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DETERMINATION OF THE ARGON ISOTOPIC RATIO OF THE SOLAR WIND USING SOHO/CELIAS/MTOF

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ABSTRACT

This study is about the first direct measurements of the ^{36}Ar/^{38}Ar ratio in the solar wind with the MTOF sensor of the CELIAS instrument on the SOHO spacecraft.

Argon is highly volatile and a minor element in the solar wind. Because of its volatility inferences about the solar and solar system argon isotopic composition from planetary samples are problematic. However, it is possible to determine the solar isotopic composition quite reliably from solar wind observations. Such determinations have been made with the Apollo foil experiments for the predominantly slow solar wind and a value consistent with the terrestrial atmospheric ^{36}Ar/^{38}Ar ratio of 5.32 had been found. Lunar soil derived ^{36}Ar/^{38}Ar ratios lie somewhat above the terrestrial value, however, they represent flux averages which are integrated over long time periods and could be affected by fractionation effects during implantation and storage.

CELIAS/MTOF has already been successfully used to examine the isotopic ratios of elements such as magnesium, neon, calcium, silicon, as well as nitrogen. Direct measurements provide the possibility to set limits to the variability of isotopic abundance ratios with different solar wind regimes, and hence, to obtain a clue on the importance of fractionation effects occurring in the solar wind.

The preliminary value of ^{36}Ar/^{38}Ar lies in the range from 5.2 to 5.9 and is consistent with indirect observations. This study will present the result in the context of solar wind fractionation models and of experimental evidence derived from in situ observations on refractory elements.

Key words: argon, isotopes, lunar, meteorite, and solar wind.

1. INTRODUCTION

Previous measurements of the ^{36}Ar/^{38}Ar ratio were obtained from terrestrial samples, meteorites, lunar soil samples, and the Apollo missions' foil experiments (Eberhardt et al., 1965; Cerutti, 1974 Eugster and Niedermann, 1988; and Wieler, 1999). The purpose of these measurements is to obtain accurate information on the isotopic composition of the Sun (i.e., 99.9% of the matter in the Solar system). Furthermore, since the Sun's central temperature has never been high enough to alter the isotopic composition of the heavy elements by nuclear reactions an accurate measurement of the isotopic composition also reflects the isotopic composition of the solar nebula. The difficulty with most of the previous measurements is the exposure of these samples over long periods of time (i.e., millions of years) to a variety of effects which may change the stored ^{36}Ar/^{38}Ar ratio, such as sputtering of energetic particles, diffusion loses, and Galactic Cosmic rays. Until now the best temporal resolution of the ^{36}Ar/^{38}Ar ratio has been ≈ 2 days with the Apollo missions' foil experiments.

The MTOF sensor of the CELIAS instrument on board the SOHO satellite is an isochronous time-of-flight mass spectrometer (Hovestadt et al., 1995) with a resolution M/ΔM of better than 100 and a temporal resolution of 5 minutes. MTOF combines an electrostatic entrance system with the carbon foil technique to obtain mass spectrometer information from the solar wind for masses between 1 and 60 AMU. MTOF consists of two main portions: WAVE and the VMASS portion (See Figure 1). The WAVE section consists of three energy over charge selection chambers. The entrance system allows a large energy range of ions to enter the sensor through a wide angular acceptance cone. Particles which pass through this region cross through a carbon foil which reduces their charge from some initial solar wind charge distribution (i.e., +8, +9, or +10 for argon) to neutral, +1, or +2. Those particles with some charge, the most common is +1, follow a hyperbolic path to an ion MCP where they are recorded as counts.

The purpose of this preliminary study is to determine if it is possible to obtain a ^{36}Ar/^{38}Ar ratio with the

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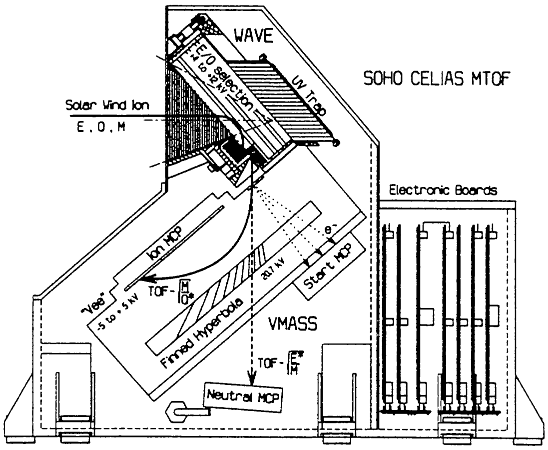

Figure 1. Schematic of the CELIAS/MTOF sensor.

CELIAS/MTOF sensor. The uncertainty for the ratio in this study is large and may never be as small as those from other previous study's techniques. However, the authors of this study hope to determine the ^{36}Ar/^{38}Ar ratio (and its variability) directly in the contemporary solar wind under different solar wind conditions, as opposed to previous studies which determined the ratio indirectly from the solar wind.

2. DATA AND PROCEDURE

In this preliminary study four days of slow solar wind were examined. These days of 1996 are 115 DOY, 118.5 DOY to 102.2 DOY, and 151.8 DOY to 153.3 DOY. Each period consists of at least a full days worth of solar wind data. The slow solar wind is considered here since it is the typical type sampled by satellites. Furthermore, these periods are during mainly steady solar wind and not temporally near any CMEs or solar wind shocks. Based on this limitation, a narrower solar wind velocity range was selected such that the two most common solar wind argon isotopes (^{36}Ar and ^{38}Ar) pass through the MTOF sensor to the ion MCP with nearly the same effective transmission. The limits of this smaller velocity range were selected on the basis of the available calibration data.

Figure 2 indicates the effective carbon foil area "seen" by an argon particle after crossing through the WAVE portion of MTOF. The dash curve indicates the results of the calibration data. Note that the calibration data represents a pencil beam of plasma which the solar wind data should resemble as the solar wind Mach number approaches infinity. The thick curve is the effective area for the ^{38}Ar isotope over various solar wind speeds and the thin curve is the effective area for the ^{36}Ar isotope. The area between the vertical lines indicates the solar wind velocity ranged used in this study. In this region the argon curves differ at most by 3% for the two isotopes.

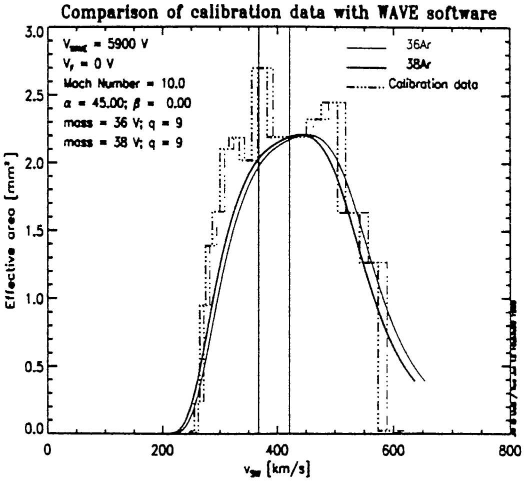

Figure 2. The effective area of the carbon foil is plotted as "seen" by the two argon isotopes in wave portion of the isochronous TOF mass spectrometer. The approximate settings of the MTOF sensor are in the upper lefthand corner as well as the general solar wind values for the four days of data. The dash curve indicates the calibration data, the thick curve is for the ^{38}Ar isotope, and the thin curve is for the ^{36}Ar isotope.

Figure 3 is a plot of the total transmission of the argon isotopes through the VMASS section of MTOF. The dashed curve is the transmission for the ^{38}Ar isotope over a range of solar wind values and the solid curves is the transmission for the ^{36}Ar isotope. Again, the vertical lines indicate the refined solar wind velocity ranged used in this study, and between the vertical lines the argon curves differ at most by 3%. It should be clear from this plot why the narrower velocity range was selected: a large solar wind speed means a bigger difference in the transmission curves and smaller solar wind speeds lead to lower total transmission values.

To summarize, initially the typical slow solar wind was examined. From there a narrow solar wind range was defined in such a way that the maximum difference between the transmission of the ^{38}Ar isotope and the ^{36}Ar isotope through the MTOF sensor is about 3%.

Once the solar wind velocity was determined the MTOF data for the first half of 1996 was examined for periods which fit the restrictions. A number of single days worth of data were found. For this study the five minute spectra for four days worth of data for the three separate periods were summed together to make one full mass spectrum (see Figure 4). With this spectrum a linear background was estimated for the ^{36}Ar, ^{38}Ar, and ^{40}Ca peaks. Furthermore, it was assumed that the argon peaks have the same shape as the strong ^{40}Ca peak, which is required for the minimum variance estimate of the argon peaks.

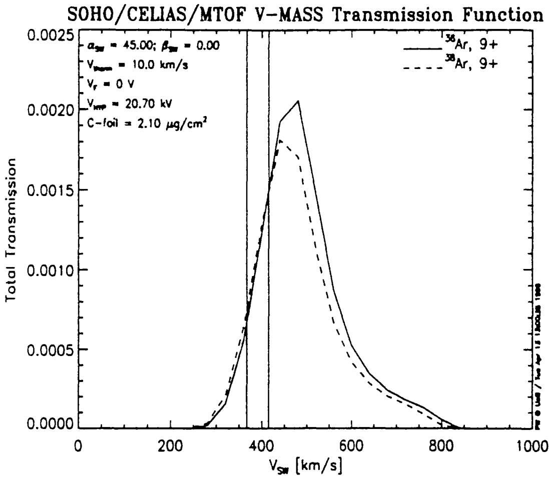

Figure 3. Total transmission of the isochronous TOF mass spectrometer is plotted for the two argon isotopes investigated in this study. The approximate settings of the MTOF sensor and the general solar wind values for the four days of data are located in the upper lefthand corner.

3. DATA ANALYSIS

The minimum variance technique gives a best estimate of a signal by minimizing the variance between the peak and the assumed peak shape. A detailed explanation of the minimum variance technique can be found in the study of Bochsler [1989].

For this study, the ^{36}Ar and ^{38}Ar peaks were assumed to have the same shape as the ^{40}Ca peak. The ^{40}Ca peak was used because it has a high SNR, it is well formed, and close (in proximity) to the argon peaks. Before making a first estimate of the argon peaks, the background is estimated and removed from the ^{40}Ca peak. For the argon and calcium peaks the background was assumed to be linear between two points. This background appears as the dash-dot line in Figure 4. After removing the background proportionality factors (s_i) are determined for 10 channels in the ^{40}Ca peak.

$$s_i = \frac{c_{i\,Ca}}{\Sigma c_{i\,Ca}}. \tag{1}$$

Once the background is determined and removed from the argon peaks, a best first estimate of the argon counts (in each peak) is based on the total number of counts in ten channels in the peak. The expected value for each channel is calculated with the first estimate, the proportionality factors from the calcium peak, and the estimate of the linear background in each argon channel:

$$\mu_i = E(A) \times s_i + E(b_i). \tag{2}$$

Weights are determined for the count rates of each channel using the proportionality factors, expected value for the channels, and the variance of the background:

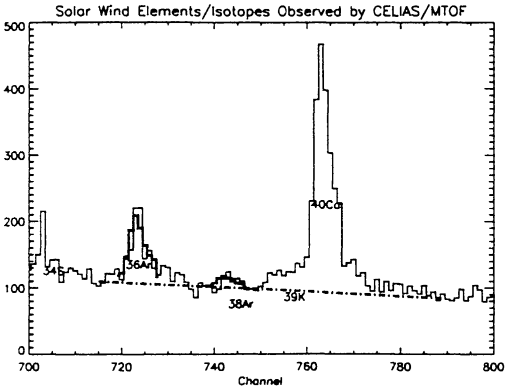

Figure 4. Sum of the five minute spectrums for the three different periods. The thin black lines represents the raw counts, the thick dashed line represents the linear background counts, and the thick black line is the minimum variance estimate of the argon peaks.

$$w_i = \frac{\frac{s_i}{\mu_i+\Delta b_i^2}}{\Sigma \frac{s_j}{\mu_j+\Delta b_j^2}}. \tag{3}$$

With the weights and the original counts a second estimate of the flux in the argon peak can be made.

$$A = w_1(c_1 - b_1) + \ldots + w_n(c_n - b_n) \tag{4}$$

where b_i is the background counts in channel i. Now the process can be repeated for a desired number of iterations with the new estimate.

For this study 10 iterations were used, but after about three iterations the argon ratio appeared to "settle" into a stable value, which differed from the previous value by less than 0.01.

4. DISCUSSION

The minimum variance best estimate result of the ^{36}Ar/^{38}Ar ratio is 5.8 ± 1.1 (i.e., an uncertainty of about 20%). This differs from the terrestrial value by ≈ 9% which hints at an enrichment in the ^{36}Ar/^{38}Ar ratio, however, this possible enrichment is masked by the large uncertainty. The uncertainty will need to be about 5% to be certain if a true enrichment exists.

Some previously published values can be found in Table 1. The largest contributer to the uncertainty in this study is the variation of the background counts which can be reduced by accumulating longer data periods. It is unclear at this time if the argon MTOF data uncertainty will ever be low enough to confirm if the enrichment is true. At present estimates, the background relative uncertainty can be reduced to about 5% with about 13 days worth of steady, slow solar wind MTOF data. Since only data from the first half of 1996 has been examined at this time the authors are confident the background uncertainty can be significantly reduced, but at the cost of temporal resolution.

Table 1. Comparison of $^{36}Ar/^{38}Ar$ ratios in the solar wind.

Measured Regime	Measured Quantity	Measured Value	Reference
Terrestrial	^{36}Ar/^{38}Ar	5.35	Heath, 1974
Terrestrial	^{36}Ar/^{38}Ar	5.35	P. Eberhardt *et al.*, 1965
Surveyor 3	^{36}Ar/^{38}Ar	5.41 ± 0.20	Warasila and Schaeffer, 1974
Lunar Soil	^{36}Ar/^{38}Ar	5.58 ± 0.03	Wieler, 1999
Lunar Meteorite	^{36}Ar/^{38}Ar	5.32 ± 0.05	Eugster *et al.*, 1986
Meteoritic	^{36}Ar/^{38}Ar	5.5 - 5.7	Becker & Pepin, 1991
Solar Wind Apollo Foil	^{36}Ar/^{38}Ar	5.4 ± 0.3	Cerutti, 1974
Solar Wind	^{36}Ar/^{38}Ar	5.8 ± 1.1	This Work

As a check, the ^{20}Ne/^{22}Ne ratio was also examined for the same data. A table of previously published values as well as the value found in this study can be found in Table 2. Note that this study is not meant to provide a new value for the ^{20}Ne/^{22}Ne ratio, but intends to demonstrate that the ^{36}Ar/^{38}Ar ratio is feasible with MTOF data. The approximate value obtained in this study is 14.7 ± 3, which differs from the Kallenbach *et al.* [1998] study by about 7%.

Table 2. Comparison of $^{20}Ne/^{22}Ne$ ratios in the solar wind.

Measured Regime	Measured Quantity	Measured Value	Reference
Terrestrial	^{20}Ne/^{22}Ne	9.78± 0.03	Holden, 1993
Apollo Foil (Apollo 16)	^{20}Ne/^{22}Ne	13.7± 0.3	Geiss *et al.*, 1972
Apollo Foil (Apollo 15)	^{20}Ne/^{22}Ne	13.6± 0.50	Geiss *et al.*, 1971
Lunar Meteorite	^{20}Ne/^{22}Ne	12.6 ± 0.10	Eugster *et al.*, 1986
Solar Wind	^{20}Ne/^{22}Ne	13.8 ± 0.8	Kallenbach *et al.*, 1998
Solar Wind	^{20}Ne/^{22}Ne	14.7 ± 3.0	This Work

The important difference between this study and the previous studies of the ^{36}Ar/^{38}Ar ratio is that these data are taken directly from the solar wind. Studies which involve lunar soils, lunar meteorites, and other meteorites obtain values which are the result of an accumulation over a period of millions (or even billions) of years. These studies do not take into account an "uncertainty" due to statistical variation of the solar wind (i.e., changes in the ^{36}Ar/^{38}Ar ratio as a result of the the first ionization potential due to variations in the velocity, sputtering of energetic particles, diffusion loses, and cosmic rays). The absolute errors given in Table 1 are merely the instrument uncertainties.

At this time the results of this research is not an advancement over the Cerutti thesis, but in the future we hope to improve this study by accumulating a larger sample. At this time data only from the first half of 1996 has been examined. In addition, a better estimate of the uncertainty is expected, which for this preliminary study is a maximum estimate. Furthermore, other data types will be examined such as different solar wind velocities, as well as different portions of the solar cycle.

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