MAGNESIUM ISOTOPIC ABUNDANCE IN SLOW AND CORONAL HOLE ASSOCIATED SOLAR WIND: SOHO/CELIAS/MTOF MEASUREMENTS.

H. Kucharek[1], F. M. Ipavich[2], R. Kallenbach[3], B. Klecker[1], H. Grünwaldt[4] M. R. Aellig[5]*, P. Bochsler [5]
[1]Max-Planck-Institut für extraterrestrische Physik, 85740 Garching, Germany
[2]Department of Physics, University of Maryland, College Park, MD 20742, USA
[3]International Space Science Institute, CH-3012 Bern, Switzerland
[4]Max-Planck-Institut für Aeronomie, 37189 Katlenburg-Lindau, Germany
[5]Physikalisches Institut der Universität Bern, CH-3012 Bern, Switzerland

ABSTRACT

Data from the high resolution Mass Time-of-Flight spectrometer MTOF and the Charge Time-Of-Flight spectrometer (CTOF) on board SOHO have been analyzed for time periods in which coronal hole or non-coronal hole type plasma has been detected in order to investigate the abundance ratios of magnesium isotopes originating from these two different source regions of the solar wind in the context of isotope fractionation. As an indicator for slow solar wind and coronal hole associated solar wind the freeze-in temperature as well as the Fe/O ratio derived from the CTOF experiment onboard SOHO have been used. A dependence of the magnesium isotopic abundance ratios on the freeze-in temperature of O^{6+}/O^{7+} as well as on the Fe/O ratio has been found which indicates a possible depletion of the heavier isotopes in the slow solar wind.

Key words: solar wind; magnesium isotopic variation; fractionation processes.

1. INTRODUCTION

The study of the solar isotopic composition is motivated by the interest in the composition of the early solar nebula which provides knowledge about the history of the solar system. It also provides the opportunity to analyze solar matter *in situ* and get information about the present day composition of the outer convective zone of the Sun. The flow dynamics of the solar wind are determined by the magnetic topology of the flux tubes. The slow solar wind originating from closed field line regions, has a low bulk velocity and high freeze-in temperature whereas the high speed solar wind having a low freeze-in temperature originates from open flux tubes in coronal holes. Thus, freeze-in temperatures are a very powerful tool for coronal diagnostic. They are established a few solar radii above the solar surface and they do not change on their way throughout the interplanetary medium. This is in contrast to the dynamic properties of the solar wind, like the solar wind speed or solar wind density. In order to investigate possible fractionation processes, data from the high resolution Mass Time-of-Flight spectrometer MTOF and the Charge Time-Of-Flight spectrometer CTOF on board SOHO have been analyzed for time periods in which coronal hole or non-coronal hole type plasma have been detected. The results obtained from this analysis indicate that heavier isotopes are depleted by 1.5% ± 1.4% per mass unit in the slow solar wind.

2. INSTRUMENTATION

For the investigation shown below we have used data of two sensors onboard SOHO: the Mass Time-Of-Flight sensor MTOF and Charge Time-Of-Flight sensor CTOF. Since details of these sensors can be found in Hovestadt et al. (1995), Kallenbach et al. (1997) for MTOF as well as Grünwaldt et al.(1997) for CTOF, we only briefly review the basic function of these sensors. In the MTOF sensor (see Figure 1 for a schematic view) highly charged solar wind ions enter the Wide Angle Variable Energy entrance system (WAVE) which is designed to suppress the solar wind proton flux and the solar UV flux. After the remaining ions leave the WAVE they can be accelerated or decelerated depending on their energy before they enter the V-shaped VMASS isochronous time-of-flight spectrometer. At the entrance to VMASS, the ions pass through a thin carbon foil where secondary electrons are released which produce a start signal at the Electron Micro-Channel Plate (EMCP). After passing through the carbon foil, particles are mostly neutral or singly ionized. In VMASS a hyperbola deflection electrode and a V-shaped ground electrode generate an electrostatic harmonic potential so that the time-of-flight (TOF) in the detector is proportional to $(M/Q)^{1/2}$ where M is the mass and Q the charge of an ion after passing through the thin carbon foil. Finally, the TOF is measured between the start and the stop signal which the ion generates at the Ion Micro Channel Plate detector (IMCP).

The CTOF sensor of the SOHO/CELIAS experiment

*Present address: MIT Center for Space Research, Cambridge, USA is a linear time-of-flight mass spectrometer (see Figure 2). It is designed to separate individual charge states of different species up to iron. The solar wind ions enter the CTOF entrance system which consists of an electrostatic energy per charge analyzer located between two quadrupole lenses. Prior to their entrance into the TOF section, the ions are accelerated by up to 23.7 keV to raise their energy above the threshold of the solid state detector and to improve the charge state resolution. The identification of solar wind ions is obtained by measuring the energy/charge, E/Q, the time-of-flight T, and the residual energy E_d deposited in the solid state detector. From this one can determine the mass, M, and the velocity, s/T, of each ion. The mass per charge ratio, M/Q, will be derived by combining the accurate measurement of E/Q in the electrostatic deflection system and the time-of-flight T. From the measurement of M and M/Q the ionic charge Q, and finally from Q and E/Q the initial energy E can be derived. For a more detailed description we refer to Hovestadt et al. (1995). It is known that charge states of minor ions in the solar wind provide a very effective tool to detect variations of the electron temperature profile in the solar corona. Due to the high sensitivity of the CTOF sensor it is possible to perform coronal diagnostic by using solar wind *in situ* measurements with high time resolution. The application of a simple model of the coronal expansion allows to calculate freeze-in temperatures which result in a parametrization of the coronal properties like the coronal electron temperature (Aellig et al. (1997)). This temperature allows us to distinguish between two types of solar wind: the slow solar wind and the coronal hole associated solar wind.

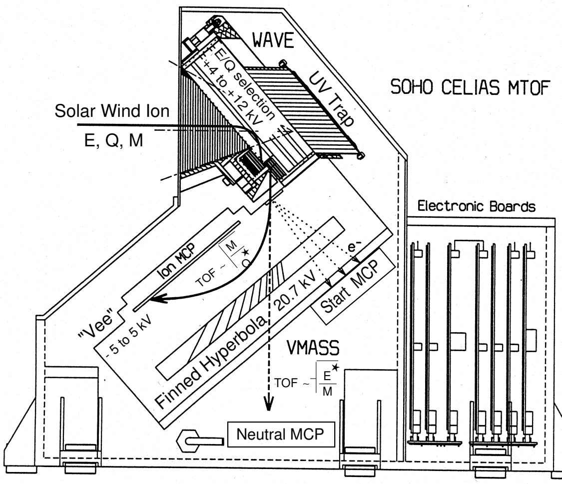

Figure 1. Schematic view of the Mass-Time-Of-Flight senor MTOF. Shown is the entrance system Wave and the time-of-flight analyzing system with the finned hyperbola.

Another important parameter to distinguish between these two classes of solar wind is the Fe/O ratio. In the solar wind, elements with low first ionization potential (FIP) ($<$ 10 eV) are systematically enriched relative to high FIP elements compared to their photospheric abundance. The enrichment factor ranges from 3-5 for slow solar wind associated

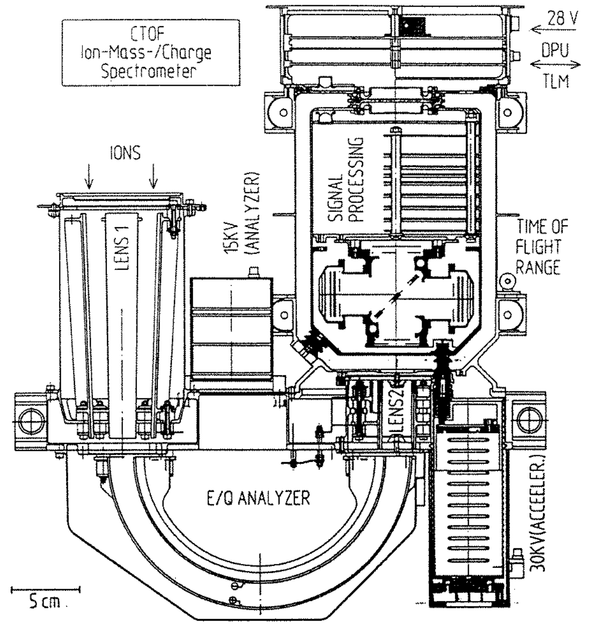

Figure 2. Schematic view of the CTOF sensor onboard SOHO.

with the streamer belt, and is about two for fast solar wind associated with coronal holes (v. Steiger et al. (1996)). Oxygen is the most prominent high FIP element whereas Fe is one of the most prominent low FIP elements. Figure 3 (from Aellig et al., 1999) shows the distribution of the Fe/O abundance ratio as a function of the solar wind bulk speed. Also shown is the corresponding fractionation factor on the right hand scale. The Fe/O ratios have been determined from CTOF data whereas the solar wind speed has been taken from the proton monitor (PM) onboard SOHO which is a subsystem of the MTOF sensor. In that data analysis by Aellig et al. (1999) a reasonable agreement was found with previous measurements for the Fe/O abundance ratio of slow solar wind (Ipavich et al., 1992) and for fast or coronal hole associated solar wind (Geiss et al., 1995). In Figure 3 two distinct regions can be identified in which the Fe/O abundance ratio is constant: for slow and fast solar wind. Usually this type of solar wind is associated with solar matter originating either from closed field lines and coronal hole regions on the Sun, respectively. For the data selection and the data analysis these two parameters have been used for the selection of the MTOF mass spectra which have been accumulated in order to determine the magnesium isotopic ratios and their possible variation caused by fractionation processes.

3. DATA SELECTION AND OBSERVATION

The MTOF mass spectra have been combined with the data derived from the CTOF experiment and selected according to the freeze-in temperature as well as the Fe/O ratio which is typical for slow solar wind or coronal hole associated solar wind, respectively.

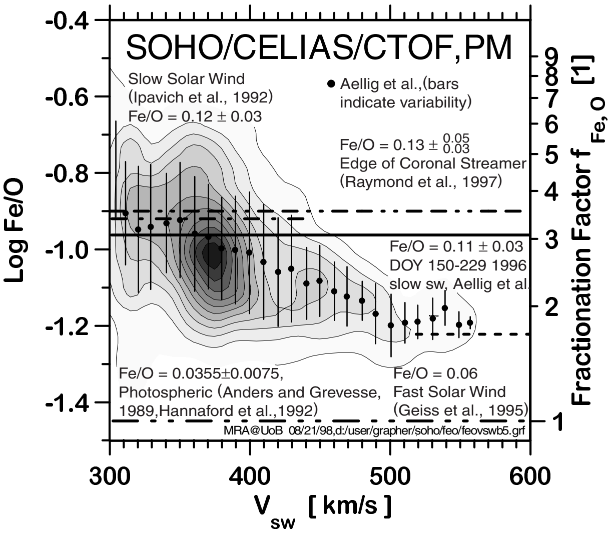

Figure 3. Distribution of the Fe/O abundance ratio and the corresponding fractionation factor measured with SOHO/CELIAS/CTOF organized by the solar wind bulk speed measured with the proton monitor onboard SOHO. The overlaid dots are the mean values for a particular bulk speed bin. Also shown are the results from previous measurements. (From Aellig et al., 1999)

For this analysis data from Day Of Year (DOY) 150 to DOY 220 from 1996 have been used where CTOF was fully operational. We will not describe the data analysis for MTOF which provides the spectra and the abundance for the magnesium isotopes in detail and we will not report on the data processing for CTOF which delivers the freeze-in temperature and the Fe/O ratio because this has been done in previous publications e.g., Kucharek et al., (1998) and Aellig at al. (1998). For the data selection we have characterized coronal hole associated solar wind by a Fe/O ratio of 0.06 whereas slow solar wind coming from closed field line structures have been identified by a Fe/O abundance ratio of 0.12. For a second selection criterion we have used the freeze-in temperature. Freeze-in temperatures for O^{6+}/O^{7+} measured in the solar wind range usually from 1.2 MK to 2 MK. Here, coronal hole solar wind is associated with a freeze-in temperature of 1.2 - 1.3 MK and slow solar wind with 1.5-2.0 MK. The MTOF spectra have been grouped into classes of Fe/O ratios and freeze-in temperatures. Within these classes of MTOF spectra the data have been filtered with respect to the instrumental isotopic fractionation which arises from modification of solar wind energy-per-charge distributions of the different isotopic species while passing through the electrostatic deflection system (WAVE). All data sets which have shown larger instrumental fractionation than ±15% have been disregarded when determining the isotopic ratios of the magnesium isotopes. In order to calculate the instrumental fractionation the entrance system voltage U_w and the post acceleration voltage V_f have been used which are available every five minutes from the housekeeping data. The dynamic parameters of the solar wind, like solar wind speed and the kinetic temperature can be obtained at the same time bases from the proton monitor which is a subsystem of MTOF. In the following section we summarize the results obtained from this investigation.

4. RESULTS

Using the above mentioned criteria and the entire time period of 60 days starting with DOY 150 to DOY 220 of 1996 we have detected slow solar wind for about 55% of the time and about 13% coronal hole associated solar wind which corresponds to about 8 days. Figure 4 shows a MTOF mass spectrum for Fe/O ratio less than 0.07 i.e. for coronal hole associated solar wind accumulated over the whole time period of 60 days. Shown are counts versus the relative channel number. All three isotopes are well above the background. The dashed line shows a fit to the measured data. The position and the height of every peak has been fitted by Lorentzian like functions with identical width. Therefore, the model function for the mass spectrum is a sum of those functions whereas the background has been assumed to be a linear function in the TOF channel numbers with a fitted constant value. Details of the model function can be found in a previous paper of Kucharek et al., (1998). Due to its high time resolution it is

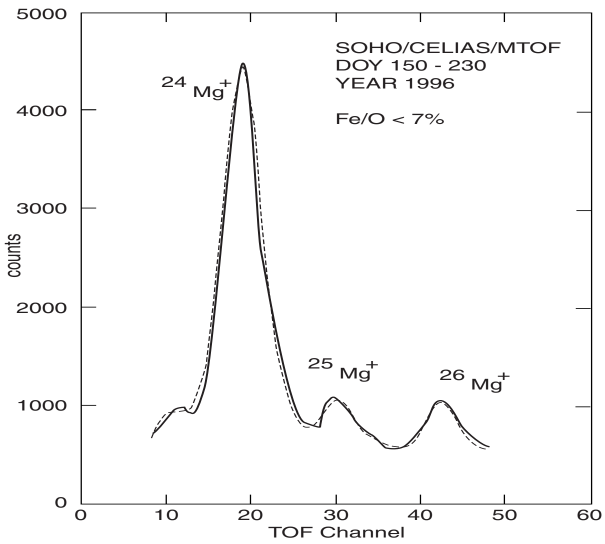

Figure 4. Mass spectrum obtained from MTOF sensor. The data have been accumulated for time periods in which the Fe/O ratio was smaller than 0.07.

possible to investigate the relative short time periods with high statistics. Therefore, it is possible to investigate isotopic abundance ratios originating from different source regions of the Sun and it is possible to study temporal events like CME's or CIR's. For these time periods we have accumulated the MTOF spectra and we have determined the isotopic abundance ratio for $^{24}Mg/^{26}Mg$ and for $^{24}Mg/^{25}Mg$. In Table 1 we have summarized the results from the investigations mentioned above by using both criteria, the Fe/O ratio and the freeze-in temperature as an indicator for slow solar wind and coronal hole associated solar wind. For comparison we have also show the terrestrial ratios for the magnesium isotopes (Anders and Grevesse, 1989). From the above results we have derived an average relative depletion of the heavier isotopes for slow solar wind of 1.5%±1.4% (2 σ error) per mass unit. Larger variations have been observed for higher Fe/O ratios and larger freeze-in temperatures. These variations are in agreement with observations by Kallenbach et al., (1998) when they used the solar wind density as an indicator for slow and coronal hole associated solar wind. They also have detected more prominent depletion at higher solar wind densities. This effect has to be investigated in more detail in the future. However, the efficiency correction of two different isotopes are of the order of a few percent. One has to be aware of the fact that we are close to the possible limits of the precision of the data reduction, the analysis tool and the sensor limits.

Table 1. Magnesium abundance ratios for slow and coronal hole associated solar wind by using the Fe/O ratio or the freeze-in temperature of O^{6+}/O^{7+} as an indicator

$^{24}Mg/^{26}Mg$:	Fe/O	Freeze-in
slow sw	7.07 ±0.12	7.2 ±0.13
coronal hole	6.8 ±0.14	6.9 ±0.15
terrestrial	7.17	7.17
$^{24}Mg/^{25}Mg$:	Fe/O	Freeze-in
slow sw	8.0 ±0.12	8.1 ±0.13
coronal hole	7.9 ±0.14	7.8 ±0.15
terrestrial	7.9	7.9

5. DISCUSSION AND CONCLUSION

Different physical processes at the Sun and in the interplanetary medium can in principal contribute to isotopic fractionation in the solar wind. Several models are under an ongoing debate. Starting at the Sun, there is the ion-neutral separation in the upper chromosphere and in the transition region and the inefficient Coulomb coupling of minor ions in the inner chorona. Furthermore, there is the process of gravitational settling in the outer convective zone of the Sun as well as in closed magnetic field structures. And finally, shocks in the interplanetary medium originating from CME's or CIR's. Theory predicts for Mg an isotopic fractionation of the order of about 0.1 % for inefficient Coulomb coupling and for ion-neutral separation. This however is much smaller than the precision of the measurement of the instruments. For the most promising effects like gravitational settling in the outer convective zone of the Sun, theory predicts an isotopic fractionation for magnesium which is of the order of 0.4% per mass unit (Bochsler, 1999). This effect is independent of solar wind conditions and would create a constant offset. The results however show an indication of a dependence of the isotopic ratios on slow solar wind or coronal hole associated solar wind. This effect is expected from the gravitational settling in closed magnetic field structures which is known as static stratification, and from Coulomb coupling of minor solar wind ions to the protons and alpha-particles in the inner corona, known as dynamic stratification. Model calculations of Bodmer and Bochsler (1996) showed that the fractionation of $^{24}Mg/\,^{26}Mg$ is larger in slow solar wind than in fast coronal hole solar wind. According to their model heavier isotopes with their smaller drag factors are depleted in the slow solar wind. Recently, Raymond et al., (1997) pointed out that the outflow velocity of minor ions is low so that dynamic stratification by inefficient Coulomb coupling likely causes the isotope fractionation. This model predicts the same behavior and the same order of magnitude of the effect as observed by this investigation. Kallenbach et al. (1997, 1997a) pointed out that heavier isotopes are depleted by a few percent in the slow solar wind, when they have investigated the Si and Ne isotopic abundance in the solar wind. The trend became more clear, when they averaged the variations of Si, Ne and Mg isotopic abundance. They have concluded that the depletion of heavier isotopes is (1.4 ± 1.3) % (2σ-error) per mass unit within a bulk velocity range of 350 - 650 km/s of the solar wind. The result obtained from this investigation agrees very well with previous results obtained by these two different methods.

ACKNOWLEDGMENTS

CELIAS is a joint effort of five hardware institutions under the lead of the Max-Planck-Institut für extraterrestrische Physik (pre-launch) and the University of Bern (post-launch). The University of Maryland is the prime hardware Institution for MTOF and the Max-Planck-Institut für Aeronomie is the prime hardware institute for CTOF. The DPU was provided by the Technical University of Braunschweig. The CELIAS experiment was supported by the DLR under the contracts 500C89056 and 500C96059.

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