Composition of magnetic cloud plasmas during 1997 and 1998

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Abstract. We present a study of the elemental composition of a sub-set of coronal mass ejections, namely events which have been identified of being of the magnetic cloud type (MC). We used plasma data from the MTOF sensor of the CELIAS instrument of the SOHO mission. So far we have investigated MCs of 1997 and 1998. The study covers the proton, alpha, and heavy ion elemental abundances. Considerable variations from event to event exist with regard to the density of the individual species with respect to regular “slow” solar wind preceding the MC plasma. However, two general features are observed. First, for the heavy elements (carbon through iron), which can be regarded as tracers in the solar wind plasma, a mass-dependent enrichment of ions monotonically increasing with mass is observed. The enrichment can be explained by a previously published theoretical model assuming coronal plasma loops on the solar surface being the precursor structure of the MC. Second, when comparing the MC plasma to regular solar wind composition, a net depletion of the lighter ions, helium through oxygen, is always observed. Proton and alpha particle abundances have to be regarded separately since they represent the main plasma.

INTRODUCTION

In a recent study it was reported that the plasma of the coronal mass ejection (CME) of 6 January 1997 was strongly mass-fractionated favoring heavier elements with respect to lighter ones [1, 2]. From the magnetic field measurements on WIND it has been concluded that the 6 January 1997 CME falls into the group of magnetic cloud (MC) events [3]. An overview of the 6 January 1997 CME event has been given by Fox et al. [4], which covers the launch of the CME, its propagation through interplanetary space, and its effect on the Earth’s magnetosphere. Following this observation, the measured mass fractionation was successfully modelled by assuming large coronal loops, being the precursors of the magnetic cloud (MC) plasma, where the mass fractionation is established by diffusion across magnetic field lines [5].

A review covering the present understanding of CMEs has been given recently by Gosling [6], for the compositional aspects of CMEs see the review by Galvin [7]. CMEs with magnetic cloud topology generally exhibit somewhat higher freeze-in temperatures, i.e., the charge-state distribution of a particular element is shifted toward higher charge states than for the ambient undisturbed solar wind [8, 9]. Observational signatures of MCs consist of an enhanced magnetic field strength, a smooth rotation of the magnetic field direction as the cloud passes the spacecraft, and a low proton temperature. It has been found earlier that near 1 AU about one third of all CMEs in the ecliptic plane are magnetic cloud events [10].

In this paper we present further experimental evidence for the elemental fractionation of heavy ions in MCs using data from the CELIAS/MTOF instrument on the SOHO mission. There were two MCs during 1997 and five MCs during 1998, which passed the SOHO spacecraft located close to the Earth at first Lagrangian point, L1. These events are listed in Table 1. We present the analysis for five of these MCs. All these CME events are of the magnetic cloud type. In addition, the events have been selected such that the charge-state distributions are similar to what is observed in regular solar wind using ACE/SWICS quick-look data. Note that this selection includes the shift of charge-states in MCs mentioned in the previous paragraph. The sequence of three CME events from 2–3 May 1998 of which the second one is of MC nature, had very unusual charge state distributions [11] which lead to the exclusion of this event from the present analysis. A more sophisticated analysis due to these complications will be necessary and will be presented in the

TABLE 1. List of magnetic clouds during 1997 and 1998 that could be observed with solar wind particle instrumentation near Earth. Exact times of analyzed intervals for the reference periods and the MCs cloud are given as day-of-year (DOY).

MC Event[*]	Ref. start time [DOY]	Ref. end time [DOY]	MC start time [DOY]	MC end time [DOY]	Solar wind speed[†] [km/s]	Remarks
10–11 Jan 1997	8.00	9.00	10.27	10.98	440	MC followed by filament
7 Nov 1997	301.00	302.20	311.30	312.50	420	CME preceding MC
2–3 May 1998	—	—	—	—	510	Multiple CMEs
2 June 1998	151.72	153.00	153.43	153.65	430	
24 June 1998	173.00	174.00	175.42	176.00	390	
25 Sep 1998	—	—	—	—	—	SOHO not operational
8 Nov 1998	310.00	311.25	312.18	313.73	520	

[*] Date the event was observed at 1 $\sim$ AU

[†] Average speed during MC duration

future. For the 25 September 1998 MC event the SOHO spacecraft was not operational.

DATA ANALYSIS

In this study we evaluated the elements C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, and Fe. From the ions recorded with the MTOF sensor, the CELIAS data processing unit accumulates time-of-flight (TOF) spectra for 5 minutes, which then are transmitted to ground. The raw counts for each mass peak of the different elements were extracted from each of the transmitted TOF spectra by fitting a model function of the peak shape and the background [12]. Subsequently, the overall efficiency of the MTOF sensor was calculated for each element and for each accumulation interval. To obtain particle fluxes for the chosen elements, the instrument response of the MTOF sensor comprising the transmission of the entrance system and the response of the isochronous TOF mass spectrometer, was taken into account in great detail [12].

The actual solar wind plasma parameters, which were measured by the Proton Monitor (PM) a sub-sensor of the MTOF sensor, are needed as input parameters for the instrument response of the MTOF sensor. The quality of the determination of the solar wind plasma parameters with the PM is quite good [13] and better than required for the determination of densities with the MTOF sensor. Another input parameter needed for the determination of the MTOF instrument response, in particular for the determination of the transmission of the entrance system, is the charge-state distribution of each element for each accumulation interval. The MTOF sensor determines only the mass of the incoming ion (with high resolution, however), but not its charge. The CTOF sensor was supposed to provide this information for a few key elements, but since mid August of 1996 problems in the CTOF sensor electronics prohibit these measurements. Thus, we had to resort to a model for the charge-state distributions of the elements. We derive the so-called freeze-in temperature from a semi-empirical model using the solar wind velocity as input parameter [12]. This model also accounts for ionization resulting from non-maxwellian electron distributions. From the freeze-in temperature we obtained charge distributions for each element by assuming an ionization equilibrium in the corona and by applying ionization and recombination rates for electronic collisions from Arnaud and co-workers [14, 15]. The application of the instrument function to the measured count rates yielded densities for the different elements. We extensively checked if the instrument function introduces a mass bias, but so far we did not find such an effect in the data analysis.

The MTOF sensor settings are cycled in a sequence consisting of four to six steps, which were optimized to cover a broad range of solar wind conditions. The stepping sequence includes two voltage settings for the entrance system and up to three values for the potential difference between the entrance system and the TOF mass spectrometer (negative, zero, and positive potential difference). For the present analysis only the steps with negative or zero potential difference have been used. In principle a time resolution of five minutes, the dwell time for each step, can be obtained if the sensitivity of the MTOF sensor is high enough for the particular element considered. For typical solar wind conditions and for the more abundant heavy elements in the solar wind, it is indeed possible to derive densities with such a high time resolution, as has been demonstrated earlier [2].

RESULTS

We compare the densities for the different elements during the MC with the corresponding densities during a reference solar wind period. To account for the variability of the solar wind with time, or with location of origin or with solar activity, we used for reference a day of

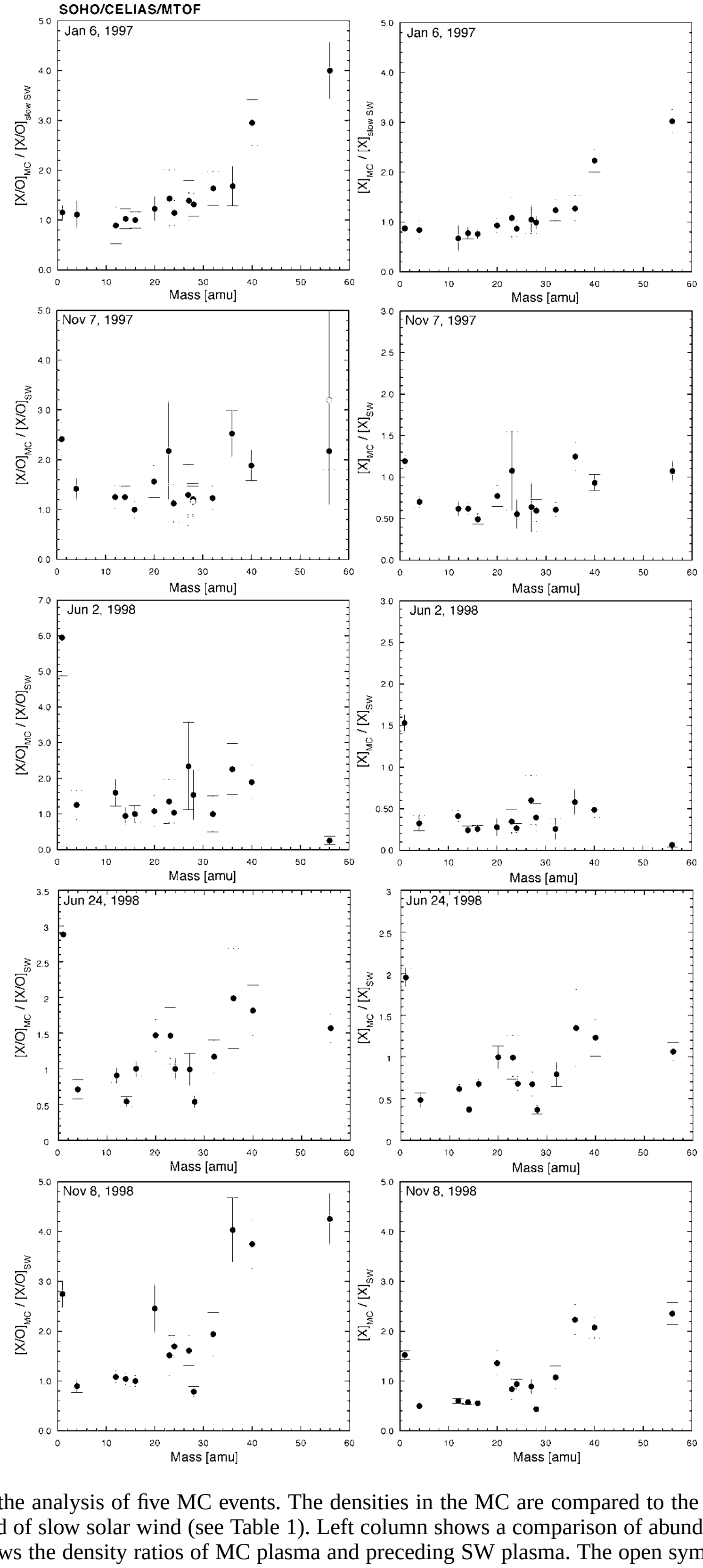

FIGURE 1. Results of the analysis of five MC events. The densities in the MC are compared to the respective densities in the preceding reference period of slow solar wind (see Table 1). Left column shows a comparison of abundance ratios with respect to oxygen; right column shows the density ratios of MC plasma and preceding SW plasma. The open symbols in the panel for the 7 November 1997 event were taken from [16].

slow solar wind preceding the MC by about a day. Since we chose reference periods preceding the MC events we can safely assume that these reference plasmas are unaffected by the disruption which caused the CME release. Note that the slow solar wind, e.g. solar wind associated with the streamer belt, is already fractionated by mechanisms governed by the first ionization potential (the FIP effect) [17, 18]. The exact time periods for the MC and the reference solar wind used in the analysis are given in Table 1.

Figure 1 shows the results for all five MC in two formats, one where data are given with reference to oxygen and one where direct comparison of MC and solar wind plasma is plotted. We derived the proton data from measurements with the PM, a sub-sensor of the MTOF sensor. The helium data as well as all the heavy ion data were derived from mass spectra recorded with the MTOF sensor. Since MTOF was designed to measure heavy ions in the solar wind He is largely suppressed by the MTOF entrance system by design; thus the determination of the He density is problematic and the He data have to be viewed with caution.

The left column in the Figure 1 shows the ratio of abundances with reference to oxygen in the MC cloud versus the solar wind reference period (that is $[X/O]_{MC}/[X/O]_{ref.\ SW}$ is plotted), which is a commonly used format to display variations in heavy ion abundances. The top panel shows a re-evaluation of the 10–11 January 1997 MC plasma considering more elements than Wurz et al. [2]. Within the error bars the initial results [2] have been reproduced. For the 7 November 1997 event there are two earlier measurements from WIND/MASS [16], $[Si/O]_{MC}/[Si/O]_{slowSW}$ and $[Fe/O]_{MC}/[Fe/O]_{slowSW}$, which have been added to the Figure. The reported Si and Fe abundance ratios agree with the present analysis within the error bars. For all five events we find that the composition of the MC is markedly different from the preceding solar wind plasma. In four out of five events we find a more or less organized mass fractionation for the heavy elements, He through Fe, with heavier ions being enriched more than the lighter ones. There is of course some event-to-event variability in the abundance of the ions and in the magnitude of the enrichment of the heavy elements. For iron the enrichment is in the range of 1.5 to 4 with respect to the preceding slow solar wind. Only for the 2 June 1998 event we find that the iron abundance is lower, by about a factor of five, than in the preceding solar wind.

To get a better understanding of what is actually going on in the MCs we have to consider the ratios of the densities in the MC versus the solar wind reference period (e.g. $[X]_{MC}/[X]_{ref.\ SW}$). These data are shown in the right column of Figure 1. At first glance the data looks qualitatively the same as the abundance data (left column) revealing again the mass fractionation. However, the striking difference is that for all events the lighter elements, with the exception of hydrogen, are actually depleted to about half to their density in the preceding solar wind plasma. Depending on the strength of the mass fractionation the densities of heavier elements reach solar wind values (events 7 November 1997 and 24 June 1998) or are even enriched compared to the solar wind (events 10 January 1997 and 8 November 1998). Again, the 2 June 1998 event does not match this pattern and we find that the iron density is only 0.06 of its solar wind value.

DISCUSSION AND CONCLUSIONS

Two things appear to be in common for the MC events presented in this study: the mass-dependent fractionation (with the exception of the 2 June 1998 event) and the substantial depletion of lighter elements. These two findings are illustrated in the summary of the data shown in Figure 2. The mass-dependent fractionation is observed for all minor ions including He. Protons, being the major constituent of the plasma, have their own life and have to be considered separately. Since the protons constitute the main plasma and the heavy elements are only tracer particles in the plasma, a different behavior of the protons is not surprising. The mass fractionation of the heavy ions can be explained well by a recent theoretical model [5], which was developed to explain the observed mass fractionation in the plasma of MC of the 10–11 January 1997 event. This model explains the mass fractionation by assuming large coronal loops as the precursor structure for the MC in which different elements are depleted as a result of diffusion across magnetic field lines. Since this diffusion is mass dependent a mass-dependent fractionation is established. This model can also reproduce the present data very well. Note that the model is based on depletion of elements from the precursor structure of the MC, which is in good agreement with the present finding of a substantial depletion of the lighter elements.

The presented sample of CME events are all magnetic cloud events. In addition, the events have been selected using ACE/SWICS quick-look data such that the charge state distributions are similar to what is observed in regular solar wind. By analyzing 56 CME events recorded with SWICS/Ulysses it was observed that MCs generally exhibit somewhat higher freeze-in temperatures compared to the ambient undisturbed solar wind [8, 9], i.e., the charge-state distributions are shifted to higher charges states. In the ecliptic the increase in freeze-in temperature correlates with solar wind speed and is largest for solar wind speeds exceeding 700 km/s [8, 9]. The MC events we analyzed are at moderate solar wind speeds (see Table 1) and therefore the charge-state distributions are similar to regular solar wind, which was ver-

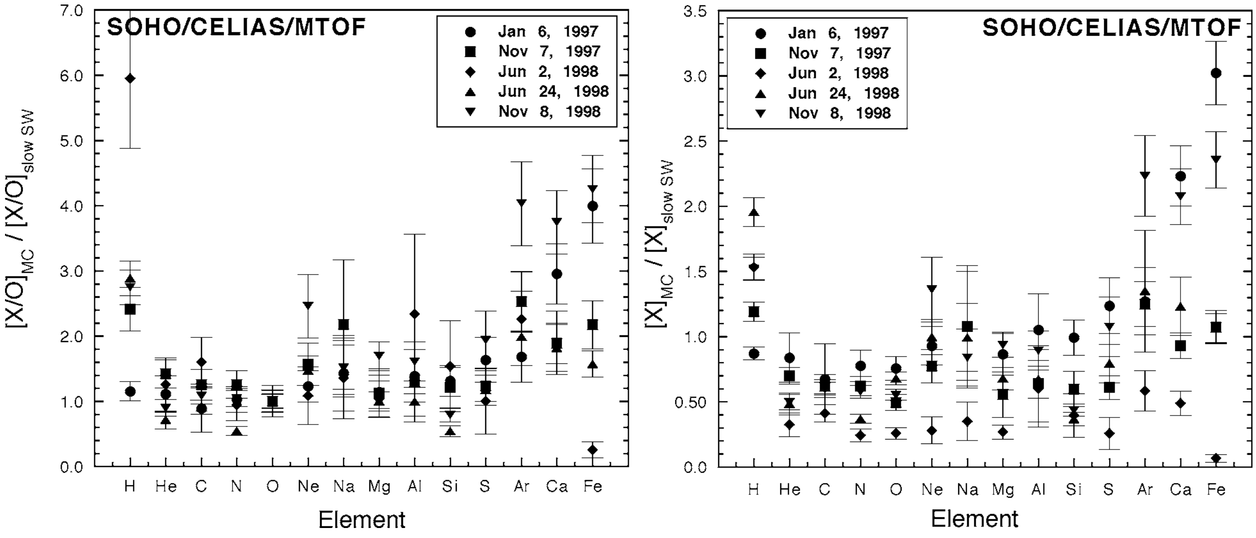

FIGURE 2. Summary of the analysis of five observed MC events showing the range of mass fractionation. Data and plotting format are the same as in Figure 1.

ified by checking the ACE/SWICS quick-look data. Our selection criteria lead to the exclusion of the 2–3 May 1998 event. Such a selection of events might introduce a bias in the result, in the sense that MCs with charge-state distributions significantly different from regular solar wind might also show different mass fractionations, if at all. On the other hand, we considered 5 out of a total of 7 events from the 1997–1998 time period in the present analysis. In addition, for the 2–3 May 1998 event an Fe/O ratio of 0.28 ± 0.10 was found [11], which is an increase of the Fe/O ratio by a factor of 2 compared to regular solar wind. This observation fits well into the general pattern of mass-dependent fractionation we observed. Thus we feel that the findings are quite representative for MCs in the ecliptic.

In the future we will analyze also the MC events from 1999 until present and extend our analysis also to events with unusual charge state distribution, like the 2–3 May 1998 event, the latter by using the actual charge-state distributions measured by ACE/SWICS. We have to await these analyses to see if the common features we found for MCs so far, the mass-dependent fractionation and the substantial depletion of lighter elements, will be observed there as well.

ACKNOWLEDGMENTS

CELIAS is a joint effort of five hardware institutions under the direction of the Max-Planck Institut für Extraterrestrische Physik (pre-launch) and the University of Bern (post-launch). The University of Maryland was the prime hardware institution for MTOF, the University of Bern provided the entrance system, and the Technical University of Braunschweig provided the DPU. This work is supported by the Swiss National Science Foundation.

REFERENCES

1. Wurz, P., Ipavich, F. M., Galvin, A. B., Bochsler, P., Aellig, M. R., Kallenbach, R., Hovestadt, D., Grünwaldt, H., Hilchenbach, M., Axford, W. I., Balsiger, H., Bürgi, A., Coplan, M. A., Geiss, J., Gliem, F., Gloeckler, G., Hefti, S., Hsieh, H. C., Klecker, B., Lee, M. A., Livi, S., Managadze, G. G., Marsch, E., Möbius, E., Neugebauer, M., Reiche, K.-U., Scholer, M., Verigin, M. I., and Wilken, B., *ESA*, **SP-415**, 395–400 (1997).
2. Wurz, P., Ipavich, F., Galvin, A., Bochsler, P., Aellig, M., Kallenbach, R., Hovestadt, D., Grünwaldt, H., Hilchenbach, M., Axford, W., Balsiger, H., Bürgi, A., Coplan, M., Geiss, J., Gliem, F., Gloeckler, G., Hefti, S., Hsieh, H. C., Klecker, B., Lee, M. A., Managadze, G. G., Marsch, E., Möbius, E., Neugebauer, M., Reiche, K.-U., Scholer, M., Verigin, M. I., and Wilken, B., *Geophys. Res. Lett.*, **25(14)**, 2557–2560 (1998).
3. Burlaga, L., Fritzenreiter, R., Lepping, R., Ogilvie, K., Szabo, A., Lazarus, A., Steinberg, J., Gloeckler, G., Howard, R., Michels, D., Farrugia, C., Lin, R. P., and Larson, D. E., *J. Geophys. Res.*, **103**, 277–286 (1998).
4. Fox, N. J., Peredo, M., and Thompson, B. J., *Geophys. Res. Lett.*, **25(14)**, 2461–2464 (1998).
5. Wurz, P., Bochsler, P., and Lee, M. A., *J. Geophys. Res.*, **105(A12)**, 27239–27249 (2000).
6. Gosling, J. T., "Coronal mass ejections: An overview", in *Coronal Mass Ejections*, edited by N. Crooker, J. A. Joselyn, and J. Feynman, Geophys. Monograph 99, American Institute of Physics, 1997, pp. 9–16.
7. Galvin, A. B., "Minor ion composition in CME-related solar wind", in *Coronal Mass Ejections*, edited by

N. Crooker, J. A. Joselyn, and J. Feynman, Geophys. Monograph 99, American Institute of Physics, 1997, pp. 253–260.

8. Henke, T., Woch, J., Mall, U., Livi, S., Wilken, B., Schwenn, R., Gloeckler, G., v. Steiger, R., Forsyth, R. J., and Balogh, A., *Geophys. Res. Lett.*, **25**, 3465–3468 (1998).
9. Neukomm, R., *Composition of Coronal Mass Ejections Derived with SWICS/Ulysses*, Phd thesis, University of Bern, Bern, Switzerland (1998).
10. Gosling, J. T., “Coronal mass ejections and magnetic flux ropes in interplanetary space”, in *Physics of Magnetic Flux Ropes*, edited by C. T. Russell, E. R. Priest, and L. C. Lee, Geophys. Monograph 58, American Institute of Physics, 1990, pp. 343–364.
11. Gloeckler, G., Hefti, S., Zurbuchen, T. H., Schwadron, N. A., Fisk, L. A., Ipavich, F. M., Geiss, J., Bochsler, P., and Wimmer-Schweingruber, R. F., *Geophys. Res. Lett.*, **26(2)**, 157–160 (1999).
12. Wurz, P., *Heavy ions in the solar wind: Results from SOHO/CELIAS/MTOF*, Habilitation thesis, University of Bern, Bern, Switzerland (1999).
13. Ipavich, F. M., Galvin, A. B., Lasley, S. E., Paquette, J. A., Hefti, S., Reiche, K.-U., Coplan, M. A., Gloeckler, G., Bochsler, P., Hovestadt, D., Grünwaldt, H., Hilchenbach, M., Gliem, F., Axford, W. I., Balsiger, H., Bürgi, A., Geiss, J., Hsieh, K. C., Kallenbach, R., Klecker, B., Lee, M. A., Mangadze, G. G., Marsch, E., Möbius, E., Neugebauer, M., Scholer, M., Verigin, M. I., Wilken, B., and Wurz, P., *J. Geophys. Res.*, **103(A8)**, 17205–17214 (1997).
14. Arnaud, M., and Rothenflug, R., *Astron. Astrophys. Suppl. Ser.*, **60**, 425–457 (1985).
15. Arnaud, M., and Raymond, J., *Astrophys. J.*, **398**, 394–406 (1992).
16. Wimmer-Schweingruber, R. F., Kern, O., and Hamilton, D. C., *Geophys. Res. Lett.*, **26(23)**, 3541–3544 (1999).
17. Geiss, J., *Space Sci. Rev.*, **33**, 201–217 (1982).
18. von Steiger, R., “Solar wind composition and charge states”, in *Solar Wind Eight*, edited by D. Winterhalter, J. T. Gosling, S. R. Habbal, W. S. Kurth, and M. Neugebauer, AIP Press, 1995, pp. 193–198.