Revealing the Spectral Type Dependence of the Coronal FIP Effect

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Abstract. The most widely studied coronal abundance anomaly is the so-called “FIP effect”, where the abundances of elements with low First Ionization Potential (FIP) are enhanced relative to the photosphere. Many studies in the past have reported a tendency for more active stars to have less of a FIP effect, and for particularly active stars to even exhibit an inverse FIP effect, where low FIP elements are depleted in the corona instead of enhanced. However, we find that this activity dependence is nonexistent among main sequence stars when the most active stars with $\log L_X > 29$ are excluded. Extremely active stars normally dominate coronal surveys since active stars are brighter and more easily observed in X-rays, but by avoiding such extremes and focusing solely on more normal stars we find a very different empirical view of the FIP effect, one in which FIP bias is dependent on spectral type instead of activity. This dependence indicates a strong connection between coronal abundance and basic photospheric characteristics.

1. Introducing the FIP Effect

For about a decade now, high quality X-ray spectra from the Chandra and XMM observatories have provided the high quality X-ray spectra necessary to study the coronal properties of cool stars. The only previous satellite to provide spectra of similar quality for these purposes was the \textit{Extreme Ultraviolet Explorer} (EUVE). Coronal abundances have proven to be of particular interest, as different stars have been found to possess different coronal abundance patterns. Though our understanding of the fractionation processes that produce these coronal abundance anomalies is limited at present, understanding these processes may prove to be helpful for understanding the heating mechanisms that create stellar coronae and coronal winds (Laming 2004, 2009).

In the solar corona and solar wind, abundances are generally found to be dependent on First Ionization Potential (FIP). Relative to the photosphere, elements with low FIP (Fe, Mg, Si, etc.) are generally found to have coronal abundances that are enhanced relative to elements with high FIP (C, N, O, Ne, etc.) (Feldman & Laming 2000). Evidence for this so-called “FIP effect” has been found for some stars of low to moderate activity (Laming et al. 1996; Drake et al. 1997; Laming & Drake 1999). However, in other cases, especially for more active stars, the FIP effect is generally either absent or sometimes an inverse FIP effect is observed, where high FIP elements have coronal abundances that are \textit{higher} relative to photospheric values (Audard et al. 2003; Huenemoerder et al. 2003; Sanz-Forcada et al. 2003).
Coronal abundances of various elements are divided by the Fe abundance and plotted versus first ionization potential (FIP) in eV for a selection of 7 moderately active G8-K5 dwarf stars. The abundance ratios are shown relative to assumed stellar photospheric ratios (log [X/Fe]∗). The dotted line crudely separates low-FIP and high-FIP elements, and colored dotted lines connect the abundances for each star within these two regimes. The high-FIP abundance levels suggest the following sequence of increasing FIP effect (i.e., abundances of low-FIP elements increase relative to high-FIP elements): 70 Oph B, ε Eri, ξ Boo B, 36 Oph A, 36 Oph B, ξ Boo A, 70 Oph A.

2. Emission Measure and Abundance Analysis

Measuring coronal abundances first requires measurements of emission line fluxes in coronal spectra, followed by an emission measure (EM) analysis to establish the temperature distribution of the X-ray emitting coronal material. Abundances for all elements represented in the set of available emission lines are derived as a byproduct of this analysis. The EM analysis can be performed in many different ways. Our preferred technique uses the PINToFALE software developed by Kashyap & Drake (2000), and the CHIANTI database of Dere et al. (1997) for line emissivities and other essential atomic information.

Using Chandra spectra and PINToFALE we have measured the coronal abundances of 7 moderately active G8-K5 main sequence stars (Wood & Linsky 2006, 2010). In Figure 1, the coronal abundances of Mg, Si, C, O, N, and Ne for these stars are divided by that of Fe, and plotted as a function of FIP. Photospheric abundance ratios (log [X/Fe]∗) are subtracted from the coronal ratios in order to assess the differences between the coronal and photospheric abundances. The stellar photospheric abundances are from Allende Prieto et al. (2004). For N and Ne, no stellar measurements are available, so we simply assume that these elements have the same abundance relative to the Sun as O.
The Allende Prieto et al. (2004) analysis involves a line-by-line comparison of solar and stellar photospheric absorption lines, so these stellar abundances are fundamentally relative values. For the purposes of Figure 1, we require absolute photospheric abundances relative to Fe, log [X/Fe]_*, so we have to combine the abundances from Allende Prieto et al. (2004) with some assumed solar abundances. We assume the reference solar abundances of Asplund et al. (2009), with the exception of Ne.

Neon is a particularly problematic element, as there are no photospheric neon lines to provide direct photospheric abundances, so for both the Sun and stars only coronal abundance measurements are available. In Figure 1, we assume that the average coronal Ne abundance of Drake & Testa (2005), measured from stars more active than the Sun, is actually more representative of the solar photosphere than the much lower solar coronal Ne abundance. This counterintuitive assumption amounts to assuming that Ne is not fractionated in the coronae of active stars but it is in the coronae of inactive stars like the Sun. If correct, this would mean that the active star coronal Ne abundance of Drake & Testa (2005) actually better represents the photospheric Ne abundance for both active and inactive stars. One justification for this is that the FIP effect modeling of Laming (2009) implies that Ne may be fractionated in inactive stars, but not in active stars. Empirically, the assumption of the stellar Ne abundance instead of the lower solar value makes Ne more consistent with the other high-FIP elements in Figure 1.

The high FIP data points in Figure 1 are connected with dotted lines. The lower the line, the stronger the FIP effect for that star. This suggests the following sequence of increasing FIP bias: 70 Oph B, ε Eri, ξ Boo B, 36 Oph A, 36 Oph B, ξ Boo A, 70 Oph A. This selection of stars exhibits a significant variation in degree of FIP effect despite the similarity of the stars in terms of spectral type and gross activity level.

3. The Spectral Type Dependence of Coronal Abundances

Comparisons of coronal abundances within various samples of stars have generally noted a tendency for the FIP effect to disappear or even reverse for more active stars (see §1). However, within the sample of moderately active G8-K5 main sequence stars discussed in §2, the variability in FIP effect exhibits no activity dependence at all (Wood & Linsky 2010). This is shown explicitly in Figure 2, which plots FIP bias versus X-ray luminosity. “FIP bias” is here quantified as the average high-FIP abundance relative to Fe, i.e., the average of the high-FIP dotted lines in Figure 1.

In Figure 2, the measurements from Wood & Linsky (2010) are supplemented with measurements of other moderately active stars, specifically the sample of early G stars from Telleschi et al. (2005) and the sample of M dwarfs from Liefke et al. (2008). In utilizing measurements from these other papers, we were careful to compute the “FIP bias” in the same manner that we have for our sample of stars, with the same assumptions about solar photospheric abundances as in Figure 1. For the Telleschi et al. (2005) sample, stellar photospheric abundances are available from Allende Prieto et al. (2004), which we take into account, but for the M dwarfs of Liefke et al. (2008) there are no such measurements and we have no recourse but to assume that the photospheres of these stars possess solar photospheric abundances. Finally, we have added a point for the Sun, using abundances listed in Feldman & Laming (2000).

Why does Figure 2 not show the activity dependence of FIP effect that has been seen in the past? The answer to this question lies in the lack of extremely active coronae in this particular sample of stars. We have deliberately excluded such stars by avoiding
Figure 2. We define “FIP Bias” as the log of the average abundance of high-FIP elements (i.e., C, N, O, and Ne) relative to Fe, such that values below 0 indicate a solar-like FIP effect and values above 0 indicate an inverse FIP effect. In effect, the FIP bias is the average of the high-FIP dotted lines in Figure 1 for that sample of stars from Wood et al. (2010). The FIP bias is here plotted versus X-ray luminosity for a sample of main sequence stars with log \( L_X < 29 \), demonstrating that the coronal abundances of such stars have no correlation with coronal activity.

ones with X-ray luminosities of log \( L_X > 29 \). From Figure 2, we conclude that the coronal abundances of main sequence stars exhibit no activity dependence at all for log \( L_X < 29 \). Considering that less than 1% of cool stars in the Galaxy will have log \( L_X > 29 \) (Güdel 2004), the activity dependence of the FIP-effect found in the past really only applies at the extremes of stellar activity. These are the stars that are most commonly observed by X-ray telescopes because they are so bright and easy to study. But our sample of more typical, ordinary stars provides a rather different picture of coronal abundance variability.

Instead of an activity dependence, the coronal abundances of our sample of stars exhibit instead a strong spectral type dependence, as shown in Figure 3. A spectral type dependence of FIP effect has been noted in the past by Güdel et al. (2007) for a sample of mostly T Tauri stars, but including some very young ZAMS stars as well. In Figure 4 we replicate their plot of Fe/Ne versus spectral type, but including also the ratios of our sample of stars from Figures 2-3. The spectral type dependence of Fe/Ne is similar for both samples, but the trend is shifted lower by about a factor of 2-3 for the very young, active sample of Güdel et al. (2007).

Figure 3 suggests to us that FIP bias is tied directly to basic photospheric properties of the star. There are two stars in the Telleschi et al. (2005) sample that are not included in Figure 3, because they have log \( L_X > 29 \) and therefore violate our policy of avoiding
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Figure 3. The “FIP Bias” defined in Figure 2 is here plotted versus spectral type for the same sample of stars, demonstrating a tight correlation of coronal abundance with spectral type for main sequence stars with \( \log L_X < 29 \).

extremes. These two stars are 47 Cas B and EK Dra, which both have rotation periods of under three days. This rapid rotation will probably exist for all main sequence stars with \( \log L_X > 29 \). If we plotted points for 47 Cas B and EK Dra in Figure 3, they would lie well above the relation defined by the other stars. Rather than proposing that magnetic activity is starting to operate somewhat differently at the activity level of 47 Cas B and EK Dra, thereby yielding a different FIP bias, we instead propose that the changes in FIP effect are ultimately driven by changes to fundamental stellar properties induced by the rapid stellar rotation.

Rotation as rapid as that possessed by 47 Cas B and EK Dra will presumably affect the atmospheric and convection zone properties of the star to some extent (e.g., Brown et al. 2008). Interacting binaries and evolved stars will also have substantial differences between their atmospheric properties and those of main sequence stars with identical spectral types. Figure 3 suggests to us that FIP bias is tied directly to basic stellar properties of the star, and not any simple coronal property like total X-ray flux or magnetic field strength. Within the theoretical paradigm of Laming (2004, 2009), in which Alfvén wave propagation through the chromosphere drives coronal abundance anomalies, it is possible to imagine that changes in basic stellar properties such as radius, surface gravity, or convective motions could affect these waves and thereby affect the coronal FIP bias. In short, we propose that the spectral type dependence of FIP bias in Figure 3 provides a more fundamental insight into the nature and cause of the FIP effect than the activity trends that have been explored in the past.
Figure 4. The coronal Fe/Ne ratio, relative to the canonical solar coronal ratio, is plotted versus spectral type for the sample of moderately active main sequence stars in Figures 2-3 (colored symbols), and also for the much younger and more active sample of T Tauri and ZAMS stars from Güdel et al. (2007). A spectral type dependence is apparent in both samples, but the trend is shifted downwards for the more active Güdel et al. (2007) stars.

References

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