SOLAR WIND COMPOSITION

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ABSTRACT

The solar wind composition is an important topic to study because the solar wind ions are matter from the outer convective zone of the Sun. In addition to learning something about the Sun, measuring the solar wind composition allows to study also plasma processes in the solar atmosphere, because these processes result in considerable elemental fractionation on all time scales. In particular we shall review what influences on solar wind composition we can expect when considering different time scales of the observations, going from solar cycle effects, to integration periods of days to months, down to the smallest time scales available with modern plasma instrumentation.

Key words: Solar Wind Composition; FIP Effect; Temporal variations.

1. INTRODUCTION

The Sun contains about 99.9% of the matter in our solar system and its surface closely reflects the protosolar nebula with the exception of He, which may be slightly depleted, and both D and Li, which have been destroyed. The solar wind carries solar material from the photosphere out into interplanetary space to distances where the composition can be measured with instrumention on spacecraft.

The solar wind plasma composition has been investigated in great detail over the past 40 years or more. It is well known that the solar wind consists mostly of protons (about 96%) and alpha particles (about 4%). Ions of heavy elements (carbon and heavier) together make up around 1 permille of the solar wind ion density and are referred to as minor ions some publications.

As of today, solar wind composition studies have been performed in interplanetary space from as close as about 0.3 AU from the Sun by the HELIOS spacecraft out to about 5.4 AU with the Ulysses spacecraft, with most measurements being performed near Earth orbit. Solar wind plasma parameters are measured even much further out with the Faraday Cups on the Voyager spacecraft. Note that most of the composition measurements are constrained to the ecliptic plane with the exception of the Ulysses spacecraft going over the solar poles.

By measuring the solar wind composition one may ultimately try to infer the solar composition. Since there are many plasma processes involved in the transport of material from the solar surface to distances of 1 AU, where solar wind composition typically is measured, these processes can and have to be studied as well. Depending on species investigated one can study different processes. The major plasma ions, protons and alpha particles, provide information about the solar wind acceleration and heating (e.g. see review by Wurz & Gabriel, 1999). The heavy elements are of minor abundance in the solar wind and thus do not influence the plasma parameters. However, they can be regarded as tracers in the solar wind plasma, which carry information of plasma processes in the solar corona, to interplanetary space. For example, the charge state distribution of the heavy ions is established in the solar corona by the ionization caused by the million-degree electrons in the coronal plasma resulting in highly-charged ions. This coronal plasma information is carried out to the location of the observer far away from the Sun in interplanetary space. The elemental composition of the solar surface, the photosphere, is also studied by optical means. Comparison of the photospheric elemental abundances with the solar wind elemental abundances allows for the study of elemental fractionation processes occurring in the solar atmosphere and during solar wind acceleration.

Finally, studying the solar wind composition is the only way to learn about the isotopic composition of the Sun, aside from the isotopes D/H, He, and CO that can be studied by optical measurements of the photosphere as well. The isotopic composition of the Sun, actually the Sun's outer convection zone, is of great interest to planetary science because it is relatively unchanged in composition from the solar nebula, the starting material of the solar system. The isotopic fractionation during solar wind acceleration is considered minor even for helium (Bodmer & Bochsler, 1998). Solar wind isotopic abundance measurements have been reviewed by Wimmer et al. (1999)

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and more recently by Wiens et al. (2004) and will not be discussed further in this paper.

Coronal mass ejections (CMEs) or other transient events in the solar atmosphere will not be discussed in this paper. Solar Energetic Particles (SEPs) are accelerated solar wind ions with energies in the range from a few MeV/nuc to a few tens MeV/nuc. SEPs originate either from close to the solar surface (impulsive events) or from the passage a shock front in interplanetary space (gradual events). The acceleration of ions to such high energies often results in severe elemental fractionations (Meyer, 1985). Nevertheless, the systematic fractionations can be removed in the data analysis and coronal abundances can be derived. This research was popular before direct compositional measurements in the solar wind were possible because of limitations in the plasma instrumentation at that time. SEP-derived coronal elemental abundances are reported in (e.g. Breneman & Stone, 1985; Meyer, 1985), recent SEP isotopic abundances are reported in (Williams et al., 1998; Leske et al., 2003), and recent reviews on SEP elemental abundances are given by (Reames, 1995, 1999). The composition of SEPs will not be discussed in this paper.

In this paper we will review solar wind elemental abundances averaged over long time scales, of the order years, over shorter time scales in the range of days to months, and finally discuss the shortest time scales accessible with modern plasma instrumentation. Each time scale shows different phenomena in the solar wind and its origin in the solar atmosphere. The longest time scale relates to a solar cycle dependence, the month time scale allows for the investigation of elemental fractionation by the so-called first ionization potential (FIP) effect, and the shortest time scale shows the temporarily and spatial small-scale plasma processes in the solar atmosphere. First we will look at the main ion species, protons and Helium, the latter is in the form of alpha particles in regular solar wind. Protons and alpha particles together make about 99.9% of the solar wind ions. Then, we will look at the heavy ions and their systematic elemental fractionation by the FIP effect.

Finally, we will review recent attempts to correlate solar wind plasma measurements with coronal abundance measurements to investigate the origin of the solar wind. There are two reports on such work, one is from the SOHO mission combining UVCS and CELIAS data (Uzzo et al., 2003) and one is combining data from UVCS and LASCO instruments on SOHO with SWOOPS and SWICS on Ulysses (Bemporad et al., 2003).

2. PROTONS AND ALPHA PARTICLES

With solar wind plasma typically two types of flows are distinguished, slow solar wind with speeds below about 400 km/s and fast solar wind exceeding this speed (Schwenn, 1990). Also other parameters differ between slow and fast solar wind (Schwenn, 1990), one being the proton density, which at Earth orbit is on average 8.3 cm^{-3} and 2.5 cm^{-3}, in slow and fast solar wind, respectively. However, the particle flux is almost constant for both types of solar wind, $2.7 \cdot 10^8$ cm^{-2} s^{-1} and $1.9 \cdot 10^8$ cm^{-2} s^{-1} (Schwenn, 1990), which was also found in a recent study using SWOOPS/Ulysses data (McComas et al., 2000). Fast solar wind has been associated with plasma outflow from coronal holes, having speeds ranging from 450 km/s up 800 km/s, and the maximum solar wind speed being linearly correlated with the apparent size of the coronal hole (Nolte et al., 1976). Slow solar wind is thought to originate from the boundaries of closed magnetic field regions on the Sun, for example from the edges and tips of the closed-field structures of the streamer belt.

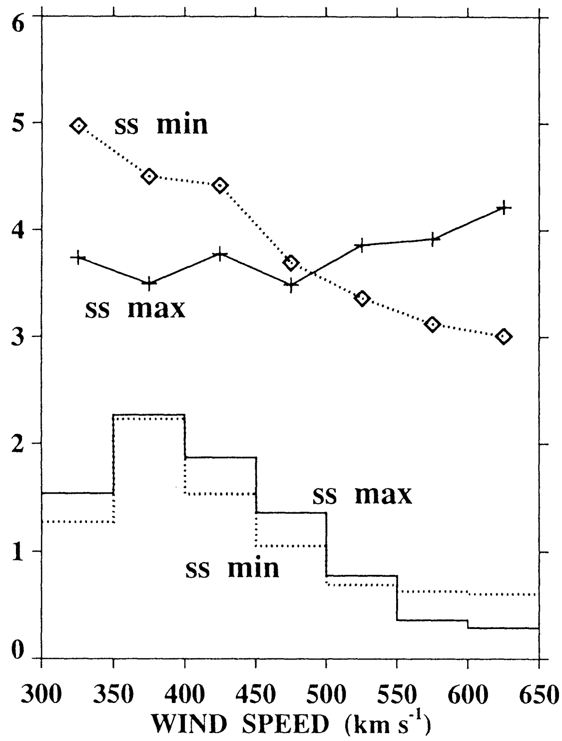

Figure 1. Average ion flux density near Earth (in units of 10^8 cm^{-2} s^{-1}) as a function of daily solar wind speed for sun spot minimum (diamonds) and sun spot maximum (crosses) periods (Figure from Wang, 1994). Histograms show the distribution of daily wind speeds during sunspot minimum (dotted line) and sun spot maximum (solid line).

Figure 1 shows the average ion flux density (i.e., the proton flux density) near Earth as a function of daily solar wind speed for periods of sunspot minimum (1975–1977 and 1985–1987) and of sunspot maximum (1979–1981 and 1989–1991) from the NSSDC OMNI data set (Wang, 1994). For solar minimum conditions, when the large-scale coronal structure is dominated by two polar coronal holes, the mass flux density declines monotonically with solar wind speed. By contrast, the mass flux distribution for solar maximum, when the coronal structure is made up of many small coronal holes all over the solar surface,

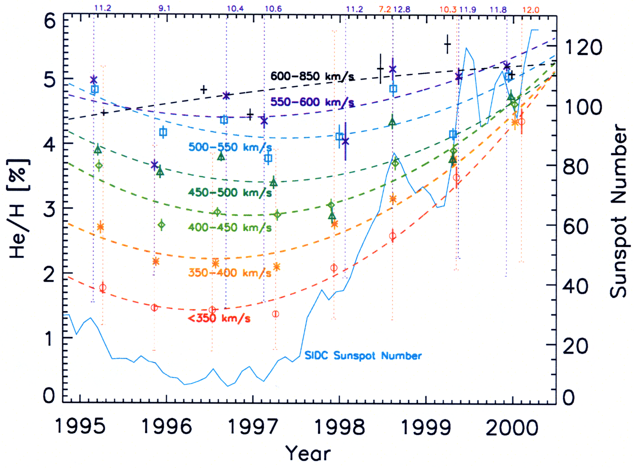

Figure 2. Solar wind helium abundance derived from Wind/SWE Faraday Cup data (Figure from Aellig et al., 2001). The solid error bars shown for each data point represent the uncertainty of the plotted mean value. For the speed ranges $<$ 350 km/s (orange) and for 550 to 600 km/s (purple) the 16% and 84% quantiles of the He/H ratio is indicated by long, dashed, error bars.

shows a flat or slowly increasing trend with solar wind speed. Overall, the large-scale variation of the solar wind proton flux is small, and the variation is somewhat larger when the proton density is considered.

The second most abundant element in the solar wind is helium, which is present at the percent level. The long-term variation of the He/H abundance ratio has been investigated recently by Aellig et al. (2001) using WIND/SWE data from the end of 1994 to early 2000. Figure 2 shows the He/H abundance ratio for the entire data set in comparison with the solar activity indicated by the sunspot number. A clear correlation with solar cycle is found in that study. For the slow solar wind in the lowest speed bin ($v_p < 350$ km/s) the average He/H ratio starts at 1.8% at the start of the observation period, then drops to 1.4% around solar minimum and rises to about 4.5% at solar maximum. The solar cycle dependence of the He/H becomes smaller the higher the solar wind speed is and only a small positive correlation remains for the highest solar wind speed bin investigated (600 – 850 km/s). In addition to the large-scale variation of the He/H ratio there are variations on smaller scales, which are indicated in Fig. 2 by the large error bars (dotted lines). We will discuss these variations later in this paper.

The He/H abundance ratio in the solar wind of a few percent has to be compared with the solar He abundance of He/H = 8.5±0.09% (Grevesse & Sauval, 1998). Obviously, a considerable fraction of the photospheric He does not end up in the solar wind as a result of the plasma processes responsible for heating the corona and accelerating the solar wind. Two-fluid models (electrons and protons) have been used widely to study the basic plasma processes in the corona. However, an adequate description of the problem of solar wind acceleration made it necessary to use multi-fluid plasma models (e.g. see review by Wurz & Gabriel, 1999). With three-fluid models (electrons, protons, and alpha particles), the He/H ratio in the solar wind has been addressed (Bürgi, 1992; Esser & Habbal, 1996; Hu & Habbal, 1999). Although helium is depleted in the solar wind with respect to the photosphere, theoretical models predicts that it is significantly enriched in the region of the temperature maximum in the corona (Bürgi, 1992; Esser & Habbal, 1996). Since He is fully ionized (alpha particle) in this region it is not possible to verify this theoretical result with spectroscopic observations. More recently, a four-fluid model has been used that includes O^{+5} ions to allow better comparison with observational data (Hu et al., 2000).

3. HEAVY ION ABUNDANCES

Composition measurements of heavy ions in the solar wind have advanced dramatically with the implementation of dedicated composition instrumentation for heavy ions, e.g. Ulysses/SWICS (Gloeckler et al., 1995), SOHO/CELIAS (Hovestadt et al., 1995), and ACE/SMS (Gloeckler et al., 1995). Basically, all elements and most of the isotopes up to iron have been measured and quantified in the solar wind plasma. As an example, Fig. 3 shows a mass spectrum of solar wind heavy ions recorded with the MTOF sensor of the CELIAS instrument on the SOHO spacecraft. Note that the charge states indicated in this figure denote the charge states inside the MTOF sensor, where recharging of the solar wind ions to low charge states occurs, and not solar wind ion charge states (Wurz, 1999).

When evaluating solar wind composition data, like the one presented in Fig. 3, one finds systematic differences between the elemental abundances in the solar wind and the photosphere, from where these ions originate. This difference, or fractionation, organises best with respect to the first ionization potential (FIP) of the element as can be seen in Fig. 4, which shows data from the MTOF sensor together with earlier data from SWICS/Ulysses (von Steiger, 1996). The FIP fractionation affects mostly elements with an ionization potential below about 10 eV, so-called low-FIP elements, and does not affect the elements with FIP higher than 10 eV. The exception is He, which is depleted in the solar wind and has been discussed above. As can be seen in Fig. 4, the FIP fractionation is stronger in the slow (interstream) solar wind than in the fast (coronal hole) solar wind, with enrichment factors of 3–5 and about 1.5, respectively, for the low-FIP elements. The reported fractionation factors vary from analysis to analysis indicating that somewhat variable processes occur in the solar atmosphere, even on the time scale of days used in these analyses. For integration periods of a few months stable FIP fractionation values are obtained and all the short-term density fluctuations in the solar wind, which can be of much larger amplitude, are averaged out (Aellig et al., 1999a; Wurz et al., 1999). In an extended study us-

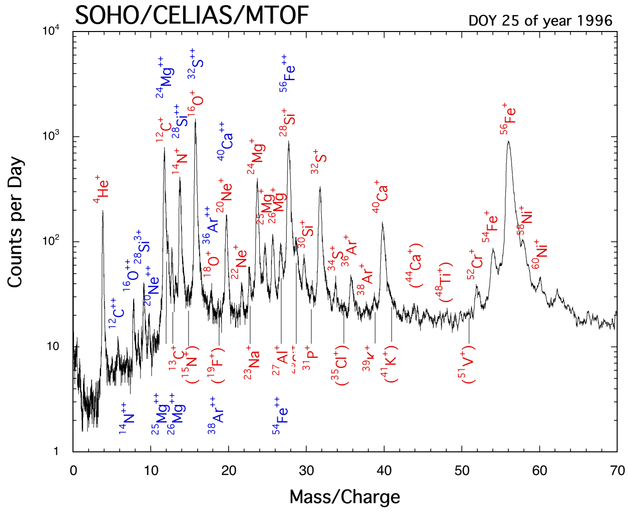

Figure 3. Mass spectrum of heavy ions in the solar wind recorded with the MTOF sensor of CELIAS/SOHO. Raw data for day 25 of 1996 are displayed. Red labels indicate singly-charged ions in the MTOF sensor, blue labels indicate doubly charged ions. Identifications shown in parenthesis are uncertain when using data accumulated for only one day.

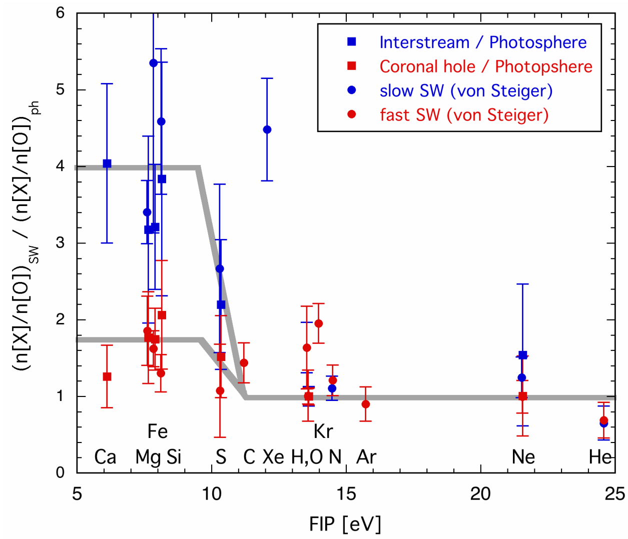

Figure 4. Comparison of solar wind (SW) abundances with the photospheric (ph) abundances. Data are from the MTOF sensor for day 8 (slow SW) and for day 13 (fast SW) of 1997. Also data from von Steiger (1996) are shown.

ing Ulysses/SWICS data von Steiger et al. (2000) found that the FIP fractionation remains the same when going from solar minimum to solar maximum as well as on the solar south and north poles.

In determining the enrichment factors oxygen is almost always used as a reference element for the abundance ratios. Although the photospheric abundances appear to be well established (Grevesse & Sauval, 1998, and references therein) these values are still under investigation and occasional revisions occur (e.g. Holweger, 2001). A lower photospheric oxygen abundance results in lowered the FIP enrichment factors in the solar wind (Aellig et al., 1999b) when using oxygen as reference. The photospheric abundances were reviewed recently by Asplund et al. (2005).

Note that the way the data is presented in Fig. 4, which is the usual way in the literature, as a solar wind abundance ratio over the corresponding photospheric abundance ratio with reference to oxygen, it cannot be said if the FIP fractionation is actually an enrichment of the low-FIP elements or a depletion of the high-FIP elements with respect to the main solar wind plasma, the protons. As discussed above, He is actually depleted with respect to Hydrogen. To address this question more directly one has to use the hydrogen density in the solar wind as reference element. This allows even better comparison to the photospheric abundances since photospheric abundances are given with reference to hydrogen (e.g. Grevesse & Sauval, 1998). A recent example for the determination of an element abundance in the solar wind using MTOF measurements is Ca, a low-FIP element, which is shown in Fig. 5 (Wurz et al., 2003). Figure 5 gives the Ca/H

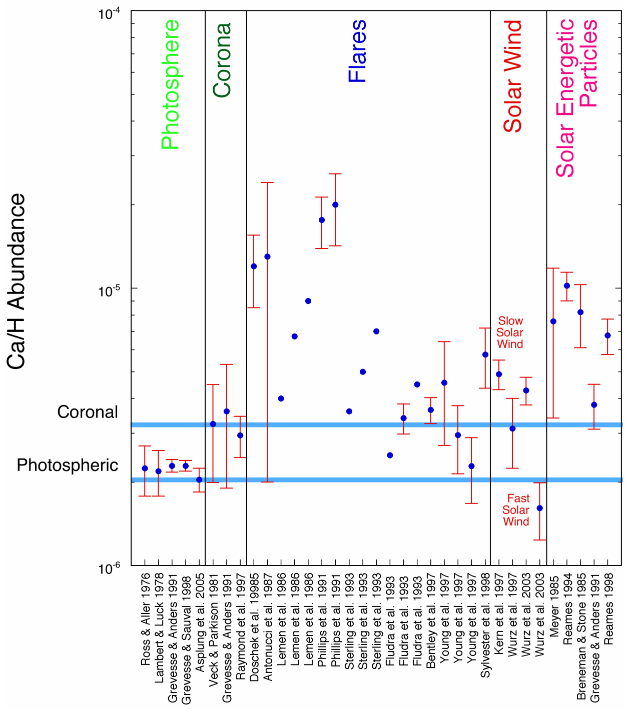

Figure 5. Summary of published Ca abundance measurements (adapted from Wurz et al., 2003). Lower blue line: Photospheric Ca abundance. Upper blue line: Coronal Ca abundance.

ratio in the solar wind together with determinations by other means, i.e., optical observations in the photosphere and corona and energetic particle measurements. For the slow solar wind the Ca/H compatible with the coronal abundance, which it is somewhat elevated from the photospheric abundance. For the fast solar wind the Ca/H ratio is much lower than the photospheric value. Since the oxygen abundance is reduced even more in the fast solar wind the Ca/O ratio appears to be enhanced in the fast solar wind (Wurz et al., 2003), which can be seen in Fig. 4.

Several mechanisms and theoretical models to explain and quantify the FIP effect have been proposed and have been reviewed by von Steiger (1996). The models agree that the initial step to the observed fractionation is partial ionization of the species and a separation of neutral and ionized particles in the chromosphere and the low corona. Most models agree on EUV radiation being the principle agent of ionization. However, the models disagree on the actual mechanism to separate the neutral from the ionized particles (see von Steiger, 1996, and references therein). Very recently Laming (2004) proposed a model where the pondermotive force arising as Alfvén waves propagating through the chromosphere of the Sun, or stars, gives rise to FIP fractionation with amplitudes in agreement with the observations.

The correlation of the elemental fractionation with the solar wind speed, caused by the FIP fractionation, is shown in Fig. 6 using SWICS/Ulysses data where the Ulysses spacecraft passed through a high-speed solar wind stream several times on its way from Jupiter toward the south solar pole passage. It has been suggested that a 1:1 relationship exists between solar wind composition and solar wind type, which could be used to decide if the sampled solar wind is of coronal origin (fast solar wind) or of interstream type (slow solar wind). However, the established solar wind abundances are only obtained from a solar wind composition measurement when suitably long averages are performed, as has been done also with the data shown in Fig. 6 where measurements of almost 10 solar rotations were averaged together in a superposed epoch analysis (Geiss et al., 1995). Figure 7 shows the actual time sequence of the same data set (von Steiger, 1994). As can be seen clearly in Fig. 7 the freeze-in temperature and the abundance ratios do not correlate well with the solar wind speed because of the short-term abundance fluctuations in the solar wind plasma.

4. TEMPORAL VARIATIONS

Until now we have focussed mainly on long-term averages and large scale variations in the density of the elements in the solar wind. However, the elemental abundances and their ratios vary on all time scales investigated, at levels much larger than discussed above. This is no surprise if one considers the highly dynamic solar atmosphere as has been seen in many observations from the SOHO and TRACE missions.

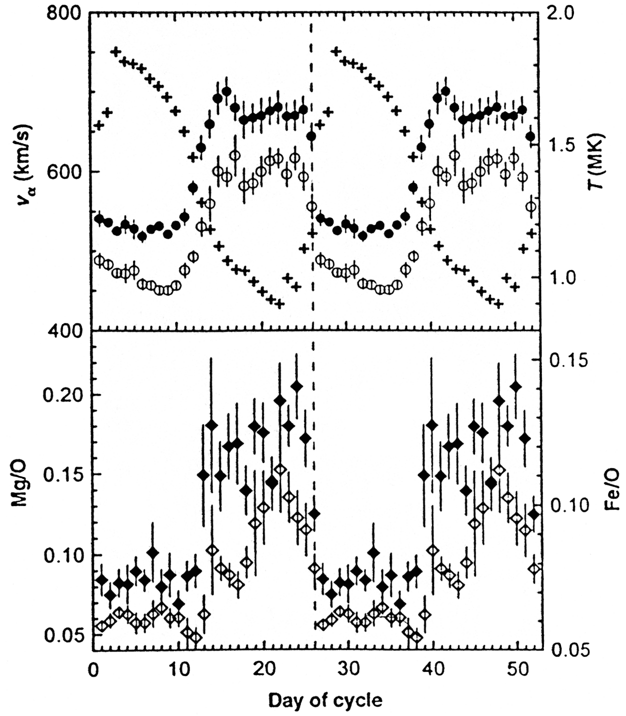

Figure 6. Superposed epoch plot of SWICS/Ulysses data from day 191 of 1992 to day 98 of 1993 when Ulysses went regularly into and out of a high-speed stream (Figure from Geiss et al., 1995). Upper panel: speed of He ions (crosses), freeze-in temperature of oxygen (full circles) and carbon (open circles). Lower panel: abundance ratios of Mg/O (full diamonds) and of Fe/O (open diamonds).

The variability of the heavy ion densities is much larger than the variability of the proton density, which constitutes the main plasma. The alpha particles generally show a much larger variation of their density than the protons (Neugebauer, 1981; McComas et al., 2000) with the variation typically being larger by a factor of 10. The alpha particle variability in the solar wind was reviewed already by Neugebauer (1981), who found that the ratio of protons to alpha particles varies in the range from $n_{\alpha/n_p} = 8.1{\cdot}10^{-4}$ to $4.17{\cdot}10^{-1}$, a variation range by a factor of 500. Similar results have been derived from SWOOPS data when the Ulysses spacecraft went over the solar south and north poles during solar minimum (Barraclough et al., 1996; McComas et al., 2000). As can be seen in Fig. 8, the He abundance variation is significantly larger for slow solar wind, which by itself is more variable, than for fast solar wind, which was prevalent at the lower southern latitudes during that time. The highest helium abundances in these data have been associated with coronal mass ejections (Barraclough et al., 1996).

The heavy ion densities also show high variability in the solar wind, again about a factor 10 more than the proton density variation (Wurz et al., 1999, 2003). Figure 9 shows Si, Ca and Fe densities with 5-min time resolution, together with the proton speed and density, from the MTOF and PM sensors, respectively, of the CELIAS instrument on SOHO. Of course, some of the variability seen in Fig. 9 is due to limited measurement statistics. When the heavy data shown in Fig. 9 are binned by solar wind speed one finds the typical FIP fractionation of Si and Fe for slow and fast solar wind, which is much smaller than the short-term fluctuations (Wurz et al., 1999).

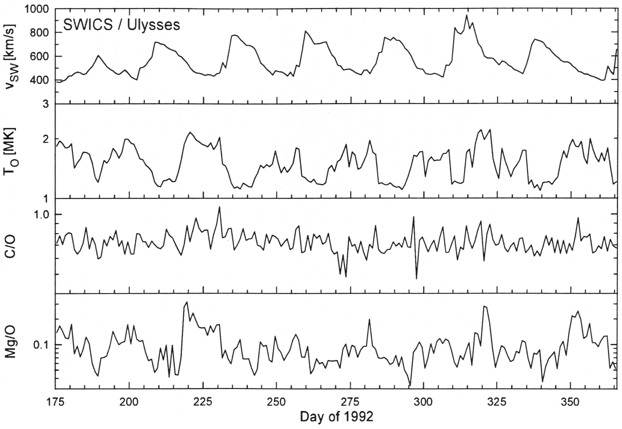

Figure 7. SWICS/Ulysses data from the second half of 1992 during the crossings of the high-speed streams (Figure from von Steiger, 1994). Top to bottom: solar wind alpha particle velocity; oxygen freeze-in temperature; C/O abundance ratio; Mg/O abundance ratio.

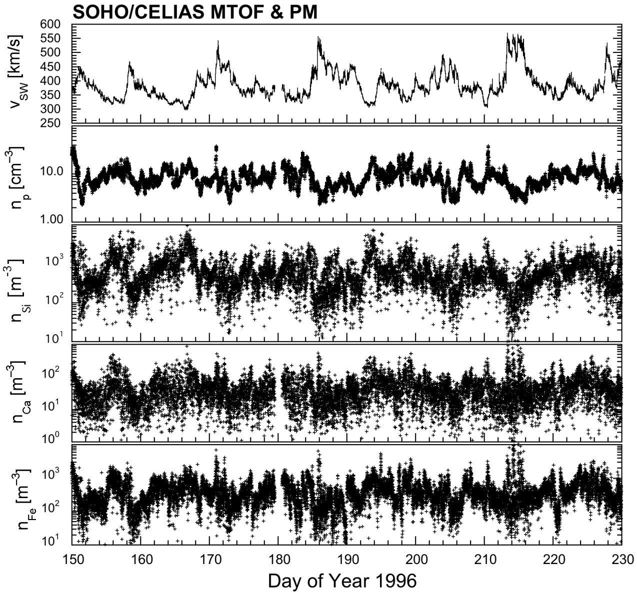

Figure 9. Densities of Si, Ca, and Fe from the MTOF sensor and proton density and speed from the PM sensor, both from the CELIAS instrument on SOHO.

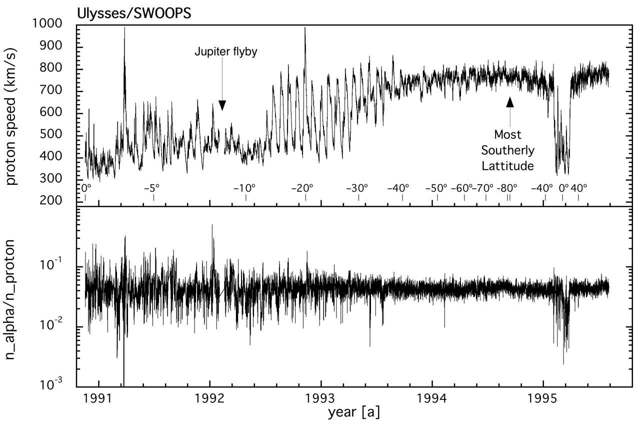

Figure 8. Solar wind plasma data from Ulysses / SWOOPS. The top panel shows the proton speed, together with the spacecraft latitude. The bottom panel shows the He/H abundance ratio.

These short-term variations in the abundance ultimately arise from temporal and spatial variations in the lower solar atmosphere. These variations lead to small structures in the solar wind and possible interactions between them. See also the discussion by Coplan et al. (2001) regarding this topic. The high abundance variability averages out when investigating longer time periods and causes no systematic fractionation in the solar wind as discussed above.

With the data from a single spacecraft, one cannot distinguish between a temporal or a spatial nature of these density variations, which are also particle flux variations. Combining observations from two or more spacecraft allows to distinguish temporal and spatial variations to some extent. Coplan et al. (2001) studied solar plasma data from SOHO, WIND, and IMP 8 spacecraft and searched for correlations betweens these measurements. They found spatial structures with length scales ranging from a few thousand kilometers up to 1 AU or more were found, corresponding to apparent time scales of about 10 s to several days, with the largest structures being known as coronal interaction regions (CIRs). In a recent study using plasma data from the ACE and WIND spacecraft it was found that the spatial scales differ for different plasma parameters considered (King & Papitashvili, 2005).

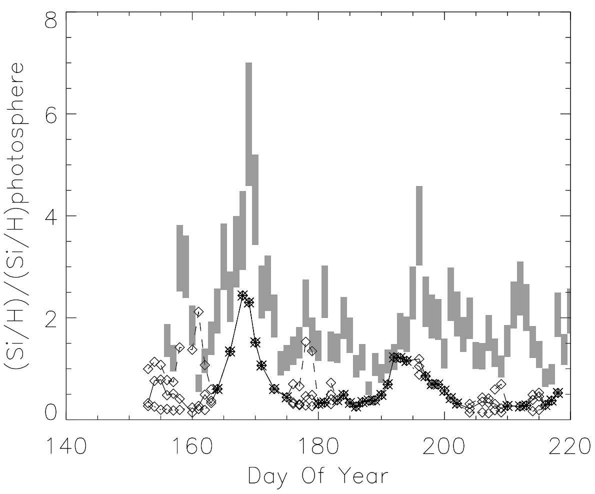

Figure 10. Silicon elemental abundances derived from UVCS/SOHO observations (asterisks and diamond symbols) and in situ plasma data from CELIAS/SOHO (grey bars, with the bar length giving the error range). Figure from Uzzo et al. (2003).

5. CORRELATION WITH CORONAL OBSERVATIONS

The origin of the fast solar wind from coronal holes has been established already some time ago. By contrast, the origin of the slow solar wind is still a topic of current research. Based on apparent similarities between elemental abundances in the slow solar wind and the legs of coronal streamers it was claimed by Raymond et al. (1997) that these regions in the solar corona are possible sources of the slow solar wind.

A comparison of oxygen, silicon, and magnesium abundances in coronal streamers with the same abundances measured *in situ* in the solar wind was performed by Uzzo et al. (2003) using the UVCS and CELIAS instruments on SOHO. During the 1996 solar minimum period, daily elemental abundances were determined on the east and west limbs of the coronal streamer belt, consisting of active streamers (streamers over active regions) and quiescent streamers (streamers above quiescent prominences). These data showed the presences of FIP fractionation in the streamer and the comparison with the *in situ* plasma data supports the concept that active-region streamers and the outer streamer structures of quiescent streamers are definitive contributors to the slow solar wind.

Figure 10 shows one of the comparisons performed by Uzzo et al. (2003) of the abundances derived from UVCS observations of the west-limb together with the *in situ* plasma data from CELIAS for a period from 1 June 1996 to 5 August 1996. The asterisks represent the active region streamers and the diamonds identify quiescent streamers. The CELIAS data have been averaged over one day to remove the short-term variability discussed above and shifted in time by about 3 days to compensate for the solar rotation and the solar wind flight time to 1 AU, the location of the spacecraft. By examining the O/H, Si/H, and Mg/H abundance ratios in the streamers and in the plasma data with respect to the photospheric values, the authors concluded that the FIP fractionation is actually a depletion of heavy elements, with oxygen depleted more than the low-FIP elements. Thus, plotting the data as has been done in Fig. 4 suggests an enhancement that is not seen when hydrogen is taken as reference.

A similar investigation has been performed by Bemporad et al. (2003) taking measurements from close to solar maximum who again used UVCS/SOHO to determine elemental abundances in the streamer and the Ulysses spacecraft to determine the plasma composition. The advantage of this setup is that, for a short time, that Ulysses is located at a vantage point perpendicular to the viewing direction of UVCS, thus likely sampling the same plasma *in situ* that is observed optically by UVCS/SOHO. This observation constellation is referred to as the SOHO-Sun-Ulysses quadrature (Suess et al., 2000). Bemporad et al. (2003) studied the abundance of several low-FIP and high-FIP elements in the streamers and they also find the presence of a FIP fractionation in the streamers as was observed as in the earlier studies (Raymond et al., 1997; Uzzo et al., 2003). However, the oxygen depletion in the streamers during solar maximum is not as high as in the streamers during solar minimum.

Figure 11 shows abundance measurements, i.e., the elemental X/H ratios in the corona with respect to the photosphere, for two streamers, A and B, close to solar maximum studied by Bemporad et al. (2003). Clearly, the FIP fractionation pattern can be seen in these data. However, streamer B, the streamer newly-formed during that observation period, does not show the general depletion of all elements, as in all the other observations, but a slight enhancement of low-FIP elements in the corona. It was argued by the authors, that this may have to do with the young age of the streamer because gravitational settling of the heavy elements, which may be the depletion process, had not had enough time to be effective. A decrease in element abundances with height was observed closer to the solar surface, which was explained in gravitational settling in the streamer together with other processes (Ko et al., 2002). Furthermore, a comparison between coronal Fe/O ratios and the *in situ* Fe/O ratio shows a good agreement using one-day averages for the solar wind plasma data (Bemporad et al., 2003).

6. CONCLUSIONS

The study of elemental abundances in the solar wind is still an active field of research as can been seen from, for example, the series of *Solar Wind* conferences, but also from the many topical sessions at larger meetings. The variability of the elemental abundances in the solar wind on all time scales and the FIP effect, and its variability, will make it difficult to derive accurate solar abun-

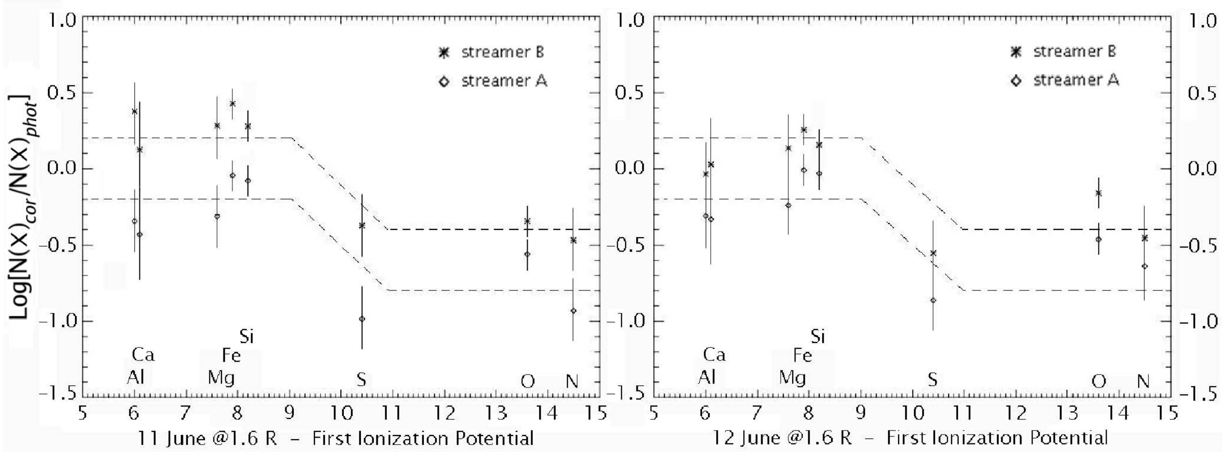

Figure 11. Coronal abundance ratios, X/H, with respect to photospheric abundances for two streamers, A and B, for two observation dates, left 11 June 2000 and right for 12 June 2000 (Figure from Bemporad et al., 2003).

dances from solar wind measurements, with the exception of isotopic determinations. However, knowing the photospheric, and perhaps coronal, abundances of the elements allows for the study of the origin on the solar surface of solar wind plasma as we discussed above. Moreover, the study of elemental abundances and charge state distributions allows the investigation of plasma processes in the solar atmosphere, where most of the fractionation processes occur. Many of these processes are of transient nature, e.g. coronal mass ejections, and with the time resolution of modern plasma instrumentation for heavy elements detailed studies can be performed.

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REFERENCES

Aellig M.R., Hefti S., Grünwaldt H., Bochsler P., Wurz P., Ipavich F.M., and Hovestadt D., 1999, Jou. Geophys. Res. 104(A11), 24769

Aellig M.R., Holweger H., Bochsler P., Wurz P., Grünwaldt H., Hefti S., Ipavich F.M., and Klecker B., 1999, in *Solar Wind Nine*, AIP Conf. Proc. 471, 255

Aellig R.A., Lazarus A.J., and Steinberg J.T., 2001, Geophys. Res. Lett. 28(14), 2767

Asplund M., Grevesse N., and Sauval A.J., 2005, ASP Conf. Ser., Vol. XXX, 1

Barraclough B.L., Feldman W.C., Gosling J.T., McComas D.J., and Phillips J.L., 1996, in *Solar Wind Eight*, AIP Conf. Proc. 382, 277

Bemporad A., Poletto G., Suess S.T., Ko Y.-K., Parenti S., Riley P., Romoli M., and Zurbuchen T.Z., 2003, Astrophys. Jou. 593, 1146

Bodmer R., and Bochsler P., 1998, Astron. Astrophys. 337, 921

Breneman H.H., and Stone E.C., 1985, Astrophys. Jou. 299, L57

Bürgi A., 1992, Jou. Geophys. Res. 97(A3), 3137

Coplan M.A., Ipavich F., King J., Ogilvie K.W., Roberts D.A., and Lazarus A.J., 2001, Jou. Geophys. Res. 106(A9), 18615

Esser R., and Habbal R.H., 1995, Geophys. Res. Lett. 1995, 22(19), 2662

Geiss J., Gloeckler G., von Steiger R., Balsiger H., Fisk L.A., Galvin A.B., Ipavich F.M., Livi S., McKenzie J.F., Ogilvie K.W., and Wilken B., 1995, Science, 268, 1033

Gloeckler G., Balsiger H., Bürgi A., Bochsler P., Fisk L.A., Galvin A.B., Geiss J., Gliem F., Hamilton D.C., Holzer T.E., Hovestadt D., Ipavich F.M., Kirsch E., Lundgren R.A., Ogilvie K.W., Sheldon R.B., and Wilken B., 1995, Sp. Sci. Rev. 71, 79

Gloeckler G., Cain J., Ipavich F.M., Tums E.O., Bedini P., Fisk L.A., Zurbuchen T.H., Bochsler P., Fischer J., Wimmer-Schweingruber R.F., Geiss J., and Kallenbach R., 1998, Sp. Sci. Rev. 86, 497

Grevesse N., and Sauval A.J., 1998, Sp. Sci. Rev. 85, 161

Hovestadt D., *et al.*, 1995, Sol. Phys. 162, 441

Holweger H., 2001, in *Solar and Galactic Composition*, AIP CP598, 23

Hu Y.Q., and Habbal S.R., 1999, Jou. Geophys. Res. 104(A8), 17045

Hu Y.Q., Esser R., and Habbal S.R., 2000, Jou. Geophys. Res. 105(A3), 5093

Ko Y.K., Raymond J.C., Li J., Ciaravella J.A., Michels J., Fineschi S., and Wu R., 2002, Astrophys. Jou. 578, 979

King J.H., and Papitashvili N.E., 2005, Jou. Geophys. Res. 110, doi:10.1029/2004JA010649

Laming M.J., 2004, Astrophys. Jou. 614, 1063

Leske R.A., Mewaldt R.A., Cohen C.M.S., Christian E.R., Cummings A.C., Slocum P.L., Stone E.C., von-Rosenvinge T.T., and Wiedenbeck M.E., 2003, in *Solar Wind Ten*, AIP Conf. Proc. 679, 616

McComas D.J., Barraclough B.L., Funsten H.O., Gosling J.T., Santiago-Muñoz E., Skoug R.M., Goldstein B.E., Neugebauer M., Riley P., and Balogh A., 2000, Jou. Geophys. Res. 105(A5), 10419

Meyer J.-M., 1985, Astrophys. Jou. Supp. Ser. 57, 151

Neugebauer M., 1981, in *Fundamentals of Cosmic Physics*, Vol. 7, (London: Gordon & Breach), 131

Nolte J.T., Krieger A.S., Timothy A.F., Gold R.E., Roelof E.C., Vaiana G., Lazarus A.J., Sullivan J.D., and McIntosh P.S., 1976, Sol. Phys. 46, 303

Raymond J.C., Kohl J.L., Noci G., et al., 1997, Sol. Phys. 175, 645

Reames D.V., 1995, Adv. Sp. Res. 15(7), 41

Reames D.V., 1999, Sp. Sci. Rev. 90, 413

Schwenn R., 1990, in *Physics of the Inner Heliosphere I*, pp 99.

Suess S.T., Poletto G., Romoli M., Neugebauer M., Goldstein B.E., and Simnett G., 2000, Jou. Geophys. Res. 105(A11), 25033

von Steiger R., 1994, Habilitation thesis, Univ. Bern, Switzerland

von Steiger R., 1996, in *Solar Wind Eight*, AIP Conf. Proc. 382, 193

von Steiger R., Schwadron N.A., Fisk L.A., Geiss J., Gloeckler G., Hefti S., Wilken B., Wimmer-Schweingruber R.F., and Zurbuchen T.H., 2000, Jou. Geophys. Res. 105(A12), 27217

Uzzo M., Ko Y.-K., Raymond J.C., Wurz P., and Ipavich F.M., 2003, Astrophys. Jou. 585, 1062

Wang Y.-M., 1994, Astrophys. Jou. 437, L67

Wiens R.C., Bochsler P., Burnett D.S., and Wimmer-Schweingruber R.F., 2004, Earth Plan. Sci. Lett. 226, 549

Williams D.L., Leske R.A., Mewaldt R.A., and Stone E.C., 1998, Sp. Sci. Rev. 85, 379

Wimmer-Schweingruber R.F., Bochsler P., and Wurz P., 1999, in *Solar Wind Nine*, AIP Conf. Proc. 471, 147

Wurz P., 1999, Habilitation thesis, Univ. Bern, Switzerland

Wurz P., and Gabriel A.H., 1999, ESA SP-446, 87

Wurz P., Aellig M.R., Bochsler P., Hefti S., Ipavich F.M., Galvin A.B., Grünwaldt H., Hilchenbach M., Gliem F., and Hovestadt D., 1999, Phys. Chem. Earth (C) 24(4), 421

Wurz P., Bochsler P., Paquette J.A., and Ipavich F.M., 2003, Astrophys. Jou. 583, 489