GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO.2, PAGES 157-160, JANUARY 15, 1999

Unusual composition of the solar wind in the 2-3 May 1998 CME observed with SWICS on ACE

G. Gloeckler,[1,2,3] L. A. Fisk,[3] S. Hefti,[3] N. A. Schwadron,[3] T. H. Zurbuchen,[3]
F. M. Ipavich,[1] J. Geiss,[4] P. Bochsler,[5] and R. F. Wimmer-Schweingruber[5]

Abstract. Elemental, isotopic and charge state abundances provide valuable information about the source and acceleration mechanism of Coronal Mass Ejections (CMEs). Even though the kinetic properties of the plasma might be subject to changes because of dynamic effects occurring during the expansion of the CME, the composition of the solar wind remains unchanged after it leaves the low corona. Data from the Solar Wind Ion Composition Spectrometer (SWICS) on ACE are used to study the elemental and charge state composition of He, O, C, N, and Fe as well as the isotopic ratio of He during the very large CME of May 2-3, 1998. We find in this CME anomalously large enrichment of $^3He^{++}/^4He^{++}$, He/O and Fe/O. During the 28 hour long cloud portion of the CME unusually cold material ($^4He^+$ and very low charge state heavy ions) was observed together with hot (high charge state ions) and normal solar wind plasma.

Introduction

Coronal Mass Ejections (CMEs), during which there is a sudden release of material from the low corona, provide a unique sample of the corona. The dynamics of the expansion of the CME reveal the interplay between the heating of the corona and the constraints imposed by the coronal magnetic field. Furthermore, CMEs are an important coupling mechanism between solar activity and terrestrial phenomena.

As with other studies of coronal processes, the composition of the plasma in CMEs has the potential of providing very unique and useful data. The elemental and isotopic composition reveals the basic or, in some cases, fractionated composition of the corona. The charge states of solar wind ions are frozen in as the material leaves the corona, and thus they reveal the electron temperature and density in the corona. To date, however, only relatively basic measurements of the elemental and charge state composition of CMEs have been made. (See Galvin [1997] for a review of compositional aspects of CMEs). Early work [*Bame, et al.*, 1979; *Schwenn et al.*, 1980; and *Zwickl et al.*, 1982] showed that He and heavier elements are overabundant in CMEs and there is enhanced He^+. Observations from the SWICS instrument on Ulysses revealed some compositional differences in CMEs, such as a high O^{7+}/O^{6+} ratio, indicating significant heating in the corona [*Galvin*, 1997]. However, at the heliocentric distance of Ulysses, statistics for measuring the composition are somewhat limited, and require integration times that restrict the ability to probe the detailed compositional structure of various CMEs.

On 2-3 May 1998 a dense, extended CME was encountered by the ACE spacecraft, orbiting about the L1 point. (See *Skoug et al.* [1998] for the plasma parameters of this CME). This CME was most likely the same as the 'halo' event detected by LASCO on SOHO on 29 April 1998 (see CME list posted by LASCO at http://lasco-www.nrl.navy.gov), and was probably associated with a long-duration M6.8 flare and possibly a prominence eruption.

As we discuss in this paper, the elemental and charge state composition of the 2-3 May CME is most unusual, and unlike any other recorded solar wind composition. The charge states of all elements measured extend over a broad spectrum, from very low to very high, indicating a wide range of temperatures which created these ions; the abundance of He and Fe are quite high compared to O; the $^4He^+/^4He^{++}$ density ratio stays around one for many hours; even ^3He is highly overabundant. We present these observations in the following section and in the final section, discuss their implications.

Observations

SWICS [*Gloeckler et al.*, 1998] uses four techniques (electrostatic deflection, post-acceleration, time-of-flight, and total energy measurements) to uniquely determine the mass, M, the charge, Q, and the energy or speed of solar wind ions, of suprathermal tails on the solar wind, and of interstellar pickup ions. The SWICS instrument on ACE is essentially the same as its counterpart on Ulysses. However, unlike Ulysses, SWICS on ACE is typically a factor of 3 closer to the Sun, and the resulting increase in density yields substantially better statistics, such that the full composition can be determined every ~12 minutes. This increased sampling rate, combined with the substantially increased density and extended spatial extent of the 2-3 May CME, make it possible for the first time to obtain detailed compositional measurements of the solar wind in a significant CME. The multiple coincidence required for the measurements makes the background extremely low, which allows determination of the composition of rare minor ions. SWICS is especially well suited to measure solar wind $^4He^+$ and the isotopic helium ratio, $^3He^{++}/^4He^{++}$, as described by *Gloeckler and Geiss* [1998a].

Shown in the top panel of Fig. 1 as a Mass vs. Mass/Charge matrix is the accumulated pulse height event data measured by SWICS for a 28 hour period beginning at 12:00 on 2 May (day 122). Clearly, the elemental and charge state abundances are well resolved. Despite some spill-over, the dominant peaks are plainly visible. The plasma parameters, such as bi-

---

[1] Department of Physics, University of Maryland, College Park, MD.

[2] Institute for Physical Sciences and Technology, University of Maryland, College Park, MD.

[3] College of Engineering, Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, Ann Arbor, MI.

[4] International Space Science Institute, Bern, Switzerland.

[5] Univeristy of Bern, Bern, Switzerland.

Paper number 1998GL900166.
0094-8276/98/1998GL900166$05.00

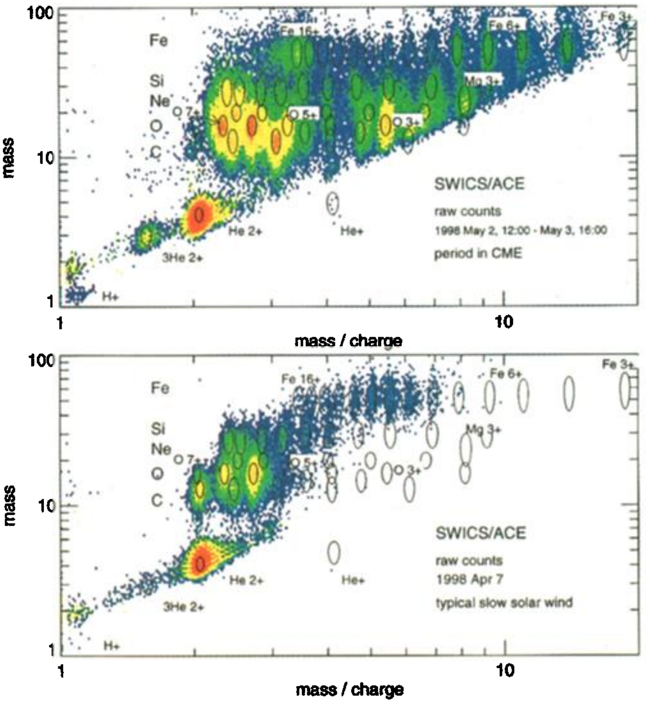

Figure 1. Mass *versus* Mass/Charge matrix. *Upper panel*: the period from 12:00 on 2 May through 16:00 on 3 May during the CME; *Lower panel*: the 24 hour period on 7 April 1998, when the solar wind was relatively slow. Selected charge states during the CME are noted in the upper panel, and repeated in the lower panel for reference. There are many more charge states observed during the CME, as compared to the slow solar wind. The full counts of H^+ and He^+ are not shown in this plot because they have insufficient energy to trigger the solid state detector. H^+ and He^+ are measured by using the time-of-flight and electrostatic deflection information.

directional anisotropies in the solar wind electrons and the characteristic rotation of the magnetic field, which identify this material to be associated with the magnetic cloud portion of the CME, are discussed in *Skoug et al.* [1998].

In the bottom panel of Fig. 1 is shown the Mass vs. Mass/Charge matrix typical of the slow solar wind. As is quite evident by comparing the two panels, the measurements in the CME contain far more charge states, from lower to higher charge states, than are present in the typical slow solar wind or even in other CMEs that have been studied. This wide range of charge states is illustrated more clearly in Fig. 2, where the histograms for the indicated Mass intervals are plotted. These M/Q histograms reveal the charge states of O (C and N due to some spill-over) and Fe. In the normal slow solar wind, created in the ~$1.5 \cdot 10^6$ K corona, the charge states of O are typically 6^+ and 7^+; yet although these ions are present in this CME, there is also a significant contribution from O^{3+}, N^{3+} and C^{2+} which should be created only in temperatures less than $0.2 \cdot 10^6$ K. Conversely, the charge states of Fe in the solar wind are typically around 9^+, 10^+ and 11^+, characteristic of a million degree corona, and yet in this CME there is a significant contribution from Fe^{16+}, which requires a hot (~$4 \cdot 10^6$ K) coronal plasma to be produced.

Figs. 1 and 2 contain data that are summed over the full 28 hour period. The time history of the event, which is what is uniquely available from SWICS on ACE, is even more revealing and is shown in Fig. 3. Here the densities of key ions are plotted relative to the density of $^4He^{++}$, averaged over the 28 hour period. As can be seen in the top and middle panels the densities of $^4He^{++}$ and O^{6+} are relatively constant during the entire period, and thus are good baseline measurements. There are dramatic changes in the composition of some of the ion species. The $^4He^+$ density, initially at a few percent of $^4He^{++}$, increases abruptly near 0:00 hours on day 123 (3 May) to where it becomes comparable to $^4He^{++}$, suggesting that the charge states of He were frozen-in at an extremely low temperature ($< 0.1 \cdot 10^6$ K). Such large $^4He^+/^4He^{++}$ ratios persisting for hours, have never been observed in the solar wind before. The increase in $^4He^+$ is accompanied by a somewhat smaller increase in O^{3+}, which, as in the case of $^4He^+$, is expected to be created in very low (~ $0.15 \cdot 10^6$ K) temperature regions. Our observation is similarly unusual in that such low charge states in the solar wind have never been clearly observed before. The abundance of Fe^{16+}, from presumably hot (~$4 \cdot 10^6$ K) coronal regions, remains high throughout much of the CME; however, near noon on day 123, it suddenly disappears. This could be an indication of cool prominence material embedded within the CME. There are also general trends in the more common ions, $^4He^{++}$, O^{6+}, and Fe^{6+}. The density of these ions, again relative to the average density of $^4He^{++}$, slowly increases throughout the CME, e.g., in the case of O^{6+}, rising by a factor of almost 10. Finally, the $^3He^{++}/^4He^{++}$ ratio is unusually high throughout the event, reaching its highest value of ~20 times that in the slow solar wind [*Gloeckler and Geiss*, 1998a] at ~7:00 hours on day 123. On the other hand, isotopic ratios of Mg and Si measured with the SWIMS instrument during this CME were the same as the corresponding ratios in the typical slow solar wind [*Wimmer-Schweingruber et al.*, 1998].

The average composition of the various elements in the CME plasma is given in Table 1. Not only are $^3He^{++}$ and $^4He^+$ highly overabundant compared with slow solar wind, but so is also He and Fe. Relative to O, He is overabundant by a factor ~10 and Fe by a factor of ~2. A general increase in the relative abundance of He and heavier ions in a CME is not

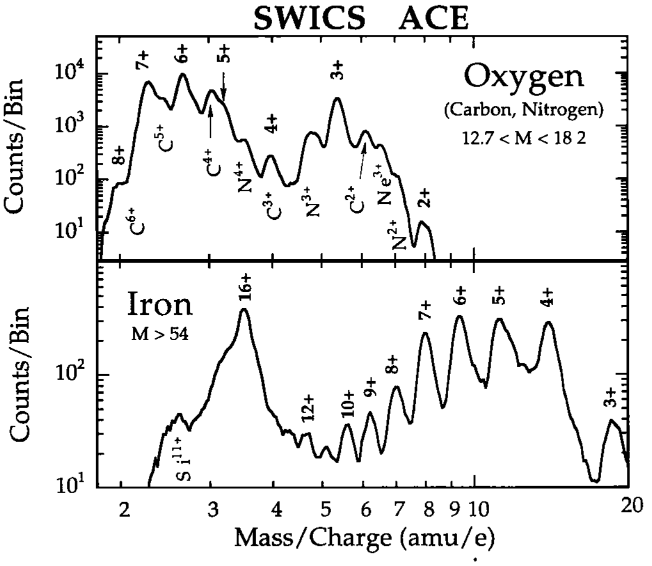

Figure 2. Charge states distributions of Oxygen (Nitrogen and Carbon through spill-over) and Iron in the 2-3 May 1998 CME. These data were averaged over a 28 hour period starting at 12:00 on 2 May. An unusually wide spectrum of charge states is observed for all of the elements measured.

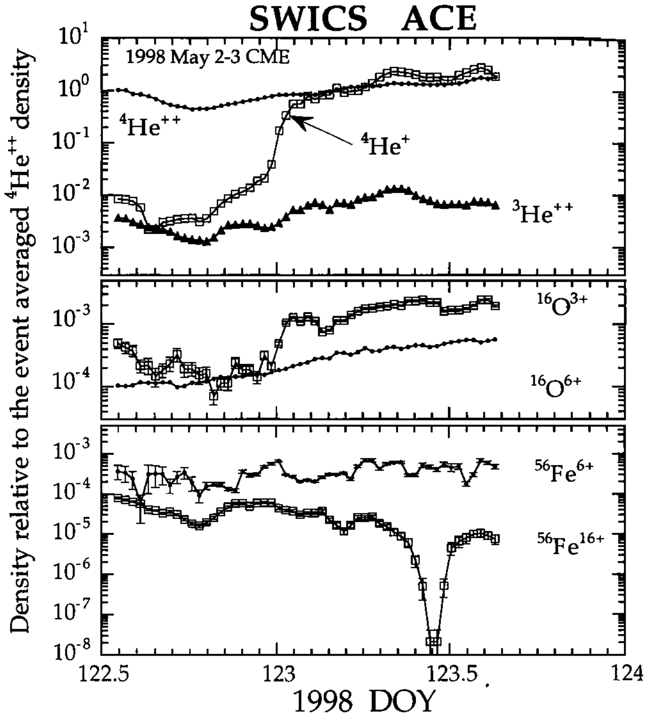

Figure 3. Density variations of $^4He^{++}$, $^4He^+$, $^3He^{++}$, O^{3+}, O^{6+}, Fe^{6+} and Fe^{16+} during the 2-3 May CME. All densities are relative to the average solar wind $^4He^{++}$ number density for the entire CME period. Each value shown is a 5-point running mean of 30-minute averaged densities. Error bars reflect only statistical errors and not systematic uncertainties. We note that while there is in general good agreement between the $^4He^{++}$ number densities measured here with SWICS with corresponding densities obtained with SWEPAM [*Skoung et al.*. 1998], systematic uncertainties (due to imprecise knowledge of efficiencies and other instrumental effects) in the densities of other ions cannot at present be ruled out. These uncertainties, however, should not change the qualitative nature of the temporal variations shown here.

unexpected [*Bame et al.*, 1979]. However, increases of this magnitude are most unusual.

The distribution functions of the key ions in the CME are also interesting since they reveal the dynamic processes that must be occurring. Shown in Fig. 4 are the velocity space density of $^4He^{++}$, $^4He^+$, and $^3He^{++}$ (multiplied by 140), plotted versus the relative speed W (particle speed divided by the solar wind speed). First, the distribution functions are quite similar, indicating that the ions have experienced similar processes. The core distributions of the thermal plasma are very narrow (thermal speed/solar wind speed ≈ 0.02), which is consistent with the CME expanding and being cooled during transit from the Sun, with the resulting decrease in the kinetic temperature. However, each of the ion species has a significant suprathermal tail, which is indicative of subsequent acceleration. Note the likely presence of interstellar pickup $^4He^+$. Interstellar neutral gas which is ionized in the solar wind is picked up and acquires a thermal velocity similar to the solar wind flow speed. In the frame of the spacecraft, then, as shown in Fig. 4, the speed of the particles without further acceleration does not exceed $W = 2$, which accounts for the knee in the distribution of $^4He^+$ at $W = 2$.

Table 1. Abundance Ratios in the 2-3 May CME Compared to the Typical Slow Wind

Ratio	2-3 May 1998 CME (this work)†	Slow Solar Wind
$^3He^{++}/^4He^{++}$	0.0072±0.0011	0.000408±0.000025*
$^4He^+/^4He^{++}$	0.70±0.35	<0.00005#
He/O	750±200	75±20‡.
Fe/O	0.28±0.10	0.12±0.03‡
Fe^{6+}/O^{3+}	0.33±0.03	--
Fe^{16+}/O^{6+}	0.10±0.01	--

†Errors are due to systematic uncertainties. Future analysis will reduce these errors significantly; **Gloeckler and Geiss* [1998a]; #*Gloeckler and Geiss* [1998b]; ‡*von Steiger et al.* [1997].

Discussion

The elemental and charge state composition observed in the May 1998 CME is most unusual and contains relative abundances and charge states not seen before in the solar wind. The relative abundance of the elements -- a substantial increase in He and to a lesser extent heavier elements such as Fe -- is unusual, but only in degree from what reasonably might be expected in a CME. The typical solar wind He/H abundance of <4% [*Neugebauer*, 1981] is lower than the solar He/H ratio. He, presumably, is not accelerated in the solar wind as effectively as H, and thus should accumulate in the base of the corona. Similarly, gravitational settling of heavier elements

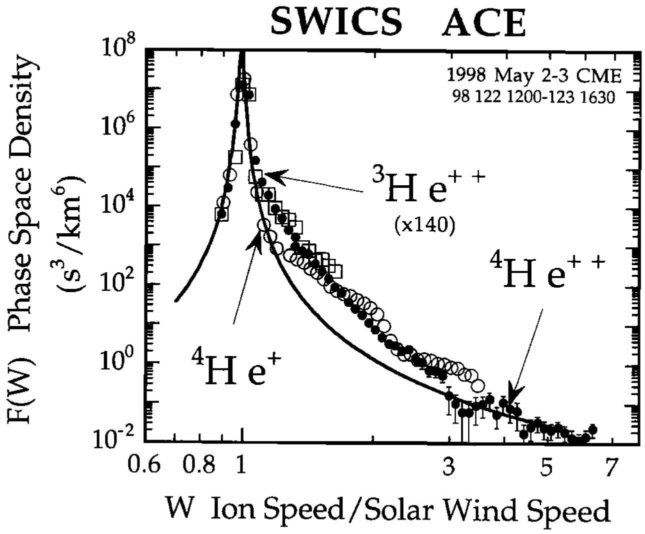

Figure 4. Velocity distribution functions of $^4He^{++}$ (solid circles), $^4He^+$ (open circles) and $^3He^{++}$ (open squares) averaged over 28.5 hours during the 2-3 May 1998 CME event. W is the ion speed divided by the solar wind proton bulk speed. The average abundance of solar wind $^4He^+$ is unusually large, being about as abundant as $^4He^{++}$. The average $^3He^{++}/^4He^{++}$ density ratio is also substantially higher than its typical solar wind value. The velocity distributions of the two charge states of ^4He are identical below $W \approx 1$, but the phase space density of $^4He^{++}$ exceeds that of $^4He^+$ above $W \approx 1.1$, and $^4He^{++}$ has a very pronounced high velocity tail. The shape of the $^3He^{++}$ velocity distribution, which has been multiplied by 140, is the same as that of $^4He^{++}$ over the entire W range of the $^3He^{++}$ spectrum and also has a significant suprathermal component. The core distributions are non-maxwellian; the curve is a kappa function fit to the $^4He^+$ distribution with $\kappa = 2.3$.

could lead to their overabundance in the corona. Even the isotopic abundance of $^3He^{++}$ in the low corona can be enhanced by the interaction of gravitational settling and wave heating [*Zurbuchen et al.*, 1998]. Thus, if the CME develops initially from material at the coronal base, it is not unreasonable that it is overabundant in He and heavier elements.

The charge state composition is much more difficult to understand and my be further complicated by the probable association of this CME with a substantial solar flare that could supply much of the high charge state material. Charge states are frozen-in as the CME propagates outward from the Sun. To freeze-in, the characteristic expansion time for a given ion must exceed the characteristic time for ionization and recombination, in which case no further evolution of the charge distribution will occur. This phenomena is well known in the usual solar wind and can be used to constrain the electron density and temperature profiles in the corona [e.g. *Ko et al.*, 1997]. In the case of a CME, the time history of the density and temperature can be more complicated. The initial density can be quite high, since the CME forms in the low corona. The initial temperature can be quite variable. If the CME forms by a sudden heating process, which increases the plasma pressure to where it overcomes the magnetic pressure and releases the CME, then the initial temperature is high, as are the charge states (e.g. Fe^{16+} could be formed). Conversely, if a prominence is embedded in the initial CME, the initial temperature and accompanying charge states could be low. The subsequent evolution of the CME could also be quite complicated and variable. The CME should expand rapidly in three dimensions and presumably cool adiabatically. The final charge states are then a function of the initial density and temperature, and their subsequent time evolution, and depending on how these parameters interplay with the ionization and recombination rates of the various ions, many different charge state distributions can result. Detailed modeling of the evolution of the charge states is currently underway.

Finally, one very distinguishing feature of this CME is the long duration of the unusual composition (see Fig. 3), indicating the coexistence of material formed in cold, hot and normal temperature regions in the corona. This is in contrast for example, to the January 1997 CME studied in some detail by *Burlaga et al.* [1998], who found high (0.01) $^4He^+/^4He^{++}$ ratios, O^{5+} and Fe^{5+} only in the few hour long high-density region associated with a prominence embedded in the CME. Undoubtedly, studying the anomalous composition seen in many CMEs is important for developing a comprehensive understanding of mechanisms by which these interesting solar phenomena form and evolve.

Acknowledgments. This work was supported, in part, by NASA contract NAG 5-6912. Special appreciation for the effort to develop the SWICS/ACE instrument and to analyze the data presented here goes to P. Bedini and C. Gloeckler respectively.

References

Bame S. J., J. R. Asbridge, W. C. Feldman, E. E. Fenimore, and J. T. Gosling, Solar wind heavy ions from flare heated coronal plasma, *Solar Phys., 62*, 179, 1979.

Burlaga, L., R. Fritzenreiter. R. Lepping, K. Ogilvie, A. Szabo, A. Lazarus, J. Steinberg, G. Gloeckler, R. Howard, D. Michels, C. Farrugia, R. P. Lin, and D. E Larson, A magnetic cloud containing prominence material: January 1997, *J. Geophys. Res., 103*, 277, 1998.

Galvin, A. B., Minor ion composition in CMEs, in *Coronal Mass Ejections*, eds. Nancy Crooker, Jo-Ann Joselyn, Joan Feynman, *Geophysical Monograph*, 99, 253, 1997.

Gloeckler, G., and J. Geiss, Measurements of the abundance of ^{3}He in the Sun and in the local interstellar cloud with SWICS on Ulysses, in *Primordial Nuclei and Their Galactic Evolution*, eds. N. Prantzos, N. Tosi, and R. von Steiger, *Space Sci. Revs., 84*, 275, 1998a.

Gloeckler, G. and J. Geiss, Interstellar and inner source pickup ions observed with SWICS on Ulysses, *Space Sci. Revs.* , in press, 1998b.

Gloeckler, G, P. Bedini,, L. A. Fisk, T. H. Zurbuchen, F. M. Ipavich, J. Cain, E. O. Tums, P. Bochsler, J. Fischer, R. F. Wimmer-Schweingruber, J. Geiss, and R. Kallenbach, Investigation of the composition of solar and interstellar matter using solar wind and pickup ion measurements with SWICS and SWIMS on the ACE spacecraft, *Space Sci. Rev.*, in press, 1998.

Ko, Y-K, L. A. Fisk, J. Geiss, G. Gloeckler, and M. Guhathakurta, An empirical study of the electron temperature and heavy ion velocities in the south polar coronal hole, *Solar Phys., 171*, 345, 1997.

Neugebauer, M., Observations of solar-wind helium, *Fundamentals of Cosmic Physics, 7*, 131, 1981.

Schwenn, R., H. Rosenbauer, and K.-H. Mühlhäuser, Singly-ionized helium in the driver gas of an interplanetary shock wave, *Geophys. Res. Lett., 7*, 201, 1980.

Skoug, R. M., S. J. Bame, W. C. Feldman, J. T. Gosling, D. J. McComas, J. T. Steinberg, R. L. Tokar, P. Riley, L. F. Burlaga, N. T. Ness, and C. W. Smith, A prolonged He enhancement within a coronal mass ejection in the solar wind, *Geophys. Res. Lett.*, this issue, 1998.

von Steiger, R., J. Geiss, and G. Gloeckler, Composition of the solar wind, in *Cosmic Winds and the Heliosphere*, eds. J. R. Jokipii, C. P. Sonnett, and M. S. Giampapa, *University of Arizona Press*, 581, 1997.

Wimmer-Schweingruber, R. F., P. Bochsler, G. Gloeckler, F. M. Ipavich, J. Geiss, R. Kallenbach, L. A. Fisk, S. Hefti, and T. H. Zurbuchen, On the bulk isotopic composition of magnesium and silicon during the May 1998 CME: ACE/SWIMS, *Geophys. Res. Lett.*, this issue, 1998.

Zurbuchen, T. H., L. A. Fisk, G. Gloeckler, and N. A. Schwadron, Element and isotopic fractionation in closed magnetic structures, *Space Sci. Revs.*, in press, 1998.

Zwickl, R. D., J. R. Asbridge, S. J. Bame, W. C. Feldman, and J. T. Gosling, He^+ and other unusual ions in the solar wind, *J. Geophys. Res., 87*, 7379, 1982.

G. Gloeckler and F. M. Ipavich, University of Maryland, Department of Physics, College Park, MD 20742. (e-mail: gg10@umail.umd.edu)

L. A. Fisk, S. Hefti, N. A. Schwadron and T. H. Zurbuchen, University of Michigan, College of Engineering, Department of Atmospheric, Oceanic and Space Sciences, 2455 Hayward Street, Ann Arbor, MI 48109. (e-mail: lafisk@umich.edu; hefti@umich.edu; nathanas@umich.edu; thomasz@umich.edu)

J. Geiss, International Space Science Institute, Hallerstrasse 6, CH-3012 Bern, Switzerland. (e-mail: geiss@issi.unibe.ch)

P. Bochsler and R. F. Wimmer-Schweingruber, University of Bern, Bern, Switzerland. (email: bochsler@soho.unibe.ch)

(Recieved September 1, 1998; accepted October 12, 1998.)