

On the Bulk Isotopic Composition of Magnesium and Silicon during the May 1998 CME: ACE/SWIMS

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Abstract. The coronal mass ejection (CME) observed at the Advanced Composition Explorer (ACE) spacecraft on May 2 and 3, 1998, exhibited very high as well as exceptionally low charge states of all ions. In addition, ^3He was considerably enhanced by in the bulk material of the CME. High $^3\text{He}/^4\text{He}$ ratios in solar energetic particles have recently been observed in some events to coincide with substantial enrichments in the heavy isotopes of heavy elements. We use data from the Solar Wind Ion Mass Spectrometer (SWIMS) on ACE to investigate whether the enrichment of the heavy isotopes in solar energetic particles is mirrored in the isotopic composition of solar wind Mg and Si. We concentrate on the time period where the unusual mixture of charge states and unusually high $^3\text{He}/^4\text{He}$ was observed to test for isotopic fractionation in such extreme solar wind conditions. We find very little or no enrichment of the neutron-rich isotopes with respect to the main isotopes. Incidentally, this is also the first report on the isotopic composition of ions with $Z > 2$ in the bulk material in a CME.

Introduction

Coronal Mass Ejections (CMEs) often exhibit unusual elemental and charge-state compositional signatures. For instance He/H very often considerably exceeds values typical of the solar wind [Hirshberg *et al.*, 1970, 1972], Fe has been reported to be enriched [Bame *et al.*, 1979; Mitchell *et al.*, 1983; Ipavich *et al.*, 1986]. Fe^{16+} and higher charge states have been observed [Bame *et al.*, 1979; Fenimore, 1980; Ipavich *et al.*, 1986], often low charge ions coexist with such high charge states [Fenimore, 1980; Schwenn *et al.*, 1980; Ipavich *et al.*, 1986; Galvin *et al.*, 1993]. See Galvin [1997] for a more complete overview of the compositional aspects of CMEs. Apart from dramatic variations in the

$^3\text{He}/^4\text{He}$ isotopic abundance ratio, the isotopic composition of CMEs has so far been unknown.

The CME observed on May 2 and 3, 1998 at the Advanced Composition Explorer (ACE) spacecraft shows a mixture of high and low charge states for all elements, as is discussed in an accompanying paper by Gloeckler *et al.* [1998]. For instance, Fe^{16+} was observed as a prominent peak, at the same time as was Fe^{6+} . Fe^{16+} is most prominent at coronal temperatures of several MK, while Fe^{6+} is already nearly completely destroyed at coronal temperatures above 0.7 MK [Arnaud and Raymond, 1992]. The plasma parameters for this CME, such as velocity, kinetic temperatures, etc. are discussed in an accompanying paper by Skoug *et al.* [1998]. The ^3He abundance relative to ^4He is considerably enhanced over its usual solar wind value and extremely variable in time, as is shown by Gloeckler *et al.* [1998].

High $^3\text{He}/^4\text{He}$ ratios in solar energetic particles have recently been observed in some events to coincide with substantial enrichments in the heavy isotopes of heavy elements such as Mg [Mason *et al.*, 1994; Leske *et al.*, 1998, b]. We use data from the Solar Wind Ion Mass Spectrometer (SWIMS) on ACE to investigate whether the enrichment of the heavy isotopes sometimes observed in solar energetic particles is mirrored in the isotopic composition of solar wind Mg and Si. We investigate the CME observed at ACE on May 2 – 3, 1998, and concentrate on the time period where the unusual mixture of charge states and unusually high $^3\text{He}/^4\text{He}$ was observed to test for isotopic fractionation in such extreme solar wind conditions.

Instrument Description and Data Analysis

We chose to analyze data from the second half of the CME (i. e. all of May 3, 1998) for two reasons, one instrumental, one physical. We did not analyze the first half of the CME in order to avoid an instrumental bias which occurs at higher solar wind speeds for the instrument settings during that time period. It decreases with decreasing solar wind speed, and can then be corrected for. We will discuss these corrections further down. The physical reason lies in

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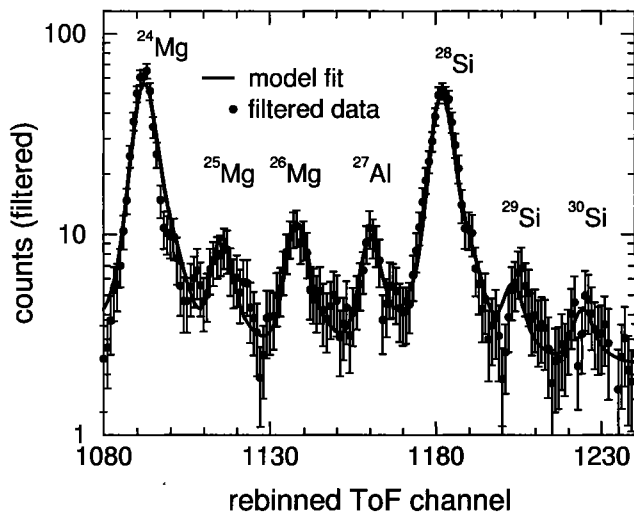


Figure 1. Optimally filtered time-of-flight spectrum and fitted model function for May 3, 1998, the second half of the May 1998 CME observed at ACE. See text for discussion.

the very unusual charge-state distribution of the solar wind observed during this time period reported in the accompanying paper by *Gloeckler et al.* [1998].

SWIMS is an isochronous time-of-flight mass spectrometer based on the carbon-foil technique. It is described in more detail by *Gloeckler et al.* [1999]. Solar wind ions are analyzed in E/q and subsequently hit a thin carbon foil. For solar wind energies, Mg and Si ions leave the carbon foil mainly as singly charged ions [*Bürgi et al.*, 1993; *Gonin et al.*, 1995]. The subsequently measured time of flight is uniquely determined by the mass per charge of the ion.

Eliminating proton-induced background, we obtained a raw time-of-flight spectrum of all of May 3, 1998. We rebinned it to eliminate a non-linearity of the time-of-flight analog-to-digital conversion electronics that enhances the even time-of-flight channels. Due to the small number of counts in each time-of-flight channel the ensuing statistical fluctuations are large, somewhat masking the signal. However, knowledge of the shape and position of the signal (i. e. the peaks) introduces additional information that can be used to extract the true signal even out of noisy data sets. A standard technique in signal processing (and in our time-of-flight analysis) is the application of a Rauch-Tung-Striebel filter [*Gelb*, 1974]. We applied this filter to the rebinned time-of-flight spectrum and fitted the model function to the thus filtered data using an iterative, non-linear Levenberg-Marquardt algorithm [*Press et al.*, 1989] to maximize likelihood. The resulting filtered time-of-flight spectrum is shown in Figure 1 together with the model function.

In order to refine the analysis, we applied two well understood correction factors. The E/q resolution of the E/q analyzer is a constant fraction of the current E/q and thus results in a correction of m_{low}/m_{high} for the heavier isotopes. For the instrument settings during the time period discussed, this is the dominant correction factor. The other correction factor is related with the angular distribution after the carbon foil. Figure 1 clearly demonstrates that these corrections aren't large. The ^{24}Mg and the ^{28}Si peaks are of comparable amplitude. Applying our corrections we obtain

a ratio $^{24}\text{Mg} / ^{28}\text{Si} = 0.94 \pm 0.07$ where the error is statistical only. This is to be compared with its photospheric value $^{24}\text{Mg} / ^{28}\text{Si} = 0.92$ [*Anders and Grevesse*, 1989]. The close agreement between the two values demonstrates that we are applying sensible correction factors, since we do not expect substantial first ionization potential (FIP) fractionation between these two low-FIP elements.

For the error analysis, we considered two sources of uncertainties: Statistics for this single event are low, we counted 63 ^{25}Mg counts, 84 ^{26}Mg counts, 27 ^{29}Si counts, and 18 ^{30}Si counts. In addition, the fitting procedure introduces its own uncertainties. These were determined using the fitted parameters to generate 100 artificial time-of-flight spectra which were subjected to the same fitting procedure as was applied to the original data. We thus found an additional uncertainty of 1.3 percent absolute. Summing quadratically, we obtain our final error estimate for the observed isotopic abundance ratios.

Results and Discussion

We report our results in Table 1. The isotopic composition observed during the May 1998 CME is consistent with meteoritic values [*Anders and Grevesse*, 1989], and previously determined values for the solar wind [*Bochsler et al.*, 1997; *Kucharek et al.*, 1998; *Wimmer-Schweingruber et al.*, 1998]. Since magnesium and silicon are refractory elements we may assume that their solar isotopic composition is largely the same as the bulk composition of primitive meteorites (e. g. *Wimmer-Schweingruber et al.* [1998]) which typically vary on the order of one per thousand per mass unit. Our analysis shows very little or no enrichment relative to the meteoritic abundances of the heavier isotopes relative to their main isotopes ^{24}Mg and ^{28}Si in the bulk of the plasma for the time period investigated. This suggests that this material was not or only weakly fractionated by mass or by mass-per-charge. The coexistence of extremely low charge states with high charge states of all elements are reminiscent of simulations of plasmoids reported by *Neukomm and Bochsler* [1996] (see e. g. their Figure 5). If this is indeed the origin of this type of solar wind, then our observations show that there is very little or no mass fractionation (e. g. by gravitation) even in the closed magnetic structures that frequently carry neutral atoms out to several solar radii above the solar surface [*Michels et al.*, 1981; *Sheeley et al.*, 1981].

Variations in isotopic abundances with different solar wind regimes must be small, as can be seen from Table 1. Sophisticated isotopic fractionation models for the solar wind set upper limits to isotopic fractionation of at most few percent per mass unit [*Bodmer and Bochsler*, 1998], consistent with in situ measurements [*Bochsler et al.*, 1997; *Kallenbach et al.*, 1997; *Wimmer-Schweingruber et al.*, 1998; *Kucharek et al.*, 1998]. *Kallenbach et al.* [1998] report a systematic depletion of the heavier isotopes of Ne, Mg, and Si on the order of 2% per mass unit for low solar wind speeds. This depletion disappears with increasing speed and their data are consistent with meteoritic composition in the high-speed wind. In view of the smallness of isotopic fractionation effects, and of the small number of counts observed by SWIMS in this CME, we did not try to investigate a possible temporal variation in the isotopic composition of this event.

Recently *Wurz et al.* [1998] have used the excellent statistical resolution of the Mass Time Of Flight (MTOF) in-

Table 1. Values for the isotopic composition of Mg and Si. Our results for the bulk plasma for May 3, the second half of the May 1998 CME are given in the line marked CME. See text for discussion.

source	$^{25}\text{Mg}/^{24}\text{Mg}$	$^{26}\text{Mg}/^{24}\text{Mg}$	ref.	$^{29}\text{Si}/^{28}\text{Si}$	$^{30}\text{Si}/^{28}\text{Si}$	ref.
FSW	12.8 ± 1.1	13.8 ± 1.2	a	—	—	
SSW	13.2 ± 1.3	15.3 ± 1.3	a	—	—	
SSW	13.0 ± 0.7	13.7 ± 1.0	b	5.0 ± 0.2	3.39 ± 0.2	h
CME	11.7 ± 2.1	14.6 ± 2.4	c	5.6 ± 1.6	3.6 ± 1.5	c
SOL	12.66	13.94	d	5.06	3.36	d
SEP _s	13.1 ± 1.9	15.1 ± 1.9	e	4.8 ± 1.1	3.2 ± 0.9	e
SEP _s	14.8 ± 3.6	14.8 ± 3.4	f	16.8 ± 16.8	2.6 ± 4.6	i
SEP _s *	25.0 ± 19.0	36.0 ± 21.0	g	—	—	

^a[Bochsler et al., 1997].

^b[Kucharek et al., 1998].

^cThis work.

^d[Anders and Grevesse, 1989].

^e[Williams et al., 1998].

^f[Mewaldt et al., 1984].

^g[Mason et al., 1994].

^h[Wimmer et al., 1998].

ⁱ[Simpson et al., 1983].

SSW denotes slow solar wind, FSW fast solar wind, CME coronal mass ejection, SOL solar system, and SEP_s solar energetic particles. Mean of asymmetric uncertainties of Mewaldt et al. [1984] and Williams et al. [1998] given.

* ³He rich event

strument aboard the SOLar and Heliospheric Observatory (SOHO) to study the elemental composition of the January 6, 1997 CME. They found elemental enrichment factors monotonically increasing with mass up to 4.0 ± 0.6 for Fe/O relative to a reference (FIP enhanced) interstream solar wind value. If the May 1998 CME had undergone the same mass dependent fractionation process, we would have expected an enrichment of ²⁶Mg relative to ²⁴Mg by a factor ~ 1.1 . Such an enrichment factor can not be excluded by our data, due to the limited statistics available. However, enrichments by factors $\sim 2-3$ found for SEP_s in a ³He-rich event by Mason et al. [1994], Leske et al. [1998], and Leske et al. [1998b] are excluded. If such enrichments are observed in the energetic particles for this event observed at ACE, then our data indicate that this enrichment must be mostly due to the acceleration process of these particles, but not of the solar wind. The source population of SEP_s may be the solar wind itself, coronal material, or the CME material, all of which are now known to be very little fractionated if at all.

To summarize, we may state that, independent of any model assumptions, the solar plasma in the second half of the May 1998 CME, that has experienced very unusual transport through the solar corona (as reflected by the observed unusual charge-state distribution) and has an extremely enriched ³He abundance, has undergone very little or no isotopic fractionation. This is important for future missions such as e.g. Genesis, which will measure the isotopic composition of different solar wind regimes with unprecedented mass resolution and consequently high sensitivity to unanticipated admixture of isotopically fractionated plasma.

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