Coronal Abundances: What are They?

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1. Introduction

Carole Jordan. Discussion I is on the topic of element abundances in the coronae of late-type stars. We include the transition region and solar wind under the term "corona". The Panel decided to centre the discussion around the following questions:

1. Do differences exist between photospheric and coronal abundances?
2. How uncertain are the atomic data used?
3. What physical processes are causing any abundance differences?

The topic of coronal abundances was chosen because over the past twenty-five years, or so, there have been observations that suggest that coronal abundances differ from those in the photosphere, in a systematic way that depends on the first ionization potential (of the neutral atom), hence the term the FIP effect. The first indications came from solar wind composition measurements (see the contribution by Galvin, below). Later analyses of X-ray and extreme ultraviolet spectra (EUV) showed the same FIP effect (see the contribution by Doschek, below).

Elements with a FIP lower than about 10 eV are classed as low FIP, and those with a FIP higher than about 10 eV are classed as high FIP. Thus, of the abundant elements, Mg, Si, Ca, Fe and Ni are low FIP elements, and H, He, C, O, Ne, S and Ar are high FIP elements, although C and S lie near the boundary between the two types. Either the high FIP elements are depleted with respect to the low FIP elements, or the low FIP elements are enhanced with respect to the high FIP elements. Solar wind measurements suggest that the former is the case. The relative abundances appear to change between different solar structures, with some evidence that the FIP effect may be small in the "quiet" Sun below 10\textsuperscript{6} K (Laming, Drake & Widing 1995).

Analyses of emission lines in spectra of stellar coronae obtained with the Extreme Ultraviolet Explorer (EUV) have led to suggestions that the FIP effect is present to some degree in some, but not all cool stars (see contribution by Drake, below). Other analyses of EUVE spectra and the lower resolution spectra from ASCA, using emissivity codes to fit the lines and continuum, have led to the conclusion that some coronae have low abundances of iron, the so-called "metal

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abundances deficient" (MAD) syndrome. However, if the continuum level is overestimated, owing to the absence of numerous weak lines from the emissivity codes, then the line to continuum method will tend to produce an Fe abundance that is too low (some specific missing transitions are discussed in Jordan 1995).

These issues are discussed in more detail in the contributions that follow.

2. Solar Abundances

GeorgeDoschek. Determining solar abundances in the Sun's atmosphere close to its surface must rely on high resolution spectroscopy, mostly in the ultraviolet (UV), EUV, and X-ray wavelength regions. Success with any given spectroscopic technique, or plasma diagnostic, depends on having high quality (i.e., good statistics and well-resolved spectral lines) calibrated spectra, accurate atomic physics, and the validity of necessary assumptions about the state of the plasma under investigation. In the last few years a number of promising abundance diagnostics have been applied using high quality spectra, with the somewhat surprising result that abundances seem to vary in different regions of the solar atmosphere due to the FIP effect. Here I will not attempt to review all the methods used to determine abundances, but will instead discuss the evidence from what I consider the best available FIP diagnostic used so far, namely the intensity ratios of Ne vi (high FIP) and Mg vi (low FIP) lines that appear in the EUV close to 400 Å. I will close my presentation by mentioning some other work in the X-ray region, and give a few references for this work. A useful review of FIP abundance work in general was published by Feldman (1992).

Most of the results I shall discuss are from analyses of EUV solar images obtained from the Naval Research Laboratory's (NRL) slitless spectrograph on SKYLAB (S082-A). This instrument produced monochromatic images on film of spectral lines between about 170 and 600 Å, with high spatial (about 2 arcsec) and spectral (about 0.1 Å for small features) resolution. The first papers on the subject using these data were by Widing, Feldman, & Bhatia (1986) and Widing & Feldman (1989). Several other papers by the same authors followed (in the ApJ) and recently, Sheeley (1996) has also analyzed S082-A data. All the results that I shall mention are from these papers. More recently (see Mason, this Discussion), lines of Ne vi and Mg vi have been observed with the Coronal Diagnostic Spectrometer (CDS) on the Solar Oscillations and Heliospheric Observatory (SOHO), and appear to show the same type of intensity ratio variations as observed in the SKYLAB data.

The Ne vi/Mg vi diagnostic depends on the fact that, in ionization equilibrium, both the Ne vi and Mg vi lines are produced over about the same temperature region of the solar atmosphere. The temperature of maximum ion concentration for both ions is close to \(4.4 \times 10^5\) K, which occurs in the "upper" transition region of the atmosphere. If the ions are formed over exactly the same temperature region (i.e., they have contribution functions with identical shapes), then the ratios of line intensities are independent of atmospheric structure, and the differential emission measure distribution. In this case, the intensity ratios depend only on the atomic physics (ionization fractions, excitation rate coefficients) and the element abundances. The ratio of the abundances can
be written as a function of the intensity ratios and atomic factors, independent of the atmospheric structure. Note that only the ratio of the Ne and Mg element abundances is determined from this diagnostic, not the absolute abundances.

In practice, no two ions have precisely identical contribution functions, but the Ne\textsc{v} and Mg\textsc{v} contribution functions are extremely close in shape up to a temperature of $5 \times 10^5$ K, above which there are differences that increase with temperature. All the results that I discuss depend on the assumptions that the lines of Ne\textsc{v} and Mg\textsc{v} are formed at about the same temperature, and there is ionization equilibrium. However, there are some checks that can be made on these assumptions, and this was done in the papers mentioned above.

Ne\textsc{v} is a B-like ion that produces four lines near 400 Å due to transitions between the ground $2s^22p$ $^2P$ term and the $2s2p^2$ $^2P$ term. Mg\textsc{v} is N-like and produces three lines near 400 Å due to transitions between the ground $2s^22p^3$ $^4S$ term and the $2s2p^4$ $^4P$ term. Thus the ions are relatively “simple” from the point of view of collisional excitation rates, unlike the situation for ions such as Fe\textsc{x} and Fe\textsc{xi}, for example. Furthermore, the transitions are all "allowed" and therefore produce intense spectral lines that can be measured with good statistics. If the relative abundances of Ne and Mg are comparable, then so are the relative strengths of the Ne and Mg lines, and thus the errors in converting photographic density to intensity are similar for both ions. Also, it is easy to detect visually any variations in the relative intensities of the Ne and Mg lines. Since the upper levels of the transitions are not metastable the electron density does not influence the intensity ratios. Finally, the Ne and Mg lines overlap in wavelength and therefore errors in instrument calibration as a function of wavelength have a negligible effect on the Ne/Mg intensity ratios. It is these properties of the Ne/Mg diagnostic, coupled with the close temperature of formation of the ions in ionization equilibrium, that make the Ne\textsc{v}/Mg\textsc{v} ratios an ideal diagnostic of the FIP effect. For the reasons given above, it is difficult to explain any significant intensity variations in terms of other than abundance variations.

Widing & Feldman have reported Ne/Mg intensity variations of about an order of magnitude between different solar structures. Examples of these easy to see variations are shown in Figure 6 of Widing & Feldman (1992) and in Figures 4, 5, and 6 of Sheeley (1996). The Ne/Mg variations are such that the relative abundance of Ne/Mg is lowest in open field structures such as a polar plume (Widing & Feldman 1992) and largest in closed field structures such as a solar flare or prominence. In addition, Sheeley (1995) suggests that photospheric Ne/Mg ratios are associated with newly emerging flux regions. In open field regions, the Ne/Mg abundance ratio is found to be about 1/10 of the proposed photospheric value. (The photospheric abundance of Ne cannot be directly measured but is instead inferred from observations of H\textsc{ii} regions). In closed field regions the Ne/Mg ratio is close to the photospheric value, or is a factor of 2–3 less than photospheric. In interplume coronal hole regions, the abundance ratio is close to, or slightly less than, photospheric.

I have stressed the close proximity in temperature of formation of the Ne\textsc{v} and Mg\textsc{v} lines and implied that the above results strongly depend on this assumption. However, this is not strictly true. Widing & Feldman have carried out emission measure analyses using lines from several Ne and Mg ionization
stages (Ne III–VII, Mg V–VIII) and find that differential emission measure variations cannot explain their results. They also find similar results for other ions with closely matched contribution functions, e.g., Ne VII and Ca IX (low FIP). Perhaps the best supporting evidence for the assumption of ionization equilibrium is provided by the temperatures derived from the fall-off of intensities of a number of lines of EUV ions as a function of height in a polar plume. Fitting hydrostatic equilibrium temperatures to the intensity decreases gives temperatures that are quite close to the predicted ionization equilibrium temperatures (see Figures 2 and 3 of Widing & Feldman 1992).

In summary, the Ne VI/Mg VI abundance diagnostic, along with supporting data and similar results from other lines of EUV ions, strongly suggest abundance variations in the solar atmosphere according to the FIP. These variations are more complex than simply a single difference between photospheric abundances and transition region and coronal abundances. Instead, the relative abundances differ from region to region, and are definitely linked to the magnetic field topology, and perhaps also to the age of the magnetic structure. The total range of abundance variations is about an order of magnitude.

In this discussion I have purposely not attempted to determine whether the high FIP elements are enhanced or depleted in coronal structures, relative to the photosphere. However, I should mention that Feldman (1992) has argued that the evidence discussed above is more consistent with an enhancement of low FIP elements in the corona relative to the photosphere.

In closing, I would like to mention some other abundance diagnostics in the X-ray region, and give some references for interested readers. In the X-ray region high resolution spectra have been obtained mainly with un-collimated Bragg crystal spectrometers. Very high resolution spectra have been obtained with instruments flown on the DoD P78–1 spacecraft (SOLEX, SOLFLEX), the NASA Solar Maximum Mission (BCS, FCS), and the Japanese Hinotori mission. In the region between about 9 and 25 Å there are lines from low and high FIP elements which have fairly good overlap of their contribution functions. One good abundance diagnostic involves Fe XVII/Ne IX line intensity ratios with Fe XVIII/Fe XVII line ratios used as a temperature indicator (e.g., McKenzie & Feldman 1992; Strong, Lemen, & Linford 1991; Schmelz et al. 1996). Considerable abundance variations (of factors of 4–5) are also found from this ratio in active region spectra. Feldman (1992) argues that the low FIP iron abundance is enhanced relative to the Ne abundance in many active region structures. Figure 1 of Schmelz et al. (1996) shows an excellent example of the Ne/Fe X-ray spectra.

At shorter X-ray wavelengths there are a number of good abundance indicators, but the instrumentation on the above missions was not designed to carry out good abundance measurements, so these diagnostics remain relatively unexploited. However, attempts have been made to determine the Ar/Ca abundance ratio from Ar XVII and Ca XIX lines near 3.2 Å (e.g., Doschek, Feldman, & Seely 1985; Antonucci et al. 1987; Doschek & Seely 1990).

Work on absolute abundances in X-ray emitting events has been investigated by Veck & Parkinson (1981), Sylwester, Lemen, & Mewe (1984) and Sterling, Doschek, & Feldman (1993). Discussing the results of this work is be-
yond the scope of this presentation, which is limited to presenting evidence for abundance variations.

Discussion

H. E. Mason: I have a comment on the results from SOHO. The SOHO-CDS results of Young & Mason (1997) show an order of magnitude difference in N(Mg)/N(Ne) in regions 1 arcmin apart in an active region. One region seems to be a compact emerging flux region, the other a larger coronal loop.

K. Phillips: If you take abundance ratios from single line ratios, you are likely to have temperature effects. A particular case in point is the Mg vi/Ne vi ratio which you illustrated; the temperature dependence is quite pronounced at log $T_e \geq 6.0$. Given the form of the emission measure distribution, this is precisely where you expect to have the most emitting material.

G. Doschek: As explained above, the emission measure distribution was considered in much of the Ne vi/Mg vi work and cannot explain the large extent of the variations found.

C. Jordan: The Mg vi/Ne vi intensity ratio does depend on $N_e$. Although the metastable $2s2p^2 4P$ term in Ne vi does not have a significant population at $N_e \leq 10^{12}$ cm$^{-3}$, the variation of the population of the $2s^22p^3 2D$ and $2P$ levels in Mg vi leads to a variation in the ground state $4S$ population of a factor of 2.1 between $N_e = 10^8$ and $10^{11}$ cm$^{-3}$. Thus density variations can lead to changes in the Mg vi/Ne vi ratio of this magnitude. Examining intensity ratios in Ne vi and Mg vi that should not vary, shows that the observational uncertainties in the line ratios can be up to a factor of 1.9. However, these uncertainties together cannot account for a range of an order of magnitude.

P. Beiersdorfer: If one accepts that the FIP effect is true, then why? Ne vi (or any of the other highly charged ions you showed) do not care about the FIP, only neutral Ne i cares. So, doesn’t it seem a necessity that one must include non-equilibrium effects in the atomic modeling for interpreting the observed line intensities?

A. K. Dupree: Just because the equilibrium contribution function appears to be the same for two ions, they may be quite different if flows result in non-equilibrium conditions. This is especially important for transition region lines where any flow (down or up) can quickly reach different temperatures. A second point; a simple $g(T_e)$ approximation will not work when you are dealing with ions near the minimum in the emission measure distribution (EMD). Also, in stars there may be local peaks in the high temperature EMD. Using only the $g(T_e)$ function assumes that the EMD is constant with $T_e$.

G. Doschek: Yes, non-equilibrium effects might be important. However, because the Ne vi and Mg vi ions are formed so near to each other in temperature in ionization equilibrium, I suspect (from a simple calculation) that very large departures from equilibrium are required to make order of magnitude changes in the Ne vi/Mg vi line ratios, as are observed. However, this statement could be wrong and needs to be checked with a non-equilibrium model. Unfortunately,
there are few non-equilibrium models and any such model will of necessity depend on assumptions regarding the geometry and dynamics that are difficult to check.

3. Stellar Abundances

Jeremy Drake. In order to determine whether or not coronal and photospheric abundances differ, it is of course necessary to have some sort of measurement or estimate of both. The task is more difficult than in the solar case because of the larger uncertainties inherent in the stellar measurements of both of these. The topic as a whole is somewhat broad and I regret that the necessity of extreme brevity prevents explicit references to many important pieces of work. I add at the end one point concerning fractionation mechanisms for which there was not time in the discussion to raise.

3.1. Stellar Photospheric Abundances

The first point to emphasize in the stellar case is that all stars do not have solar photospheric abundances. In the case of the Sun, there is a distinct advantage in that the fundamental parameters that define a model atmosphere — effective temperature, surface gravity and the abundances of metals — are known with much greater precision than for the average star. In the solar photosphere many element abundances are known to better than 0.1 dex. Exceptions are the abundances of the noble gases He, Ne and Ar: these are uncertain or unknown in all late-type stars since they do not exhibit lines suitable for abundance analysis in photospheric spectra. Instead, their abundances can only be inferred from in situ measurements of the solar wind (which is compositionally fractionated relative to the photosphere! See, e.g., the other presentations in this session), or from local galactic estimates based on nebulae or early-type stars. The Sun is perhaps on average slightly metal-rich, by 0.1–0.2 dex or so, for its age if compared with similar stars in the same galactic neighborhood for which there exist high-quality photospheric measurements (e.g., see Edvardsson et al. 1993).

One major problem in studying stellar coronal abundances is that the stars of interest for their outer atmospheric activity (and EUV and X-ray brightness) — e.g., RS CVn’s, dMe’s, rapid rotators — have generally not been the targets of detailed photospheric abundance studies. Partly this is because of the difficulties of such studies: composite spectra, rotationally smeared-out lines; and for the M dwarfs, large uncertainties in stellar parameters, strong molecular blanketing and relatively uncertain atmospheric models. The effects of starspots and high levels of chromospheric activity on derived abundances are also not yet well understood. For these types of stars, the uncertainty of available abundances will depend on circumstances, but will be of order 0.2 dex or larger. For F–K dwarfs, and with good spectroscopic material, photospheric abundances can be determined to about 0.1 dex; for giants to about 0.15 or 0.2 dex. Unfortunately, often only the Fe abundance has been determined. The case of the RS CVn’s highlights the difficulties. The best available work for a large sample of stars is that of Randich and co-workers (e.g., Randich et al. 1994). The sample appears rather metal deficient ([Fe/H] ~ −0.5 is typical) for its average age; moreover, differences of factors of up to 3 were found between the two components of the
same binary systems — a situation very difficult to understand in terms of stellar evolution and more likely a result of difficulties in untangling composite spectra.

3.2. Coronal Abundances

Coronal abundances have been reviewed recently by Drake (S. A.) (1996), and Drake (1996). The observational material comprises the moderate resolution ($\lambda/\Delta\lambda \sim 300$) EUVE spectra in which individual spectral lines are resolved and low resolution ASCA CCD pulse height distributions in which some line complexes can be resolved. Some abundances based on ROSAT PSPC pulse height distributions have been published; I am skeptical that the very low resolution produces meaningful results. Recent results from the Beppo-SAX LECS are also beginning to appear — see Favata, elsewhere in this volume.

Atomic Data Issues The different regimes of spectral resolution, from the higher end in which individual lines can be resolved, to low resolution pulse height spectra, pose different atomic data problems. In the former, we are generally concerned with the accuracy of the excitation rates of the diagnostic lines; global plasma model fits to EUVE spectra and to lower resolution spectra, in which individual lines cannot be resolved, are also subject to problems of the completeness of existing plasma radiative loss models. In particular, transitions from $n = 2$ to $n = 5$ and higher levels have been neglected but are collectively probably responsible for a significant amount of flux (e.g., see Brickhouse, elsewhere in this volume).

Results: FIP? MAD? The very general result of coronal metallicity studies is that nearly all coronae appear significantly metal-poor relative to the solar photosphere (the “Coronal MAD Syndrome”). This general result does not appear immediately convincing when viewed in the light of possible inadequacies in the modeling techniques for low resolution ASCA spectra (2-T fits using incomplete radiative loss models), in addition to expectations of “cosmic” abundances in active stars, and that metal paucity runs opposite to the solar FIP effect in which low FIP metals appear enhanced. Nevertheless, as stressed in Section 3.1, the photospheres of many of the subject stars, and in particular, the RS CVn’s, appear metal poor by average factors of about 3 relative to the Sun. The coronal results for these stars in general appear to largely reflect the photospheric abundances! (I also point to the difficulty in obtaining, and the corresponding uncertainty in, the solar coronal metallicity: there is in fact no full-disk X-ray measure of the average solar coronal metallicity relative to H). There is also reasonable agreement between EUVE and ASCA results for some stars regarding global metallicity as represented by Fe/H (e.g., Drake & Kashyap, this volume). One notable exception is Capella, for which ASCA fits indicate significant metal paucity, whereas EUVE continua suggest [Fe/H]~ 0 (e.g., Drake 1996).

There is, however, a tendency in the low resolution domain for derived abundances to be too low as line flux is smeared into a pseudo-continuum. This is likely to be a problem for the cooler coronae ($\log T \leq 6.8$ or so; e.g., $\alpha$ Cen AB, $\epsilon$ Eri etc) for which a firm continuum detection is not generally possible. Note that missing line flux in a spectral model will also tend to lower abundances derived from a global model fit. One also has to be very careful in interpreting
the results of fits to ASCA spectra in which all the element abundances are allowed to vary independently. Such fits can produce complete nonsense; one notable example being the abundance of N which global model fitting often suggests is non-existent in stellar coronae! One has to be very careful as to what drives the model fits, and it must also be noted that the confidence intervals for such parameterized model fits bear no relation to the actual uncertainties in the derived parameters. The 90% confidence limits on ASCA abundances are often very small (often much less than 0.1 dex); I think the reality is that global metallicities are uncertain by up to factors of two as a result of relatively crude modeling and uncertainties in atomic data, calibration etc. Missing lines in radiative loss models in the EUV range can also lead to uncertainties larger than the statistics indicate for global model fits.

The strongest case for a MAD corona relative to its photosphere is that of AB Dor: its coronal composition appears deficient by a factor of 3 relative to its photosphere — a factor significantly larger than the likely errors in either measurement (e.g. Drake 1996). The best case for a FIP Effect is that of α Cen AB. Two stars that show very similar coronal spectra to α Cen AB are the Sun and Procyon. Analysis of the same lines in the EUV spectra of these three stars indicate FIP Effects in the Sun and α Cen AB but not in Procyon. The differential nature of this study presents a strong case for the similarity between the solar and α Cen AB coronal compositions, but a lack of compositional fractionation according to FIP in Procyon.

### 3.3. Fractionation Between Photosphere and Corona

Fractionation mechanisms are mentioned in more detail below by Antoinette Galvin (see also Drake 1996). The natural conceptual inertia is to assume that the very small mass of a corona sitting on top of the sun or star must have the same composition. However, I think the question can be equally posed in the opposite sense: in order for coronal and photospheric compositions to be the same, there must be sufficient mixing to counter natural processes (e.g., thermal diffusion, gravitational settling, Coulomb drag in the net mass flow into the solar wind, flows across magnetic field lines in partially neutral plasma) which will tend to compositionally fractionate the corona. Is there sufficient mixing between stellar photospheres and coronae to equalize their compositions? The preponderance of evidence for the Sun and stars suggests not. The details remain to be discovered.

### Discussion

**S. L. Skinner:** I show an ASCA spectrum of the weak-lined T Tauri star V773 Tau, during an intense X-ray flare. This is probably the best X-ray spectrum available to date for any T Tauri star, and it contains about $3 \times 10^4$ counts in the SIS0 detector. We find a very low abundance of Fe, about 0.26 of the solar value.

**J. L. Linsky:** I believe that the question of stellar coronal abundances should be re-examined with the higher resolution and quality spectra that will be possible from AXAF and XMM. I illustrate this with some viewgraphs comparing a 69 ks
spectrum of Capella, obtained with EUVE, and a simulation of a 60 ks spectrum to be obtained with the AXAF LETG.

J. J. Drake: Well, a statement of the obvious but well worth making to reinforce the need for higher quality observations to push down the uncertainties. I add that the exposure times required (several 10's of ks for AXAF grating spectra of the X-ray brightest stars) will seem long, but urge review panels to allocate sufficient exposure time to obtain well-exposed spectra. I refer back to the text of my talk regarding the uncertainties in the existing results. I hope that more realistic estimates of abundance uncertainties will be made in future papers; part of the skepticism of some toward existing results I think stems from an inattention to this in some publications.

A. Maggio: The instrument calibration is important in stellar abundance determinations. The molecular structure of filters and CCD detectors causes fine absorption features near absorption edges, which have only recently been revealed by precise synchrotron beam measurements. Approximations of the energy response near absorption edges, based on Hencke coefficients, in general over-predict the actual instrumental effective area. Systematic errors in element abundances may result when prominent emission lines fall near instrumental absorption edges, e.g., the N\textsuperscript{VI}, N\textsuperscript{VII} lines near the O edge (∼0.5 keV). This may explain the systematic low N abundances derived from the analysis of ASCA/SIS spectra.

J. J. Drake: In my opinion the N abundances derived from ASCA spectra are not realistic and this is one explanation. A possible way to get further clues to N abundances is to look at the relative differences between otherwise similar stellar spectra. The issue of optical constants is also a big problem for future high resolution X-ray spectra and is an important point. The effort of Dr. Maggio and colleagues at Palermo in these areas, and especially toward the calibration of AXAF, is extremely valuable. Theoretical calculations in the close-coupling approximation of optical constants for O and C have recently been completed by Dr. Brendan McLaughlin and the Belfast group. However, these are for isolated atoms and will not include the perturbations caused by valence interactions and lattice structure in the solid state which give rise to the additional edge structure. For other atoms present in X-ray instruments, good calculations are lacking and high resolution synchrotron data are the only answer.

R. A. Stern: I stress that, in the next era of X-ray observations we should examine stars with a wide range of activity levels, to flush out parameter space for theoretical models.

J. J. Drake: I agree this is vital. The existing database of ASCA and EUVE data should allow us to go some way in parameter space. In order to minimize uncertainties in ASCA modeling, the full emission measure distribution determined from EUVE spectra is extremely valuable. Unfortunately, (as you know), joint EUVE and ASCA analyses are difficult and time-consuming, and such a study requires a concerted effort. What is lacking are observations of a range of stars towards solar-like activity levels, since these have generally been too faint for existing instrumentation.
4. In-Situ Solar Abundance Measurements

**Toni Galvin.** In-situ minor ion \((Z > 2)\) measurements of solar wind, solar energetic particle (SEP) and co-rotating interaction region (CIR) energetic particles are sometimes used to infer coronal and even photospheric abundances when reliable spectroscopic measurements are not available (e.g., Ne and Ar: Grevesse & Anders 1989; Grevesse et al. 1992). Gradual event SEP composition measurements gave the first indication that variations in elemental abundances relative to photospheric values existed and appeared to be well organized according to the first ionization potential of the element. (Crawford et al. 1972; Hovestadt 1974).

It is assumed that little or no biasing in minor ion \((Z > 2)\) composition occurs in the solar wind acceleration process, and hence the solar wind minor ion relative abundances are expected to be a good proxy for coronal abundances. Acceleration and other biasing effects are expected in the SEP and CIR energetic ions. However, these populations have been useful in extending the number of elements available for study.

4.1. Solar Wind

There are three basic categories of solar wind flow type based on the coronal origin: coronal hole-associated solar wind; the interplanetary manifestation of coronal mass ejections (CMEs); and “slow” or “interstream” solar wind (which excludes slow solar wind of known coronal hole or CME origin). The coronal source of interstream solar wind is still a matter of debate, but two possibilities are coronal streamers (Feldman et al. 1981) or a coronal hole boundary phenomenon (Hundhausen 1977; Schwadron et al. 1997).

The in-ecliptic solar wind abundance ratios relative to oxygen compared to photospheric values are given in Figure 1 for the three types of solar wind flow types. The low-FIP elements in interstream and CME-related solar wind are approximately 2.5 to 5 times over-abundant compared to high-FIP elements. Elements such as S, C, P, which have FIP near 10 eV, show transitional enhancements. In-ecliptic coronal hole solar wind show a reduced or perhaps no FIP effect (less than a factor of 2). Preliminary results from Ulysses by Ipavich et al. (1995) indicate the possibility of a modest increase in the FIP effect for the polar coronal holes, compared to in-ecliptic values (more analysis is needed).

When average abundance ratios are quoted, it should be noted that some elements show systematic variations while others do not. As shown in Figure 4 of von Steiger & Geiss (1997), daily C/O averages exhibit little variation, and \(C/O = 0.7(\pm 0.1)\) within both the interstream and coronal hole solar wind. However, their Figure 5 (covering the same solar wind data set) indicates that while the coronal hole value of Mg/O = 0.08(±0.02) is relatively constant, the interstream Mg/O ratio shows a clear positive correlation with ionization temperature, systematically varying by over a factor of 2.

H has a FIP close to that of O. As with abundance ratios obtained relative to O, the solar wind abundances relative to protons depend upon solar wind flow type, an effect that has been most extensively reported for Fe. Ipavich et al. (1986) observe Fe/H density ratios of \(100 - 135 \times 10^{-6}\) for two CME-related events and \(32 - 33 \times 10^{-6}\) for two coronal hole periods. (Note the close
Figure 1. Interstream, CME-related, and coronal hole-associated solar wind abundances, normalized to O and photospheric values, as a function of FIP. Data are from in-ecliptic and near-ecliptic measurements.
agreement between the coronal hole values and the photospheric value given in Table 1). Mitchell et al. (1983) report CME-related Fe/H flux ratios enhanced by a factor of 4 to 5 over coronal hole solar wind. Bame et al. (1979) report an average CME-related Fe/H ratio that is 2 times higher than the average interstream value of $53 \times 10^{-6}$ given by Bame et al. (1975). Selected solar wind measurements relative to hydrogen are given in Table 1. There are special cases of CME-related solar wind in which solar wind He$^+$ has been observed. The singly charged helium should not exist in measurable amounts at coronal temperatures, and it has been suggested that the single charge state helium in the solar wind may be a marker for prominence material. The Fe/H ratio appears to be enhanced relative to photospheric values in these events. The He$^+$ results should be considered preliminary owing to the limited number of events and the present uncertainties in the data analysis.

### 4.2. Gradual Event Solar Energetic Particles

Gradual event SEPs are correlated with the occurrence of large solar flares, however the particles themselves are believed to be accelerated by the CME-driven coronal shock out of the plasma above the associated active region (e.g., Reames 1992). The acceleration process introduces a compositional bias dependent on the ion’s atomic mass to ionic charge ratio ($A/Q$), with a trend for species with larger $A/Q$ to be less abundant at higher energies. Mazur et al. (1993) have shown that the gradual event SEP composition approaches the original coronal composition at low SEP energies, and their abundance ratios show a FIP effect similar to that seen in interstream solar wind. The inclusion of SEP data greatly extends the number of resolved elements (see Figure 2), although new solar wind composition experiments on SOHO (CELIAS) and WIND (SMS) are beginning to match the energetic particle experiments for their species resolution.
4.3. Impulsive Flare Solar Particle Events

Particles accelerated at the site of impulsive solar flares show distinct compositions with unusual enhancements in elemental and isotopic abundances. These enhancements, especially the $^3$He enrichment, are likely caused by wave-particle resonant interactions during the acceleration process (e.g., Reames 1993). The heavy element ($Z > 2$) enrichments, which can exceed factors of 10 to 40, may also originate from an enriched heavy ion coronal environment at the acceleration site (Mason et al. 1994).

4.4. Co-Rotating Interaction Region Energetic Particles

A moderate FIP effect (a factor of 2.5) is observed in energetic particles associated with co-rotating interaction regions. CIRs result from the overtaking of a slow solar wind by the fast solar wind from coronal holes. Forward and reverse shock pairs may form, bounding the CIR, usually beyond 1 AU. Particle acceleration is believed to occur at the stronger reverse shock, and hence the primary source population for the energetic particles has been believed to be the fast (coronal hole) solar wind (e.g., Reames et al. 1991). As such, the CIR energetic particle population has been considered a proxy measurement for coronal hole solar wind. However, Mason et al. (1997) observe CIR abundances that appear to be an average of the expected interstream and coronal hole values. They also note that the C/O and Ne/O ratios increase as a function of increasing solar wind speed and suggest that other interplanetary particle populations may be contributing sources. It is now known that interstellar and local pickup ions (e.g., H$^+$, He$^+$, O$^+$, C$^+$), which have speeds extending to twice the solar wind speed, are readily accelerated at interplanetary shocks. The most abundant of the pickup ions at 1 AU is interstellar He$^+$, and recent observations by WIND (SMS) and SOHO (CELIAS) indicate this source population contributes between 10% to 50% of the helium abundance observed in the CIR energetic particles near earth during the solar minimum conditions of 1995–1996 (S. Chotoo and M. Hilchenbach, private communication, 1997). While the CIR energetic ions form a good supplementary measurement, the previous assumption that they represent a simple sample of coronal hole solar wind requires modification.

Discussion

C. Jordan: Your review is very valuable for those more familiar with spectroscopic analyses.

5. Atomic Data Issues

John Raymond. The derivation of coronal abundances depends upon measured emission line intensities and theoretical predictions for the emissivities. Uncertainties in the measured intensities include radiometric calibration errors and any corrections for interstellar absorption (dust, interstellar absorption lines, or photoelectric absorption). The measurement uncertainties can often be minimized by choosing lines at nearby wavelengths, but that may limit the analysis to the abundance ratios of a few pairs of elements.
Table 1. Solar wind density ratios relative to hydrogen.

<table>
<thead>
<tr>
<th>Solar Wind Flow Type</th>
<th>O/H $\times 10^{-4}$</th>
<th>Si/H $\times 10^{-6}$</th>
<th>Fe/H $\times 10^{-6}$</th>
<th>Fe/He $\times 10^{-3}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermittent range</td>
<td>1.9–8.4</td>
<td>28–117</td>
<td>14–139</td>
<td>0.5–6.9</td>
<td>Bame et al. (1975)</td>
</tr>
<tr>
<td>(average ±factor 2)</td>
<td>(5.2)</td>
<td>(75)</td>
<td>(53)</td>
<td>(1.9)</td>
<td></td>
</tr>
<tr>
<td>CME-related (average)</td>
<td>3.5–10</td>
<td>58–121</td>
<td>0.6–1.3</td>
<td>Bame et al. (1979)</td>
<td></td>
</tr>
<tr>
<td>(average)</td>
<td>(6.0)</td>
<td>(91)</td>
<td>(0.8)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>He$^+$ events</td>
<td>6.9–17</td>
<td>140–350(?)</td>
<td>2.1–4(?)</td>
<td>Zwickl et al. (1982)</td>
<td></td>
</tr>
<tr>
<td>(average)</td>
<td>170</td>
<td>150±50(?)</td>
<td></td>
<td>Ipavich et al. (1986)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Preliminary</td>
<td></td>
<td>Preliminary</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Result</td>
<td></td>
<td>Result</td>
<td></td>
</tr>
<tr>
<td>Coronal Hole (average)</td>
<td>32–33</td>
<td>0.8</td>
<td>Ipavich et al. (1986)</td>
<td>Galvin et al. (1987)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(32 ± 6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosphere</td>
<td>7.4 ± 1.3</td>
<td>35 ± 4</td>
<td>32 ± 1</td>
<td>Grevesse &amp; Anders (1989)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grevesse et al. (1992)</td>
<td></td>
</tr>
</tbody>
</table>

Uncertainties in the predicted emissivities include uncertainties in the ionization state populations and uncertainties in the excitation rates of the lines observed. It is usually tacitly assumed that the electron velocity distribution is Maxwellian, that photo-ionization may be neglected, that resonant scattering within the corona is unimportant, and that the ionization state has relaxed to equilibrium. All of these are questionable assumptions. Solar wind particle measurements show non-Maxwellian velocity distributions. The He$^+$ lines seem to indicate photo-ionization. The Fe Xvii line ratios suggest resonant scattering. And, impulsive heating in solar flares seems guaranteed to produce nonequilibrium ionization. Nevertheless, all these assumptions might be adequate in the quiet corona.

No one really knows what uncertainties should be assumed for the atomic rates. Typical estimates include roughly 20–30% uncertainties in the ionization and recombination rates. If these systematically affect similar ions in similar ways (e.g., all the ionization cross sections overestimated), the errors may cancel in abundance derivations. The largest uncertainties at the moment are probably in dielectronic recombination and the density dependence due to the population of metastable levels, and the inherent density and field dependence of dielectronic recombination.

Uncertainties in the excitation rates vary widely, depending on the calculations available (or if one is lucky, the laboratory measurements), on the complexity of the ion, and on the particular line (strong resonance lines have more reliable cross sections). Liedahl has recently demonstrated an unexpectedly strong contribution from cascades from high excitation states in Fe x. Resonances in the excitation cross sections are important in some cases, but they have been
computed for only a small number of transitions. Overall uncertainties probably span the range of 10\% (strong transitions of the simplest ions) to a factor of 2.

5.1. New Results from UVCS

Most abundance determinations provide abundances relative to O or Si owing to the lack of H lines in the observed wavelength band. A recent measurement of abundances in solar coronal streamers with the UVCS instrument aboard the SOHO satellite shows the FIP effect quite clearly (O, S and Ar depleted relative to Mg, Al, Si, Ca and Fe by a factor of 3). It also shows that the low-FIP elements are close to photospheric absolute abundances along the edge of the streamer (high-FIP about 1/3 photospheric), while in the streamer core the low-FIP elements are about 1/3 photospheric and the high-FIP around 1/10 the photospheric values relative to hydrogen. The low abundances in the closed field region of the streamer core suggest gravitational settling.

Discussion

A. van Ballegooijen: You see different abundances within the same streamer. Doesn’t this mean that there are other effects involved besides the FIP effect?

J. C. Raymond: Between the time you asked this question and the time I’m answering, you have produced a spectacular set of numerical models which show that gravitational settling in the closed field region and a slow wind solution along the edges of the streamer, as dictated by the field geometry, explain the UVCS data quite well.

N. Brickhouse: We reported some simultaneous EUVE and ASCA observations of Capella, which are relevant to the atomic data issues (Brickhouse et al. 1997). From the EUVE short-wavelength spectra the line to “continuum” ratio can be measured, the latter including any unresolved weak lines. The emission measure distribution was derived from the detected lines of Fe, and was used to predict the continuum level, and make comparisons with the observations. This gave a lower limit of N(Fe)/N(H) = 0.88. This abundance and the emission measure distribution were then used in the analysis of the ASCA spectra. However, no acceptable fit to the ASCA spectra could be found. There is a recurring problem in fitting the spectral band around 10 Å, which suggests that lines might be missing from the emissivity codes. Preliminary calculations by Liedahl & Brickhouse (in progress), suggest that these may be high n (n > 5) lines.

C. Jordan: Fawcett et al. (1987) identified many transitions with Δn = 2 and 3 in Fe xx to Fe xxiv in a solar flare spectrum between 8 Å and 10 Å, which are not treated in any detail in the emissivity codes.

K. Schatten: From the concern about non-equilibrium conditions that Andrea Dupree raised, folded with the observational intensity formula that George Doschek showed, it seems that the raw observations do not require the material to be in equilibrium, so can you say how the lack of equilibrium affects the models/observations/interpretation, etc.?
J. Raymond: It is straightforward to compute the emission given any temperature-density history for the gas. The problem is that the evolution is poorly known. A moderately extreme example is impulsive heating followed by radiative cooling in microflares (Raymond 1991), which shows an increase of a factor of 2 in high excitation lines compared to low excitation lines, but smaller effects for ratios of lines of similar excitation.

M. Laming: Lines of $\Delta n = 1, 2, 3$ have high excitation potentials and are therefore highly temperature sensitive through the Boltzmann factor, $\exp(-\Delta E/kT)$. The ASCA bandpass is comprised solely of these lines, and (interpreting) active stellar coronae might present problems. Other temperature indicators (thermal bremsstrahlung continuum, the ratio of dielectric recombination lines to resonance lines) might go some way to mitigating the situation. Things are much more secure when dealing with $\Delta n = 0$ transitions, e.g. Ne vi/Mg vi.

J. J. Drake: This is also a very important point in the context of high resolution AXAF HETG and LETG spectra. AXAF LETG spectra can observe lines from $\Delta n = 1, 2, 3$ transitions, but also EUV $\Delta n = 0$ transitions from ions with $n = 2$ electrons. The $\Delta n = 0$ lines will provide an important check.

T. Ayres: There seem to be no good solar data below about 200 Å!

C. Jordan: That is not strictly true; there are the early photoelectric spectra obtained by the Air Force Cambridge group, down to about 50 Å, and the early photographic spectra obtained by the NRL and UKAEA Culham groups, down to about 20 Å. These were used to make the line identifications. Many instruments have recorded the He I-like ion lines and other sections of spectra below 170 Å. The early solar spectra corresponding to the EUVE wavebands are summarized in Jordan (1995). It is true is that there has not been a recent solar instrument which has observed over a wide wavelength range below 170 Å.

6. What Physical Processes are Causing Abundance Differences

Carole Jordan. All Panel members were asked to think about this question, but it turned out to be difficult to give answers! Some of the points below were made in discussion by the Panel and participants, but we received no written versions of the questions to reproduce here.

Work by Wang (1996) was mentioned; he proposed that upward drag on ions by protons could selectively remove low FIP elements from the chromosphere, thus enhancing their abundance in the corona, relative to the high FIP elements. However, the transient mechanism suggested for driving the process (transient heating of the corona, followed by chromospheric evaporation), has not been investigated outside flares.

In her presentation, Galvin discussed several mechanisms which are thought to cause fractionation during particle acceleration processes. She stressed that many models have been proposed, which could explain either enhancement or depletion of low FIP elements, but none is generally accepted.

Some of the low FIP elements (e.g., Si, Ca) are known to have their ionization influenced by the strong H Lyman $\alpha$ line, as are the intermediate elements,
S and C. The populations of O I and O II are controlled by charge exchange with H I and H II. The relevance of these processes has not been investigated.

The importance of considering the diffusion distances and times, and effects of flows, was stressed.

7. Conclusions

Carole Jordan. The strongest spectroscopic evidence for variations in abundances between different solar features is provided by the ratio of the Mg vi and Ne vi line fluxes, which span an order of magnitude. Effects that have been investigated cannot account for this large variation. The variations appear to be related to the magnetic field configuration, with the higher Ne/Mg abundances occurring in newly emerged magnetic flux (see, e.g., Sheeley 1995). Processes that have not yet been investigated in this context are flows, time-dependent ionization and the dependence on \( N_e \) of dielectronic recombination. There is less evidence that the FIP effect occurs in the average “quiet Sun”. Laming et al. (1995) found clear evidence for non-photospheric abundances only at coronal temperatures \( T_e > 10^6 \) K, which is difficult to understand in terms of a FIP effect. However, apart from in-ecliptic coronal holes, the solar wind does show a clear FIP effect. The correlation of the interstream Mg/O ratio with the ionization temperature (found from the number of ions in different charge states) has not yet been explained in terms of any process causing a FIP effect.

For stellar coronae, Drake has reminded us that the photospheric abundances may not be solar, particularly in evolved stars. The interpretation of low resolution spectra relies on fitting with emissivity codes, and we have heard several warnings about the absence of lines from the codes and instrumental effects.

A great deal of progress has been made in calculating the collision strengths of the stronger transitions in ions with relatively simple electron configurations, but as Mason (1994) points out, further work is needed on more complex ions such as Fe x to Fe xiv. Ionization equilibrium ion populations taking into account the density dependence of dielectronic recombination are required, particularly for the analysis of the more active stars.

Finally, further work is required on the physical processes that could cause a FIP effect, which seem to originate in the chromosphere (below about 10^4 K), where the low FIP elements are ionized, but the high FIP elements are still neutral.

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