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CORONAL ABUNDANCES AND THEIR VARIATION

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ABSTRACT

This contract supports the investigation of elemental abundances in the solar corona, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer on the *Solar Maximum Mission*. The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, and information on the extent and circumstances of their variability. This report is a summation of the data analysis and reporting activities which occurred during the period 15 April 1994 to 15 April 1995.

Subject terms: Solar corona, X-ray spectra, elemental abundances, abundance variability

CORONAL ABUNDANCES AND THEIR VARIATION

I. INTRODUCTION

This is an annual progress report for contract NASW-4814. It is being submitted six weeks before completion of the second year of the contract to permit timely evaluation of progress and, it is hoped, timely continuation of funding for the next year. It includes and supersedes material submitted in a semi-annual report in December 1994.

The contract supports an investigation of elemental abundances in the outer atmosphere of the Sun, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer (FCS) on the *Solar Maximum Mission (SMM)*, a NASA mission dedicated to solar observations from 1980 through 1989. The FCS instrument acquired an excellent data base for studying the relative amounts of oxygen, neon, magnesium, and iron in solar active regions in various states of evolution and activity. The project includes analysis of this data base to decouple the effects of temperature and abundance, to assess different theoretical calculations of spectral line intensities for use in the study, and to account for the possible effects of opacity due to resonance scattering of certain bright lines. The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, information on the extent of their variability, identification of possible correlations of variability with active region properties, and clarification of a possible association between abundance variability and active region dynamics.

II. BACKGROUND

Spectroscopic data from *SMM* and other spacecraft show that coronal abundances in closed coronal structures present a more complex story than the simple two-step distribution of abundances (of elements with high versus low First Ionization Potential (FIP)) relative to photospheric values, seen in the slow solar wind (SSW) and in Solar Energetic Particle (SEP) events. It is not entirely clear how to connect the abundances measured in closed and open structures, although some insights have been obtained recently, as observers from the different disciplines have interacted more.

In general the SSW and SEP values obtained for open structures involve large-scale spatial averages and long-duration temporal averages, while the spectroscopic measurements sample specific loop structures, including those which have recently been filled or heated. (In the case of the FCS, the measurements preferentially selected the brightest part of a given active region to maximize the counting statistics; in many cases the brightest loops are likely to have been the most recently heated, and the observed abundance variations may reflect the different conditions under which the loops were energized, or the speed with which they were filled with material in lower layers. The composition differences observed in the fast and slow solar wind, namely, the smaller low-FIP/high-FIP enhancement in the fast wind (von Steiger et al., 1995 Adv. Space Res., Vol. 15, No. 7, pp. 3-12) suggests that the element separation mechanism does in fact operate on a diffusion timescale as most models predict. Although SEPs are associated with energetic events, it now appears that the particles originate in ambient coronal material that overlies the loops involved in a flare, rather than the flare loops themselves, based on the fact that the effective temperature reflects active region rather than flare conditions (D. Reames, 1995 Adv. Space Res., Vol 15, No. 7, pp 41-51).

There is also disagreement between the spectroscopic and particle measurements of the normalization of abundances relative to hydrogen, and in fact some disagreement among the different spectroscopic measurements. Knowing the abundances relative to hydrogen is crucial for many aspects of solar spectral data interpretation, beginning with converting line intensities to emission measure (i.e., the amount of emitting material). An attempt to reconcile some of the different spectroscopic measurements was made in the invited review of coronal spectroscopic results given by the PI in Hamburg in July 1994 (Adv. Space Res., Vol 15, No. 7, pp. 13-22, 1995; see attached reprint).

Previous work by us (e.g., Strong et al. 1991, Saba & Strong 1993) and by others (e.g., McKenzie and Feldman 1992) has showed that ratios of low-FIP to high-FIP elements appear to vary at least about a factor of four, approximately from the photospheric values to the nominal coronal values defined by the SEP results. The precise upper and lower boundary values depend on the theoretical line emissivity calculations used for both the abundance line ratios and the temperature diagnostics. The question of the shortest observed timescale for variability hinges on the correctness of the line emissivity calculations as well, since the predicted emissivities are used to untangle changes in the abundance from evolution in the temperature. A key component in the predicted emissivity is the ionization fraction, i.e., how much of the element as a function of temperature is in the correct stage of ionization to emit the observed line; under typical "coronal conditions" of low density and local thermodynamic equilbrium, the ionization fraction is a factor which multiplies the effective probability of transition between the electron levels corresponding to the energy of the observed line.

III. CURRENT PROGRESS

During the reporting period, 15 April 1994 to 15 April 1995, progress has been made in the following areas:

(a) understanding better the uncertainties in disentangling the effects of abundance variations from temperature evolution or a multithermal temperature distribution, a key concern of many critics of abundance studies.

Although it is not yet possible to choose definitively the best ionization balance calculations using the FCS data alone, we have been able to show that the scatter in the abundance values is not consistent with simple temperature evolution alone, no matter what ionization balance calculation is chosen. We expect to make further progress in assessing some of the available ionization balance calculations as a result of the systematic fitting under way of additional lines in the FCS spectral database.

The additional lines fitted will also provide additional temperature diagnostic ratios, for cross-checking the mean temperature derived from Fe XVIII/Fe XVII ratios (and hence another way to assess the iron ion fractions). It will also make it possible to quantify the distribution in temperature and perform a more thorough check on possible effects of multithermal plasma. Although preliminary studies (Saba & Strong, Adv. Space Res. 13, No.9, 391; Waljeski et al. 1994, Ap. J., 429, 909-923) indicate that this is not a problem for the basic FCS active region abundance study, use of an isothermal approximation has been criticized as a major shortcoming of this and other abundance analyses.)

(b) quantifying the role of resonance scattering in the measured line intensities and the inferred abundances.

We have ruled out optical depth effects as a major source of apparent abundance variability. From our recent analysis, it now appears that the magnitude of resonance scattering in the FCS data is likely to be much smaller than inferred by Waljeski et al. Although in principle optical depth effects could be a severe problem, in practice, there is no real evidence that lines other than the problematic Fe XVII line at 15.01 Å is strongly affected. For example, the other bright Fe XVII resonance lines appear to be at their expected strengths within the uncertainties when counting statistics and relative uncertainties in theoretical calculations of the line emissivities (A. Bhatia, priv. comm) are taken into account. The systematic refitting of the FCS spectral database mentioned above will enable us to use Fe lines other than the line at 15.01 Å (which may be strongly affected by resonance scattering or which may be a more complicated line to model than accounted for by current calculations).

(c) assessing other spectroscopic measurements of abundance variability and of absolute elemental abundances (i.e., abundances normalized relative to hydrogen).

To provide context for the FCS abundance measurements, we have sought to understand some of the other abundance results in the literature. Some of the differences can be understood on the basis of selection effects or detector fields of view (see Saba & Strong, 1992 Proc. of the First SOHO Workshop, ESA SP-348, 347, and attached review article).

At the current time, it is not clear what the best answer on normalization is from spectroscopic measurements. Some of the key issues, such as possible contamination of the continuum in some line-to-continuum studies, are laid out in the review article attached. It is likely that progress will be made in the near future, but not by this investigation. Contrary to the report of Waljeski et al, and our own expectations of a year ago, it does not appear that resonance scattering is a viable tool for determining absolute abundances, at least not at the present time. Implementing this method requires modeling of the source geometry, and a good estimate of the filling factor (or, equivalently, an independent density measurement).

Although it is probably not possible to get a good estimate from the FCS data alone, it may be possible to combine X-ray/XUV data with radio and compare emission measures (e.g., from Yohkoh + SERTS + Owens Valley). It is not true, as previously thought by many in the community, that broad-band instruments are insensitive to abundance variability. (For example, for the Yohkoh SXT, the derived emission measure scales nearly linearly with the inverse of the assumed Fe:H abundance.) But combining the different temperature sensitivities of filter measurements and spectroscopic measurements may allow more leverage on the problem of unfolding temperature and abundance effects.

(d) detecting and exploring anomalous abundances in active regions.

In parallel with the continuing line-ratio analysis, we are undertaking a different approach to the abundance analysis which provides complementary information to, and verification of, the line-ratio method. This alternate method involves using the calculated emissivities for each line as a function of temperature to overlay the respective emission measure curves of the lines. As appropriate, effects of resonance scatter (determined by using an Fe XVII line ratio to obtain the opacity of the 15.01 Å line, and scaling the other lines accordingly) can be taken into account in adjusting the "source" line intensities as needed. One proceeds by assuming a set of relative abundances, which can be initially taken to be the "adopted coronal" values, for example (or the initial abundance guesses can be guided by the line ratio results). If the plasma is approximately isothermal (to within the FCS temperature resolution), as is likely to be the case for stable active region conditions, then the assumed relative abundances and any resonance scattering effects for the O VIII, Ne IX, and Mg XI lines can be iterated until the overlying curves for each line all intersect in a single location on the emission measure/temperature plot. Additional lines from the given elements can be used to deconvolve possible effects from the presence of multithermal plasma or to verify the validity of the isothermal approximation.

In a simpler form, this approach has been used successfully in a number of previous analyses, including the recent work of Waljeski *et al*, where the analysis included the emission measure curves of broadband data as well. The advantages of combining this method with the line-ratio analysis are (i) that it provides a result that is less sensitive to any specific temperature diagnostic and (ii) that it makes it easier to keep track of the joint relative abundances of the four elements O, Ne, Mg, and Fe, without having to explicitly divide out the temperature dependences. In turn, this will guide the deconvolution of temperature and abundance effects which is the goal of the line-ratio analysis. This combined approach can be exploited more vigorously when the final line fits are available for a larger subset of the FCS database. This dual approach will become even more important when the analysis is expanded to include long-duration events, in which a multithermal plasma distribution is expected.

IV. PUBLICATIONS AND PRESENTATIONS

During the reporting period, a paper to which Saba made extensive contributions appeared in the literature: *The Composition of a Coronal Active Region*, by K. Waljeski, D. Moses, K.P. Dere, J.L.R. Saba, K.T. Strong, D.F. Webb, and D.M. Zarro, Astrophysical Journal, 429, 909-923, July 1994.

An invited review on *Spectroscopic Measurements of Element Abundances in the Solar Corona: Variations on the FIP Theme* was given by Saba at the 30th Assembly of the Committee on Space Research (COSPAR), in Hamburg, Germany in July 1994, in Session E2.1 on *Element Abundance Variations in the Sun and the Heliosphere*, which Saba helped organize. The paper was refereed and published in Advances in Space Research, Vol 15, no. 7, pp 13-22. A reprint is attached.

A talk was given by Saba at the joint American Geophysical Union–American Astronomical Society/Solar Physics Division Meeting in Baltimore, Maryland, in May 1994 on *A*

Reexamination of the Impact of Resonance Scattering on FCS Active Region Abundance Measurements (abstract in EOS, Vol. 75, No. 16, p. 290, 1994).

Two abstracts reporting results of the FCS abundance analysis have been submitted to the upcoming meeting of the Solar Physics Division of the American Astronomical Society in Memphis, TN, in June: *Measurements of Active Abundances with the SMM Flat Crystal Spectrometer,* by Saba with collaborator K.T. Strong, and *Ne/O, Mg/O, and Fe/O Abundances Derived Spectroscopically for Coronal Plasma,* with J.T. Schmelz and T.R. Miller, a collaborating colleague and her student at Rhodes College. Copies of these abstracts are attached.

A paper reporting on results of the FCS abundance study, taking into account the effects of resonance scattering and comparing the use of different ionization balance calculations, is being prepared for submission to the Astrophysical Journal. A paper titled *Anomalous Coronal Neon Abundances in Quiescent Active Regions* is in preparation for submission to Astrophysical Journal Letters by J.T. Schmelz, J.L.R. Saba, D. Ghosh, and K.T. Strong.

Measurements of Active Region Abundances with the SMM Flat Crystal Spectrometer

J.L.R. Saba (LSAL & SDAC @ NASA/GSFC) and K.T. Strong (LSAL)

Soft X-ray spectra from the *Solar Maximum Mission* Flat Crystal Spectrometer (FCS) allow us to examine coronal composition in a substantial sample of active regions in quiescent and postflare states. We can look for departures from the standard coronal pattern found in solar energetic particles, in which elements with low First Ionization Potential (FIP) are enhanced with respect to high-FIP elements by a factor of three to four relative to their photospheric ratios, by studying the relative amounts of Ne (with FIP = 21.6 eV), O (13.6 eV), Fe (7.86 eV), and Mg (7.65 eV). In our FCS analysis to date, a variety of abundance-diagnostic line ratios have been plotted against a sensitive temperature diagnostic given by the ratio of Fe XVII and Fe XVIII resonance lines, with theoretical curves showing the predicted temperature behaviors overplotted for comparison with the data. Now we convert the line flux ratios explicitly to relative abundance ratios at a given temperature so that the joint behavior of Ne:O:Fe:Mg can be examined under a variety of coronal conditions. In particular, we seek to establish whether our results are consistent with the hypothesis that neon exhibits the most anomalous behavior of the four elements in the study. We compare the results for two cases in which resonance scattering is assumed to be (1) minimal and (2) significant for the most affected lines.

This work was supported by NASA contract NASW-4814 and the Lockheed Independent Research Program.

Ne/O, Mg/O, and Fe/O Abundances Derived Spectroscopically for Coronal Plasma

J.T. Schmelz, T.R. Miller (Rhodes College), J.L.R. Saba (Lockheed)

We analyze soft X-ray spectra from the Solar Maximum Mission Flat Crystal Spectrometer to derive Ne/O, Mg/O, and Fe/O abundance ratios. The analysis requires a temperature diagnostic; the ratio of Fe XVIII at 14.22Å to Fe XVII at 15.25Å was chosen since it is abundance-independent. Then, for example, to calculate the Ne/O abundance ratio, we use the Ne IX resonance line at 13.45Å and the O VIII line at 18.97Å. The measured fluxes and the calculated temperature are inserted into the following equation:

$$\frac{F_{Ne}}{F_O} = \frac{A_{Ne}\ G_{Ne}(T)}{A_O\ G_O(T)} = a_{Ne-O}\ \frac{G_{Ne}(T)}{G_O(T)}$$

where F is the flux measured at Earth in units of ergs s^{-1} cm^{-2}, A is the abundance *with respect to hydrogen* of the element producing the line, $G(T)$ is the emissivity function (a temperature dependent term depending on the excitation and ionization properties of the atom producing the line). The result is independent of A, and depends only on a, the abundance of one trace element with respect to the other. In addition, to calculate the other ratios, we use the Mg XI line at 9.17Å and the Fe XVII line at 15.25Å.

The results for each abundance ratio for the 34 different spectra analyzed are plotted in a histogram format and compared directly to the analysis done in recent years for Solar Energetic Particles.

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16. ABSTRACT
This contract supports the investigation of elemental abundances in the solar corona, principally through analysis of high-resolution soft X-ray spectra from the Flat Crystal Spectrometer on NASA's Solar Maximum Mission. The goals of the study are a characterization of the mean values of relative abundances of elements accessible in the FCS data, and information on the extent and circumstances of their variability. This report is a summation of the data analysis and reporting activities which occurred during the period of the contract, 15 April 1994 to 15 April 1995.

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