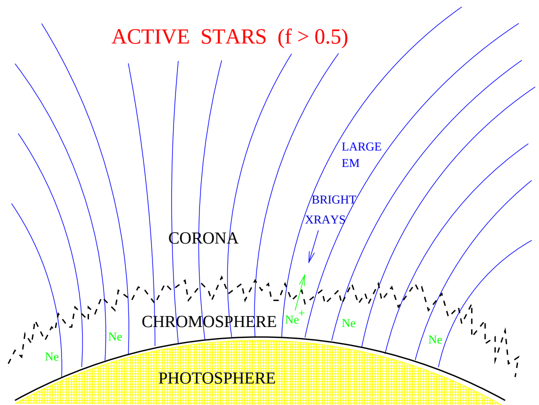

Figure 2. A schematic model for the atmospheres of active stars for which magnetic fields cover a very large fraction of their photospheres. Over most of the chromosphere the low FIP elements are ionized and the high FIP elements are neutral. If most of the X-ray emission from the star comes from a small number of flux tubes, the bright X-rays and EUV radiation from these flux tubes can photoionize the high FIP elements at their footpoints. Then 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.

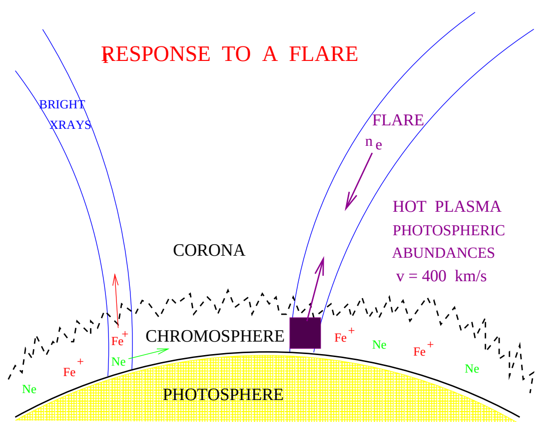

Figure 3. A schematic model for the response of a stellar atmosphere to a flare in the corona. The flare produces a beam of high energy electrons that travel down the field lines and rapidly heat the gas in the chromosphere and photosphere at the loop footpoints. The dark region of the chromosphere and upper photosphere indicates where the rapid heating occurs and the arrow shows the rapid expansion ($v \approx 400$ km s^{-1}) of highly ionized plasma with solar abundances.