IMPLICATIONS OF CORONAL ABUNDANCE VARIATIONS

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Abstract

High resolution soft X-ray spectra acquired by the Flat Crystal Spectrometer on *Solar Maximum Mission* have yielded exciting new information on the composition of the dynamic corona above solar active regions. In the brightest parts of these regions, the relative abundances of O, Ne, Mg, and Fe are found to vary from photospheric composition values to (and beyond) the typical "coronal" values found for solar energetic particles. This abundance variability complicates data interpretation but may ultimately offer new clues to the processes which supply and heat the corona.

1. Introduction

One of the big surprises to come from observations by the *Solar Maximum Mission (SMM)* Flat Crystal Spectrometer (FCS) was the large variation in elemental abundances found in quiescent and post-flare active regions, both from one region to another and for a given region from day to day (Strong *et al.* 1991). This variation may reflect a range in boundary conditions for the processes which heat and supply mass to coronal loops, and the detailed information on the variation should help constrain models of these processes. Abundance variability also has a large impact on data analysis and interpretation, and implications for theoretical models of coronal loops and astrophysical plasmas.

2. Observations and Analysis

Details of the FCS instrument are provided by Acton *et al.* (1980). After the *SMM* repair in April 1984, the FCS acquired an extensive spectral data base which includes long spectral scans at a single spatial location in the X-ray cores of solar active regions. Ratios of lines from the FCS long spectral scans can be used to determine relative abundances for certain elements such as O, Ne, Mg, and Fe and to look for abundance anomalies and variability.

For many *but not all* active regions, various line ratios (involving O VIII at 18.97 Å, Ne IX at 13.45 Å, Mg XI at 9.17 Å, Si XIII at 6.65 Å, Fe XVII at 16.78 Å, and Fe XVIII at 13.24 Å) give consistent values of T_e when the line emissivity calculations of Mewe et al. (1985) are used, provided the "adopted coronal" abundances of Meyer (1985) are substituted for photospheric abundances. Although observations made with modest spatial resolution require a differential emission measure (DEM) description of flaring loops, with a distribution of plasma over a range of temperatures, X-ray emission from quiescent active region loops appears to be well described by a single temperature or a range of temperatures narrow compared with the FCS measurement uncertainty (Saba and Strong 1991). Where the assumption of an isothermal plasma is valid, it is possible to use an abundance-independent line ratio diagnostic, such as the ratio of Fe XVIII to Fe XVII lines, to characterize the temperature of the plasma, and then in parallel to examine flux ratios of lines from different elements which are invariant or which vary only slowly with temperature over the temperature regime of interest to obtain the relative abundances of the respective elements. An example of a temperature-independent, abundance-diagnostic ratio is the ratio of the Fe XVII line at 15.01 Å to the Ne IX line at 13.45 Å, which is predicted by Mewe *et al.* to be flat over a broad range of active region temperatures, from about 2 MK to 7 MK.

3. Results

At the brightest portions of quiescent and postflare active regions where the FCS spectra were scanned, FCS line flux ratios reveal large variations in relative abundances of several elements. When the emissivity calculations of Mewe *et al.* are used to convert line flux ratios to elemental abundance ratios, the ratios of Fe/Ne, Fe/O, Mg/Ne, and Mg/O are found to range at least from the photospheric values to the nominal "coronal" values found in solar energetic particles (SEPs), a factor of 4 or 5 higher. Current ideas on coronal composition suggest an elemental fractionation based on first ionization potential (FIP) of the element, so that low-FIP elements (such as Fe and Mg) are enhanced in the corona relative to high-FIP elements (such as O and Ne), as compared with the photospheric composition. Other abundance research has shown that the enhancement factor is not a constant but depends on the kind of structure observed (Widing and Feldman 1989, Feldman *et al.* 1991), and may vary by an order of magnitude. The FCS results, as well as results from the P78-1 SOLEX instrument (McKenzie and Feldman 1991) show that the enhancement factor also varies dramatically even within nonflaring active regions. There is as yet no clear pattern in the abundance variability, although correlations are being sought in the data. When the observed ratios have nonphotospheric values, from the FCS spectral data alone it is not possible to tell if the low-FIP elements are enhanced or the high-FIP elements are depleted (or both), or whether all the heavy elements are enhanced (with respect to hydrogen), but the low-FIP elements by a greater amount. This issue is important for normalizing emission measures and for physical models, but it is not possible to measure directly the absolute abundance of an element relative to hydrogen using FCS line-to-continuum measurements since the FCS continuum is faint and difficult to differentiate from background.

4. Discussion

Previously, we have discussed the details of the FCS abundance variability results to date, and the effects of the ionization balance calculations chosen and possible systematic effects from resonance scattering (Saba and Strong 1992, 1993). Here we concentrate on the impact of the observed abundance variability on data analysis and interpretation.

Effect on data analysis and interpretation. Knowledge of the composition of the emitting plasma is implicitly assumed in deriving temperature, emission measure ($\equiv \int {n_e}^2 dV$, where n_e is the electron density and dV is the elemental emission volume), and DEM from emission line spectra. *Even if different temperature lines from a single ion species are used*, if there is an abundance difference with height, it will be difficult to understand emission measure with height without an independent measure of the element abundance relative to hydrogen. Temperatures and emission measures derived from broadband filter data are also significantly affected by abundance variability when line emission dominates the spectrum. For example, Waljeski *et al.* (1994) estimate that iron lines contribute about 80% of the filtered spectrum observed by the AS&E rocket instrument for active regions with the "adopted coronal" abundances of Meyer (1985). Multilayer images are dramatically affected by abundance variability. If abundances vary significantly between different types of structures as it appears, then there is no one-to-one correspondence between observed intensity and the amount of emitting material across the disk. Hence relative amounts of emitting material in different features may be impossible to interpret without independent abundance information from line spectra.

Role in theoretical calculations. In addition to its effect on first-level data analysis, abundance variability can also have a major impact on the theoretical calculations used to glean physics from the derived physical parameters. Identifying the emission mechanism often relies on a comparison of the relative emission in different wavebands, so that an assumption of incorrect abundances can lead to an incorrect source model. What may be less obvious is the extent to which abundances affect such calculations as the radiative loss function. An incorrect assumption of abundances can lead to an inaccurate radiative cooling time and an incorrect assessment of whether continuous energy input is required. The radiative loss curve also predicts the stability of coronal structures at a given temperature. Cook *et al.* (1989) have demonstrated the major differences between the radiative loss curves for photospheric and "adopted coronal" abundances and the dominant role that iron plays in the radiative losses at coronal temperatures and in the structural stability of coronal loops at different temperatures.

Constraints on element selection mechanism(s). Coronal abundance variability is currently an area of active research. Many of the observational facts, such as when abundance anomalies occur, the maximum range of variation of particular elements for given structures, and the relevant temporal and spatial scales for variability, are still largely unknown. The FCS spectra provide an excellent data base for addressing these issues. The detailed results of the ongoing FCS analysis should provide useful constraints on possible mechanisms for abundance variability. A variety of mechanisms have been proposed to explain the systematic differences between average coronal and photospheric composition, based on the idea that some element differentiation process operates in a temperature regime near 10,000 K where low-FIP elements have become ionized and are thus subject to electromagnetic fields while high-FIP elements remain essentially neutral. But the simple, single step-function distribution proposed to explain SEP composition does not seem to apply to all spectroscopic measurements of coronal abundances. One of the important tasks remaining is to understand how the SEP abundance results and spectroscopic measurements of coronal abundances fit together.

New information on the dynamic corona. The existing results from the FCS and other instruments suggest that the element selection mechanism is intimately tied to the physical processes for supplying and heating coronal loops. For some impulsive events and compact structures, the spectroscopically measured abundances are close to photospheric values. In other cases low-FIP elements appear enhanced relative to high-FIP elements by factors whose magnitude depends on as yet unknown factors. Perhaps the element selection mechanism, operating on a diffusion timescale, works with different efficiency under different circumstances. In other cases, there might be competing mechanisms at work, such as photoionization by a bath of soft X-rays in certain flares which show an enhanced abundance of neon (a high-FIP element), which does not fit the FIP pattern at all (see Murphy *et al.* 1991, and Schmelz 1993).

Using language more often associated with flare dynamics, we speculate that some of the large range of abundance variability corresponds to whether the coronal loops are filled by processes analogous to "explosive chromospheric evaporation" (which would presumably yield more photospheric abundances) or "gentle evaporation" (which might allow the low-FIP/high-FIP element selection mechanism to operate more efficiently). Although many important observational details of the abundance variability must still be worked out, it is already clear that our new picture of the highly dynamic corona must be expanded to include highly variable abundances before the data themselves can be understood and subsequent realistic models can be devised. At that point, the measured abundances of trace elements may become a useful diagnostic of the physical conditions and processes which fill coronal loops (with plasma of a given composition).

5. Conclusions

Abundance measurements from the FCS and other instruments suggest that there are large variations in the abundances of some elements in the corona, perhaps an order of magnitude in some cases. This will have a large impact on derivations of electron temperature and emission measure from spectral emission lines, from broadband filter data such as those from SXT on *Yohkoh*, and from multilayer images. If in fact the abundance of iron in the corona varies by a factor of ten between structures and within certain kinds of regions, the implications are extremely important for the interpretation of multilayer images from instruments such as the EUV Imaging Telescope on SOHO, for calculations of radiative cooling times, and for the structural stability of coronal loops as a function of temperature.

At present, the observed abundance variability is primarily a major complication to data analysis and interpretation. However, once it is better understood, it may provide a brand new diagnostic tool for probing the physical conditions in lower layers of the solar atmosphere and may offer new clues to the mechanisms of coronal supply and heating.

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