THE ELEMENTAL COMPOSITION OF THE SOLAR CORONA: ABBUNDANCE NORMALIZATION AND POSSIBLE ABBUNDANCE VARIABILITY

J.T. Schmelz
University of Memphis
Physics Department, Memphis, TN USA
Phone: 901-678-2419, jschmelz@memphis.edu

Abstract

Knowledge of the abundances of trace elements relative to hydrogen — absolute abundances — in solar coronal plasma is essential for the understanding of plasma conditions. Both spectroscopic and solar energetic particle data agree that the coronal-to-photospheric abundance ratios of elements with low First Ionization Potential (FIP < 10 eV) seem to be enhanced by about a factor of four relative to those with high FIP (> 11 eV). The observations, however, do not agree on the normalization of the trace elements with respect to hydrogen, a result which is problematic in both the spectroscopic and particle data analysis.

Two different empirical models of coronal abundance normalization have been suggested in the literature: (1) low-FIP elements may be enhanced by about a factor of four with respect to their photospheric values while high-FIP elements are the same in the corona and the photosphere; or (2) low-FIP elements may be the same in the corona and the photosphere while high-FIP elements are depleted by about a factor of four with respect to their photospheric values.

This abundance normalization not only affects spectroscopic data, but broadband data as well. We will use the example of the Yohkoh Soft X-ray Telescope (SXT) thin aluminum filter to show how important the abundances are in determining the plasma temperature and emission measure from the filter ratio method.

Finally, we need to know if abundances vary as a function of height in the solar atmosphere, or as a function of coronal feature, or as a function of time. The answer may very well be yes, but the burden of proof must be on the observer to convince the community that there is no other way to explain the results.

Introduction

The coronal composition was something we used to know. Just 15 years ago, we could find the absolute abundance of any element we wanted by simply looking it up in Astrophysical Quantities. But these abundances were determined primarily from photospheric observations. Now we know that the coronal composition is not only different from that of the photosphere, it is also a lot harder to determine. In so many cases of interest in the corona, essentially all of the hydrogen is ionized and there are no hydrogen spectral lines. So there is no easy way to normalize the trace elements to the main component of the plasma, that is, the hydrogen.

So what do we do in these cases? We have to be more clever. There are a few ways in which this cleverness has helped pin down the abundance normalization: (1) for in situ measurements of solar energetic particles; (2) for X-ray spectroscopy of flaring plasma where the intensity of a resonance line is compared with the intensity of nearby uncontaminated continuum.

Let us start with a list of things that we know (or at least think we know) about the coronal composition.

1. Coronal and photospheric abundances are different;
2. This difference is related to the element’s First Ionization Potential (FIP);
3. Low-FIP elements (metals with FIP < 10 eV) are enhanced with respect to high-FIP elements (CNO and Noble gasses with FIP > 11 eV) by about a factor of 4;
4. The FIP effect holds for closed coronal loops (observed with X-ray and EUV spectroscopy);
5. The FIP effect holds for Solar Energetic Particle events and the slow-speed solar wind (observed in situ);
6. The FIP effect is greatly diminished (or not present) in the fast-speed solar wind and in the corona of certain stars;
7. There are excellent examples of abundance variability published in the literature;
8. A mechanism (or mechanisms) operating in the chromosphere at T~10^4 K works to separate ions (low FIPs) from neutrals (high FIPs);
9. This mechanism helps and/or hinders the atom’s access to the corona.

Abundance Normalization

There are two standard models that attempt to explain the normalization of elemental abundances in the corona. They are both empirical. Figure 1a shows a plot of coronal/photospheric abundances on the y-axis and FIP on the x-axis. Model (1) is from Feldman et al. (1992) where low-FIP elements are enhanced by about a factor of four with respect to their photospheric values while high-FIP elements are the same in the corona and the photosphere; Model (2) is from Meyer (1985) where low-FIP elements are the same in the corona and the photosphere while high-FIP elements are depleted by about a factor of four with respect to their photospheric values.

Figure 1. Coronal/Photospheric Abundances vs. FIP

In the literature, we are all guilty of oversimplifying the FIP problem – where all low-FIP enhancements (no matter how small) are used as evidence for model (1) and all high FIP depletions (no matter how small) are used as evidence for model (2). An example is shown in Figure 1b. The data points are from a paper by Reames (1995) who analyzed 43 solar energetic particle events. It is obvious from this plot why these results are often quoted as evidence for model (1). But notice that Reames normalized with respect to oxygen, not hydrogen, and the position of hydrogen in this plot is not at one; rather, it is enhanced. In addition, the y-axis is on a log scale.

Figure 1c shows the same data, but two changes were made in the way they are displayed. The first change is that the y-axis is linear rather than log. The second change is that the data points have been normalized with respect to hydrogen. In this plot, it is no longer obvious that model (1) is correct. In fact, there is both low FIP enhancement as well as high FIP depletion.

In Figure 1d, more data have been added. The first two entries represent particle data analyzed by Reames (1995). The remainder of the data points are from X-ray spectroscopy observations of solar flares: Veck & Parkinson (1981) who analyzed OSO-8 data, Sterling et al. (1993) who analyzed P78-1 data, Sylwester et al. (1998) who analyzed SMM-BCS data and Fludra & Schmelz (1999) who analyzed Yohkoh-BCS data.

The data do not all agree, but they do agree a lot better than the competing models would have us believe. In fact, it is obvious from this plot that neither of these two empirical models does a good job of representing the data. The data tell us over and over that there is both low FIP enhancement as well as high FIP depletion – each by a factor of two.

Fludra & Schmelz (1999) calculated the weighted mean for all the low FIP data points in Figure 1, and found that they are enhanced, on average, by a factor of 2.10. They did the same for the high FIPs – they are depleted, on average, by a factor of 0.65. With those averages, they calculated the values for the “hybrid” abundances. These hybrid abundances are determined, by definition, by multiplying the photospheric values of all the low FIP elements like Fe by 2.10, all the high FIP elements like Ne by 0.65, and interpolating between these two for the intermediate FIP elements like S. The result is a set of abundances that seems to best represent the average coronal plasma.

In this empirical model, there is both low-FIP enhancement as well as high-FIP depletion, each by...
about a factor of two. The data clearly show that it is impossible for one model to satisfy all observations. It is also vital to account for the possibility of abundance variability when analyzing any data set. However, it is often useful to begin the analysis with an assumed set of coronal abundances. The hybrid abundances represent the best average values for all available data.

There are at least two major caveats to these results: (1) There are excellent examples of abundance variability in the literature. Fludra & Schmelz (1999) are not claiming that abundances do not vary. They are saying that if you need a set of abundances to begin your analysis, you should probably start with these, and understand how differences in the abundances will affect your result. (2) Two authors have published some relatively new abundance results based on the analysis of UV data taken of coronal streamers. Abundances of the trace elements can be normalized to hydrogen using the Lyman beta line. Results from SUMER data published by Feldman et al. 1998 show better agreement with model (1), while results from UVCS data published by Raymond et al. (1997) show better agreement with model (2). So just as we think we are making some headway on the plasma in closed coronal loops, we find that the streamer results do not agree at all. We can only hope that these results will begin to converge when the analysis of this type of data becomes more routine.

Implications for Broadband Data

Everyone knows how important the abundances are when analyzing spectral line data. It turns out that they may be just as important when analyzing broadband data. An example, adapted from a paper by Schmelz et al. (1999), is shown in Figure 2a. Here, the SXT response is plotted as a function of temperature for the different analysis filters. These curves are generated by folding a synthetic solar spectrum through the effective area of each filter. The standard SXT spectrum is generated using elemental abundances from Meyer (1985) and ion fractions from Arnaud & Rothenflug (1985). Figure 2b shows exactly the same thing except that the y-axis is plotted on a linear scale.

The dashed line in each plot is the response for the thin Al filter. Figures 2c and 2d show how the response for the thin Al filter changes when different assumptions about the elemental abundances and ion fractions are used to generate the synthetic solar spectrum. The dashed line in Figure 2c is the same as that in Figure 2b – the response for the thin Al filter generated with Meyer abundances (model 1) and Arnaud & Rothenflug (1985) ion fractions. The line above it is the response for the same model generated with Raymond & Arnaud (1992) ion fractions for iron. The line above that is the response generated with Feldman (1992) abundances (model 2) and Arnaud & Rothenflug (1985) ion fractions. The top line is the response generated with Feldman (1992) abundances and Raymond & Arnaud (1992) ion fractions for iron. It is obvious from this plot that the abundances and ion fractions chosen to compute the synthetic solar spectrum make a tremendous difference in the response functions.

In Figure 2d, these curves have been normalized to the

![Figure 2. SXT responses as a function of temperature.](image-url)
standard SXT response function. The dashed line is the 
standard thin Al response (Meyer abundances and 
Arnaud & Rothenflug ion fractions) divided by itself. 
The solid curve just above it shows the response 
function generated using Meyer abundances and Arnaud 
& Raymond ion fractions for iron divided by the 
standard; the next curve shows the response generated 
with Feldman abundances and Arnaud & Rothenflug 
ion fractions divided by the standard. The top line is the 
response generated with Feldman abundances and 
Arnaud & Raymond ion fractions for iron divided by 
the standard. The changes are a complex function of 
temperature. They also affect the different filters in 
different ways so the effects do not necessarily cancel 
out when a ratio of the observed data in two different 
filters is used to determine a temperature.

Elemental Abundance Variability

Figure 3 is from a paper by Schmelz et al. (1996). It 
shows part of the soft X-ray spectrum taken with the 
Flat Crystal Spectrometer on SMM for two quiescent 
active regions with the same temperature structure. 
The lines on the right are from Fe XVII and Fe XVIII 
transitions. Notice how similar the intensities are in 
panel 1 and panel 2. The three lines on the left are the 
neon triplet near 13.5 A. Notice how different the 
intensities are in the two panels. One obvious 

![Figure 3. Soft X-ray spectrum of two quiescent active regions taken by the Flat Crystal Spectrometer on Solar Maximum Mission.](image)

explanation for the differences was that the neon 
abundance was different in these two active regions, but 
the authors looked at many different problems that 
might mimic an abundance variation – errors with the 
atomic physics or the ionization fractions, line 
contamination, calibration uncertainties, episodic 
heating, optical depth, and multithermal plasma. None 
of these effects could explain the data.

This is a good recipe for anyone with an unusual or 
controversial result – abundance variations in different 
solar features, with height in the solar atmosphere, and 
with time. Assume that the result is wrong and convince 
yourself that it may be right by a process of elimination.

Conclusions

(1) Both particle data and spectroscopy data show that 
there is both low FIP enhancement and high FIP 
depletion of coronal abundances, each by about a factor 
of two. (2) The hybrid abundances do a much better job 
of representing the average (active region) coronal 
plasma than either of the two models currently in the 
literature. (3) There are well-documented examples of 
abundance variations in the literature. The burden 
of proof is on the observer to show that the results cannot 
be explained by another means (e.g., temperature 
variations, multithermal plasma, simplistic assumptions 
about the atomic physics). (4) Theoreticians need to 
 improve their models to explain both low-FIP 
enhancements as well as high-FIP depletions.

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