Looking for the FIP Effect in EUV Spectra: Examining the Solar Case

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Systematic differences between elemental abundances in the corona and in the photosphere have been found in the Sun. The abundance anomalies are correlated with the first ionization potentials (FIP) of the elements. The overall pattern is that low-FIP elements are preferentially enhanced relative to high-FIP elements by about a factor of four; the transition occurs at about 10 eV. This phenomenon has been measured in the solar wind and solar energetic particle composition, and in EUV and X-ray spectra of the corona and flares. The FIP effect should eventually offer valuable clues into the process of heating, ionization and injection of material into coronal and flaring loops for the Sun and other stars. The situation for the Sun is remarkably complex: substantial abundance differences occur between different types of coronal structures, and variations occur over time in the same region and from flare to flare. Anomalies such as enhanced Ne/O ratios, distinctly at odds with the basic FIP pattern, have been reported for some flares. Are the high-FIP elements underabundant or the low-FIP elements overabundant with respect to hydrogen? This issue, which has a significant impact in physical interpretation of coronal spectra, is still a subject of controversy and an area of vigorous research.

1. Introduction

The ability of the *Extreme Ultraviolet Explorer* to carry out coronal spectroscopy has opened a number of opportunities to make progress in solar-stellar astrophysics, e.g., the determination of differential emission measures (Mewe et al. 1996), the measurement of coronal densities (Brickhouse et al. 1996; Schmitt, Haisch, & Drake 1994). These capabilities are beginning to constrain how solar outer atmospheric 0 may be scaled to various stellar conditions. However there is also an interesting new opportunity for EUV spectroscopy to contribute in the other direction by shedding light on a solar phenomenon which is not yet well understood: the First Ionization Potential (FIP) effect. Although originally discovered in cosmic rays, the FIP effect of interest here is an empirical relationship between abundance anomalies of heavy elements in highly ionized states in the solar corona and the ionization potentials of those elements in their neutral states (anomalous in comparison to the photospheric composition). This could yield valuable clues into the process of heating, ionization and injection of material into coronal and flaring loops, as well as into more open coronal field structures. Work by Drake, Laming, & Widing (1995a, 1996) and Drake et al. (1995) has begun to explore the evidence of a FIP effect in stellar coronae. Other similar investigations can be anticipated. A concise overview of the solar situation should be useful, given that the solar FIP literature could be characterized as not an easy read for the non-specialist.

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TABLE 1. Photospheric Abundance of Major Elements and Their First Ionization Potentials

Atomic Number	Element	log Phot. Abund.	FIP (eV)
1	H	12	13.6
2	He	10.99 ± 0.04	24.6
6	C	8.55 ± 0.05	11.3
7	N	7.97 ± 0.07	14.5
8	O	8.87 ± 0.07	13.6
10	Ne	8.09 ± 0.10	21.6
11	Na	6.32 ± 0.03	5.1
12	Mg	7.58 ± 0.02	7.6
13	Al	6.48 ± 0.02	6.0
14	Si	7.55 ± 0.02	8.1
16	S	7.24 ± 0.06	10.4
18	Ar	6.56 ± 0.10	15.8
20	Ca	6.35 ± 0.02	6.1
26	Fe	7.51 ± 0.01	7.9
28	Ni	6.25 ± 0.02	7.6

2. Brief History

One of the assumptions of classical stellar atmospheres theory has been that the composition does not spatially vary in the upper layers of a star. (Thermonuclear-process gradients of course exist in the interior.) The first evidence for solar abundance anomalies were acquired in UV and EUV spectrograms taken during a series of sounding rocket flights between March 1959 and May 1963. These were analyzed by Pottasch in several papers, but in particular we point to Pottasch (1964) which contains a listing (in his Table IV) of the 14 most abundant elements comparing their chromospheric and transition region abundances to the then-standard photospheric ones; this paper is also well-known as the origin of the differential emission measure technique. The elements Mg, Al and Si were found to be three times more abundant in the upper atmosphere than in the photosphere; Fe was about ten times more abundant. Further references to other papers from that era and into the 1970s may be found in the introductory discussion of the recent Drake et al. (1995) paper.

The key discovery was the recognition of a pattern not in solar atmospheric abundances, but in the galactic cosmic ray (GCR) composition. Cassé & Goret (1978) noted the correlation between GCR abundances and the FIP of heavy elements. Table 1 lists the abundances of the major elements along with the potentials, in eV, required to the neutral species (Anders & Grevesse 1989; Grevesse & Noels 1993). Elements with FIP's < 10 eV were found to be enhanced relative to those with higher FIP.

Cassé and Goret specifically considered the possibility that flare stars might be significant contributors to the supply of GCR's. The prevailing view had been that supernovae were the primary, if not exclusive, source of cosmic rays. In the case of the Sun, solar energetic particle (SEP) events certainly feed material into interplanetary space, most of which will ultimately flow out into the interstellar medium. Analysis of the solar data was a major undertaking in which Meyer (1985a) analyzed all existing spacecraft observations of SEP events and came to the conclusion that: "All data show the imprint of an ever-present basic composition pattern... that differs from the photospheric composition by a simple bias related to first ionization potential." The SEP study, accumulated solar wind data, and evidence for coronal gas abundance anomalies all of a similar sort led to the proposal by Meyer (1985b) that GCR's originate not in supernova ejecta, but in late-type stellar coronal material. The complexity of the data and the interpretation in this fashion is well illustrated in the Meyer (1985b) article: It is a rare example of an ApJ Supplement paper with its own table of contents preceding the abstract.

3. FIP Observations of the Solar Corona

In its simplest form, the observation is that in the solar corona, heavy elements with low-FIP (< 10 eV) appear preferentially enhanced by about a factor of four relative to high-FIP (> 10 eV) ones. Figure 1 illustrates this. It shows the abundances and their uncertainties for the photosphere (light box symbols) vs. the corona (heavy-lined dotted symbols). There is a clear segregation above 10 eV. The data have been normalized for Si. This highlights one of the major problems: It is not yet settled whether the high-FIP elements are underabundant in the corona with respect to hydrogen, as the figure makes things look, or whether the low-FIP elements are overabundant, which the Si-normalization would thus misrepresent.

Actually, this composition bias is not found uniformly over the surface of the Sun and the range can be much broader than a factor of four (e.g., Feldman 1992; Meyer 1993a,b). According to Athay (1994): "In the transition region and corona the abundance of low-FIP elements relative to their photospheric values may vary by a factor of 1 to 15 depending on the region's characteristics." EUV observations of many localized features on the surface of the Sun (mainly more or less compact, active region or flaring loops), first gave the impression that, the more open the magnetic field structure, the larger the FIP effect (Widing & Feldman 1989; Sheeley 1995). This apparent positive correlation between FIP effect and opening of the field lines seemed dramatically confirmed by the very large low-FIP element enhancements found in specific diffuse, open-field structures within coronal holes, the polar plumes, as well as in other diverging field structures: Mg/Ne ratios 10 to 20 times as large as in the photosphere were observed (whereas the relative abundances of Ca, Na and Mg in the plume are photospheric within a factor of 2) (Widing & Feldman 1989, 1992). However it now appears that a specific (diffusion) mechanism (by Marsch and collaborators; Laming, private communication) may account for the plume abundances; the large open coronal holes have a more photospheric composition.

Of special interest in the context of EUV astronomy are the *Skylab* observations analyzed by Widing & Feldman (1989) since they involve spectroheliograms in the 315–625 Å regime. In particular they examined the ratios of of Ne VI to Mg VI line emission around 400 Å (see also Sheeley 1995). The range of observed Mg/Ne ratios extended over a factor of 20.

On a larger scale, by contrast, the FIP effect is most prominent over predominantly closed-field regions, which can include both quiet Sun and active regions. In the large open-field regions, primarily coronal holes with their associated cooler, high-speed streams, the composition is closer to photospheric (Meyer 1993a,b; von Steiger et al. 1995). Such a trend is drawn from a variety of data ranging from EUV and X-ray spectroscopy to in-situ measurements of the solar wind and interplanetary energetic particles, from observation of stable coronal structures to flares and flare-associated events. In the stellar case, the only available measurement is spectroscopy, but this does not necessarily mean that the non-spectroscopic solar data are irrelevant, since the relative contributions to a single disk-integrated stellar coronal spectrum may involve a different mix of structures than for the Sun.

Regarding active region and flare observations, a closer investigation suggests that they might be understood in terms of emerging, new, photospheric, non-FIP-biased material,

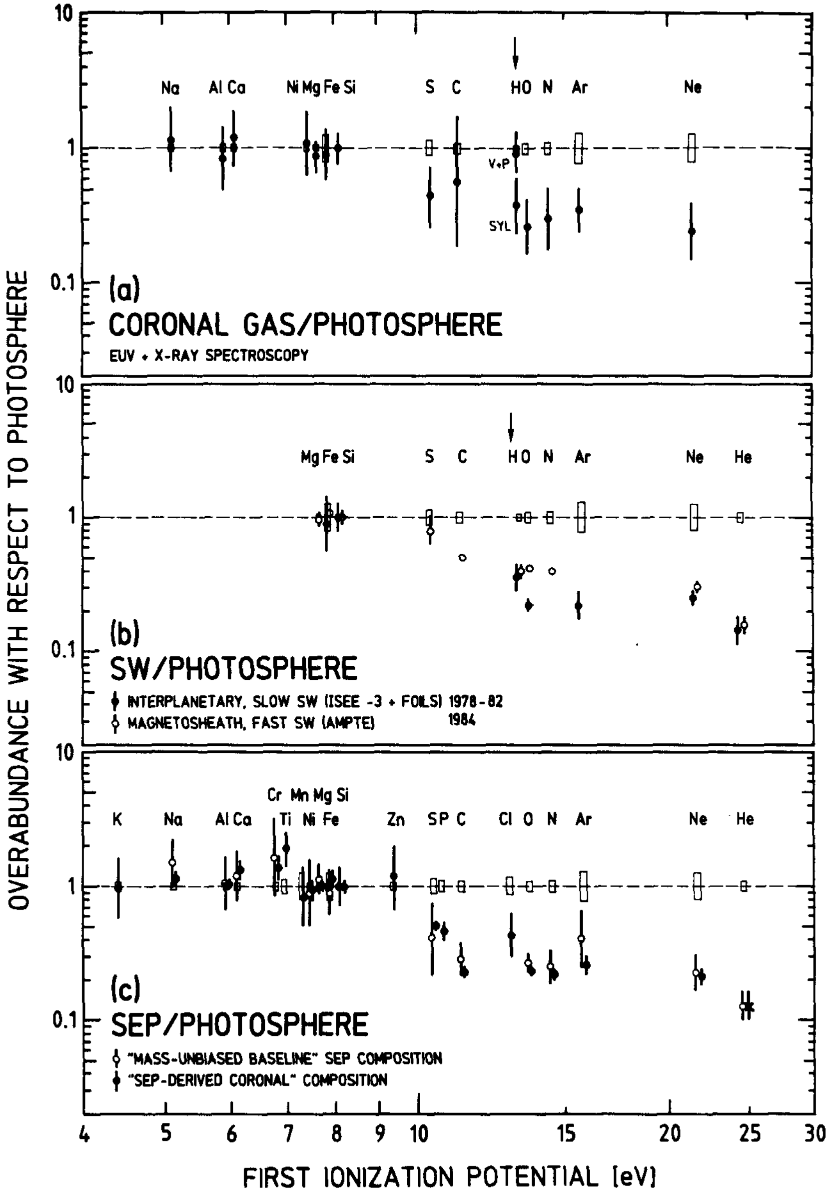

FIGURE 1. Change of elemental abundance as a function of first ionization potential between the photosphere (light box symbols) vs. the corona (heavy-lined dotted symbols) for coronal structures, the solar wind (SW) and solar energetic particles (SEP). Normalization has been forced for Si. The issue remains whether the high-FIP elements are underabundant or the low-FIP elements overabundant with respect to hydrogen. Evidence favors the latter; see Figure 2 (from Meyer 1993a).

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which progressively changes its composition as it rises into the corona, over time scales of a day. As the material expands, the scale size of the magnetic field grows accordingly. It now seems most likely that the magnetic field opening just accompanies the rise of the gas, but is not the cause for its change in composition. So, the correlation between composition and opening of the field within active regions and flares, while real, is probably irrelevant (Meyer 1993a,b; Sheeley 1995). As for the extreme contrast between the polar plume and the wider coronal hole FIP effects, it is not understood. Maybe, all this just tells us that the magnetic field geometry is not the most crucial parameter controlling the intensity of the FIP effect.

One way around such apparent contradictions is to bypass the poorly understood details and let the Sun provide its own average FIP effect by examining a full-disk spectrum. The photoelectric recording of the 50–300 Å solar spectrum obtained with a rocket on 1969 April 4 by Malinovsky & Heroux (1973) provides such data. Although no flares took place during the few minute exposure, solar activity was near a maximum: the sunspot number had peaked in November 1968, but the flare maximum was still a year away (see Table 1 of Haisch, Antunes, & Schmitt 1995). With ~ 0.25 Å resolution and this wavelength coverage, it is quite similar to *EUVE* stellar spectra. This stellar-like solar spectrum has been thoroughly reanalyzed using modern atomic data by Laming et al. (1995). Their conclusion is that the canonical factor of $\sim 3-4$ relative enhancement for low-FIP elements appears provided one uses lines formed at $T \geq 10^6$ K; whether or not the FIP effect disappears below that temperature is not well determined by this spectrum since the major transition region lines are at longer wavelengths. Nevertheless, such a break in abundance pattern would be consistent with the fact that the chromospheric network disappears in spectroheliograms originating at $\sim 10^6$ K. This leads to the suggestion that the discrepancies between FIP effect in various discrete solar features may be resolved by considering the height of formation of the observed feature since different types of structures dominate above vs. below 10^6 K. One must also keep in mind that this spectrum is after all a single snapshot of the Sun, which may, or may not, be representative of the Sun at different times or in different activity states.

Two further complexities regarding the solar FIP observations are that variations occur from flare to flare and even over the course of time for a given active region; and that there are non-negligible changes in the ratios of elements *within* either of the groups, e.g., an enhancement of the Ne/O ratio—both being high FIP elements—in some flares (Schmelz 1993) and active regions (Strong, Lemen, & Linford 1991). Sylwester, Lemen, & Mewe (1984) were the first to find spectroscopic evidence for the variation of the coronal Ca abundance in high-temperature solar flare plasmas. On the basis of over 200 spectra taken by the Solar Maximum Mission Flat Crystal Spectrometer, Strong, Lemen, & Linford (1991) found that the relative abundance of Fe/Ne can vary by as much as a factor of about 7 and could change on timescales of less than 1 h. Good reviews of the solar EUV and X-ray spectroscopic results can be found in Feldman (1992) and Saba (1995).

4. Absolute Calibration of the FIP Effect

The overall FIP pattern of relative enhancements is now well established but the key question is not resolved: Are the high-FIP elements underabundant or the low-FIP elements overabundant with respect to hydrogen? Absolute coronal abundances were first derived from flare observations involving both X-ray lines and the continuum by Veck & Parkinson (1981). In the absence of hydrogen lines, the continuum provides the necessary reference point. The following absolute abundances were reported: Si

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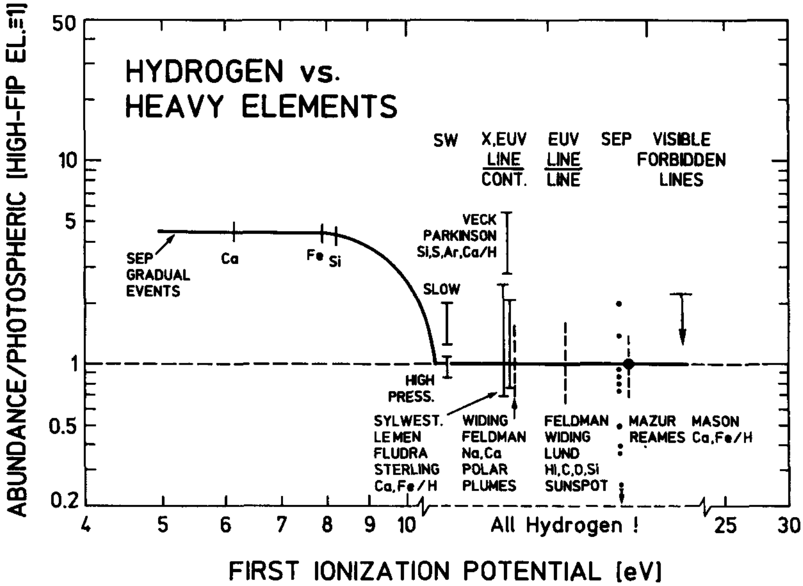

FIGURE 2. Compilation of data attempting to anchor the FIP pattern to hydrogen. The evidence favors the interpretation that low-FIP elements are genuinely overabundant (from Meyer 1993a).

($7.7^{+0.2}_{-0.3}$), Ca ($6.5^{+0.1}_{-0.2}$), S ($6.9^{+0.1}_{-0.3}$), and Ar ($6.4^{+0.2}_{-0.3}$). Comparison to Table 1 shows somewhat better agreement with the interpretation that the high-FIP elements S and Ar are underabundant than that the low-FIP elements Si and Ca are enhanced.

Since then, a wide variety of observations with entirely different techniques, ranging from EUV and X-ray spectroscopy to in-situ measurements of solar wind and energetic particles, have pointed to the opposite conclusion: they seem to converge on an absolute enhancement of the low-FIP elements; high-FIP elements appear to have roughly photospheric abundances relative to H, or to be only slightly depleted (Meyer 1993a,b; Mazur et al. 1993; Reames 1995; von Steiger et al. 1995). Note that such a behaviour, if confirmed, is not surprising, since H itself is a high-FIP element, which is neutral or ionized at about the same temperatures as other high-FIP elements.

Very recent X-ray studies, a line-to-continuum study by Fludra & Schmelz (1995), and a line-to-line study by Phillips et al. (1994, 1995) seem, however, to support the earlier analysis of Veck & Parkinson (1981) indicating a depletion of high-FIP elements. A discussion of some of the problems involved in all EUV and X-ray determinations of absolute abundances can be found in Saba (1995). As an illustration of how difficult this type of determination is, we examine here the procedure followed by Phillips et al. (1994) in analyzing X-ray flare data provided by the Bragg Crystal Spectrometer onboard the *Yohkoh* satellite. Two very different Fe lines lie close together in the X-ray spectrum and can thus be observed by the same instrument with good relative calibration: the Fe XXV resonance line at 1.850 Å, and the Fe Kα and Kβ fluorescence line at 1.936/1.940 and 1.757 Å respectively. The former is the usual type of collisionally excited line, in this case that of He-like Fe. The K lines involve inner shell transitions. If one of the innermost electrons (in the K-shell) is removed by photoionization, this vacancy will be quickly filled in by an electron from one of the next higher levels. The most common involves a transition from the L-shell, which would yield the Fe Kα lines, but transitions from the M-shell are also possible, and these give rise to the Kβ line. The K lines can be formed in more than one ionization stage of Fe, since the energy level structure for these innermost shells changes little as a function of the number of outermost filled shells. The strength of both the Fe XXV and the Fe K lines depend on nearly the same emission measure of hot ($\sim$ 20 MK) material during a flare: the former because that material is the source of the collisional excitation, the latter because irradiation from the material gives rise to the photoionization leading to fluorescence. The line ratio during a flare is thus a function of known atomic physics parameters, a common hot coronal emission measure, and the ratio of coronal [Fe/H] (see eqn. 7 of Phillips et al. 1994). Their conclusion was that the abundance of Fe, a low-FIP element, was not more than a factor of 2 larger in the corona than in the photosphere, again suggesting a high-FIP element underabundance (see Phillips et al. 1995 for the Kα line discussion).

So, while most data still converge towards an overabundance of low-FIP elements relative to hydrogen, the high-FIP element abundances being photospheric or only slightly depressed, the question of this absolute calibration cannot be considered entirely settled.

At this time it remains difficult to synthesize the diverse and contradictory solar observations into a single coherent picture. As variable as it appears to be, there is a FIP effect, and it is encouraging that the one attempt to analyze sun-as-a-star data (Laming, Drake, & Widing 1995) did succeed in observing this.

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