Composition of Magnetic Cloud Plasmas During 1997 and 1998

P. Wurz (1), R.F. Wimmer-Schweingruber (1), F. Allegrini (1), P. Bochsler (1), A.B. Galvin (2), J. Paquette (3), and F.M. Ipavich (3)

1) Physikalisches Institut, Universität Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

2) EOS Space Sciences, Univesity of New Hampshire, Morse Hall, Durham, NH 03824, USA

3) Dept. Physics and Astronomy, University of Maryland, College park, MD 20742, USA

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 CELIAS instrument on SOHO sapcecraft. The study covers proton, alpha, and heavy ion 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 plasma. However, for the heavy elements, which can be regarded as tracers in the plasma, there is a general trend that the heavier ions are enriched compared to the lighter ions. This trend can be explained by a theoretical model of the precursor plasma loops on the surface of the Sun before launch of the CME [Wurz et al., 2000]. Proton and alpha particle abundances hava to be regarded separately since they represent the main plasma.

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 ~ AU

† Average speed during MC duration

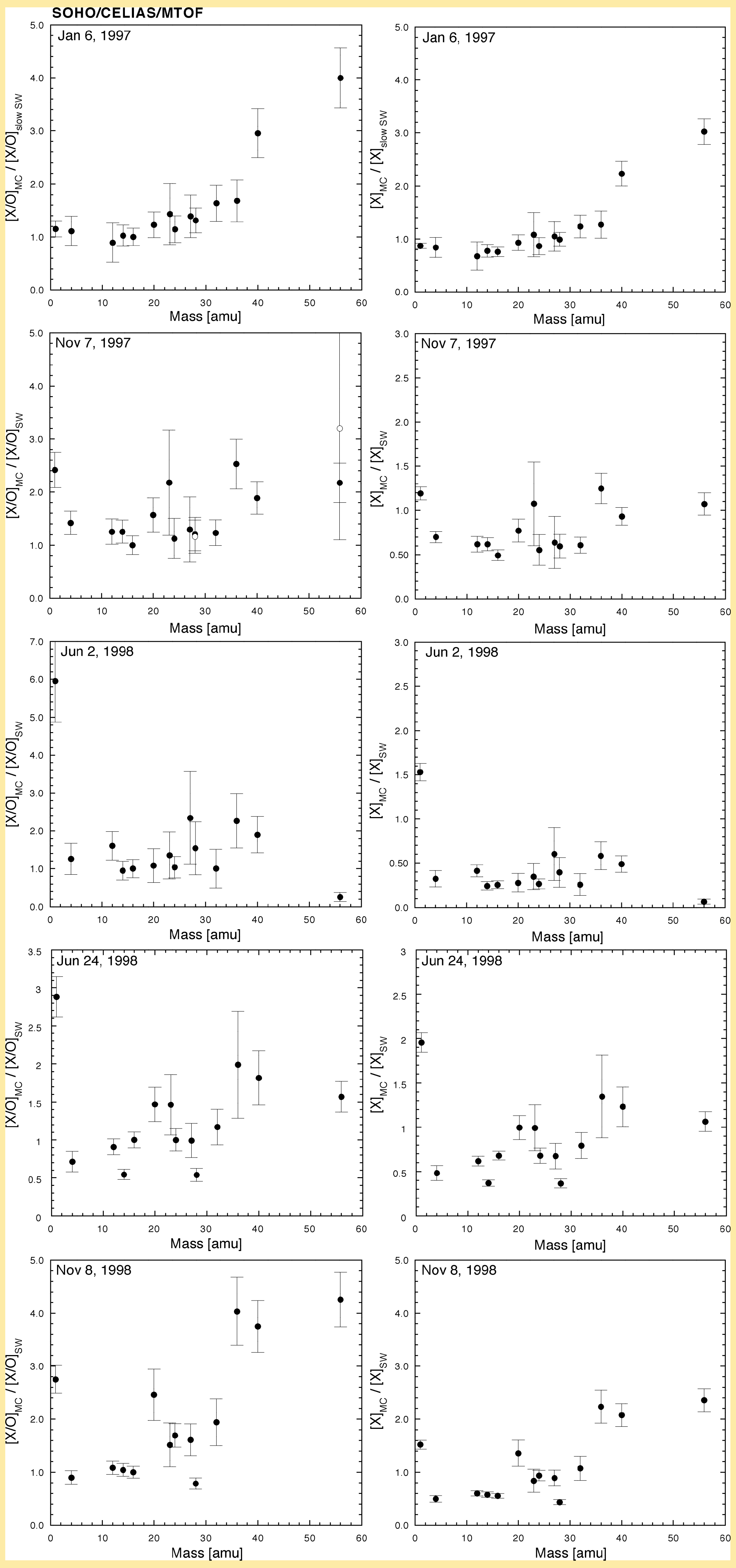

FIGURE 1: Results of the analysis of five MC events. The densities in the MC are compared to the respective densities in the preceding reference period of slow solar wind (see Table 1). Left column shows a comparison of abundance ratios with respect to oxygen; right column shows the density ratios of MC plasma and preceding SW plasma. The open symbols in the panel for the 7 November 1997 event were taken from [Wimmer et al., 1999].

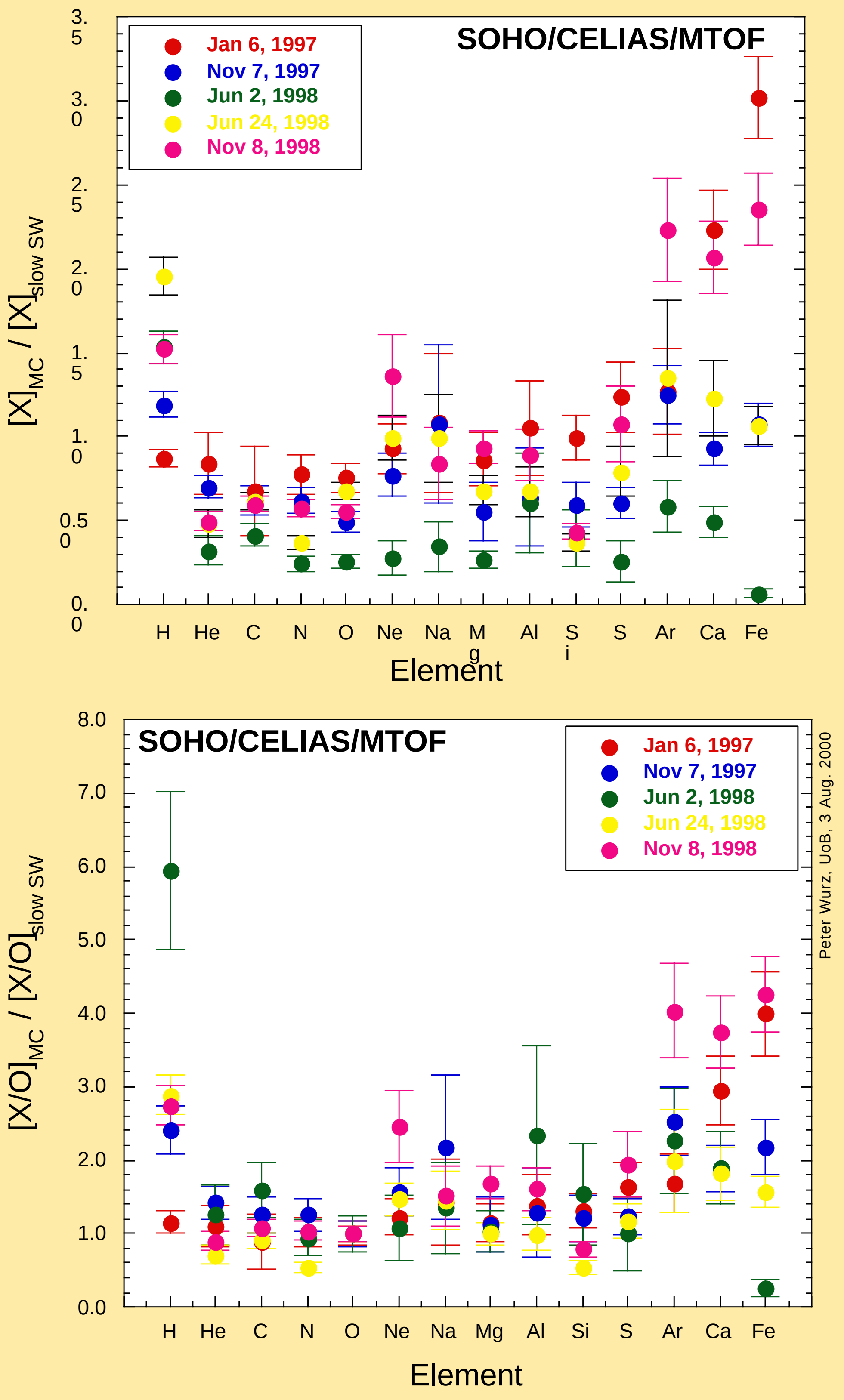

FIGURE 2: Summary of the analysis of five observed MC events showing the range of mass fractionation. Data and plotting format are the same as in Figure 1.

Fit to data: $a = 10^4 m;\ \ T_1 = 10^5 K;\ \ T_2 = 10^5 K;\ n_p = 2.5 \cdot 10^{17} m^{-3}$

MC Event	**T_e [K]**	**B [T]**	**t [s]**
10–11 Jan 1997	2.3 10^6	0.0005	37’500
7 Nov 1997	2.0 10^6	0.0005	12’500
2–3 May 1998	—	—	—
2 June 1998	2.0 10^6	0.0004	15’000
24 June 1998	2.0 10^6	0.0007	40’000
25 Sep 1998	—	—	—
8 Nov 1998	2.6 10^6	0.0006	42’500

References

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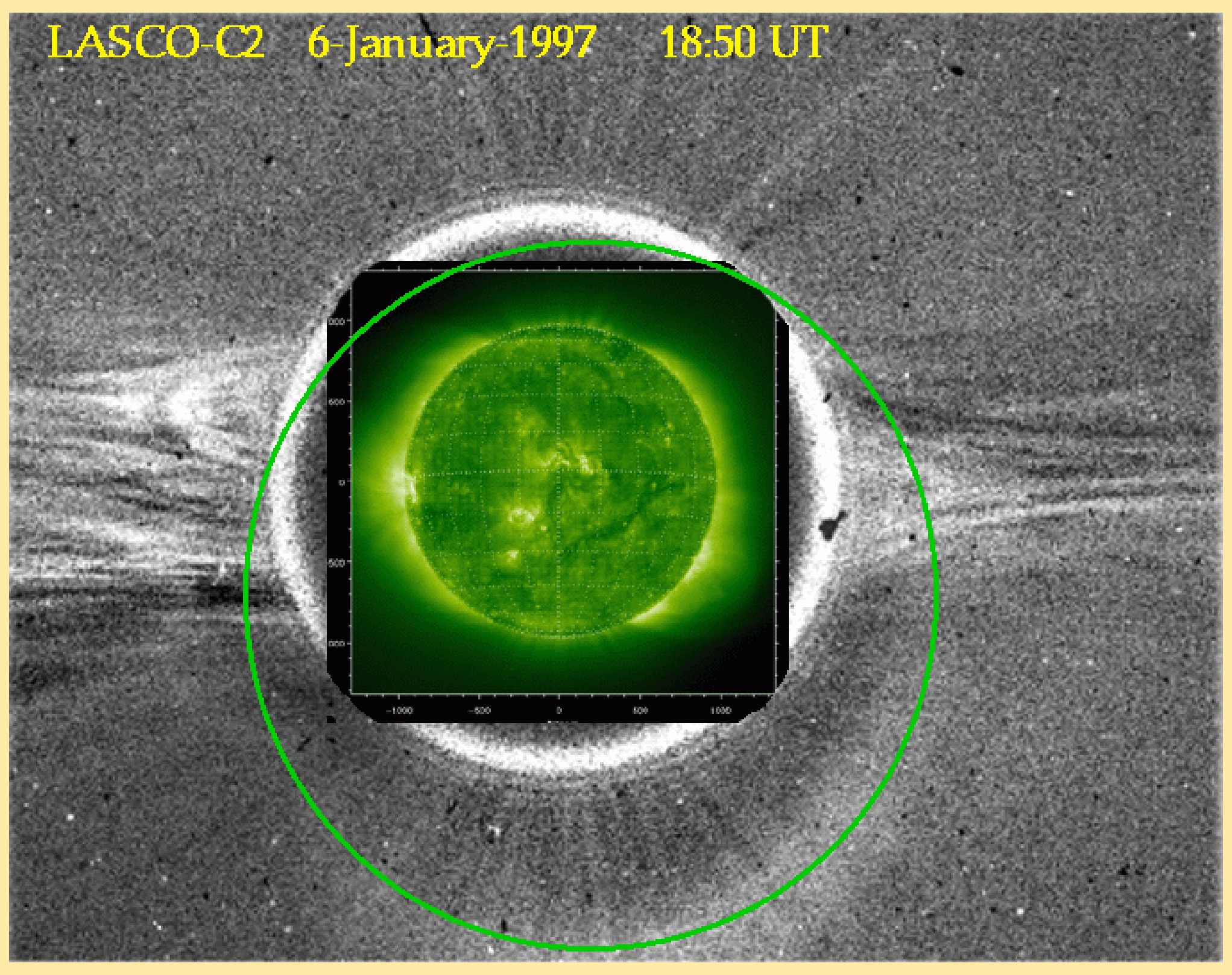

The CME was first observed by LASCO (Large Angle Spectrometric Coronagraph), a coronagraph on SOHO, and appeared in the LASCO C2 field of view at about 16 UT on January 6, 1997 (the C2 field of view begins at 2 solar radii). The image above is a projection of an EIT image of the sun from a previous rotation onto the LASCO image. By completing the circle formed by the halo (the green ring), one can see that the event encompasses disk center.

Model

Our model of the mass release to form a CME is as follows: A loop system emerges from the solar surface and takes with it photospheric material. Due to the expansion of the cross section of a part of the loops with the height a magnetic bottle is established between the two footpoints, which traps electrons and ions inside this structure. The confinement of plasma in a magnetic bottle is an imperfect process, because there is always a loss cone in velocity space from which ions can escape. Note that the loss cone is independent of the mass or charge of the particle. The loop heats up and the hot electrons subsequently bring the trapped ions into higher ionization states corresponding to the temperature of the electrons in the loop. We assume the hot loop model for our calculation, with electron temperatures similar to those of the solar corona. The footpoints of the loop move, and if this movement winds up the magnetic field lines of a loop enough, the loop will disintegrate and set free the trapped plasma material into an expansion into space. Let us assume that the disintegrated loop evolves to be the CME. Of course, a single loop will not release sufficient material to account for the mass of the CME as it was observed. It will take many loops to disintegrate at the same time to come up with the mass. From the sequence of images of the filament one can deduce quite some activity on this part of the solar surface. Since the filament could be observed on the solar surface for more than ten days before the release of the CME (the filament became visible on the east limb of the Sun on the morning of December 28, 1996), the loops will also have existed for the same time period. The plasma inside the loop is reasonably trapped by the magnetic bottle structure of the loop. However, we also have to consider diffusion across magnetic field lines, which results in a loss of ions from the loop. The diffusion across magnetic field lines is given by the corresponding diffusion coefficient

$$D_T = \frac{D_0}{1+\omega_c^2\tau^2} \qquad \omega_c = \frac{q}{m} e B$$

$$\upsilon_{jk} = \frac{1}{\tau} = \frac{16}{3}\sqrt{\pi}\,\frac{\sqrt{\mu_{jk}}}{m_j}\left(\frac{Z_j Z_k e^2}{4\pi\varepsilon_0}\right)^2 \left(2\pi\, T_{jk}\right)^{-\frac{3}{2}} \ln\Lambda\, n_k$$

$$\ln\Lambda = \ln\left(12\pi\, N\lambda_D^3\right) \qquad \lambda_D = \sqrt{\frac{\varepsilon_0 k_B T_p}{e^2 n_p}} \qquad \mu_{jk} = \frac{m_j\, m_k}{m_j + m_k} \qquad T_{jk} = \mu_{jk}\left(\frac{T_j}{m_j} + \frac{T_k}{m_k}\right) \qquad D_{0,i} = \frac{k_B T}{m_i \upsilon_{ij}}$$

Tube geometry is cylindrical, outside is vacuum:

$$n(r,0) = \begin{cases} n_0 & 0 \leq |r| < a \\ 0 & a \leq |r| \leq \infty \end{cases} \qquad n(a,t) = 0$$

For this problem we have to solve the diffusion equation in cylindrical coordinates

$$\frac{\partial n_s}{\partial t} = D_T\, r\,\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial n_s}{\partial r}\right) = D_T\left(\frac{\partial^2 n_s}{\partial r^2} + \frac{1}{r}\frac{\partial n_s}{\partial r}\right)$$

$$n(r,t) = n_0 \sum_{j=1}^{\infty} \frac{2}{\alpha_j}\, e^{\frac{-\alpha_j^2}{a^2} D_T\, t}\, \frac{J_0\left(\alpha_j \frac{r}{a}\right)}{J_1\left(\alpha_j\right)}$$

Integrating over the flux tube gives

$$N(t) = 2\pi \int_0^a n(r,t)\, r\, d r = 2\pi\, n_0 \sum_{j=1}^{\infty} \frac{2}{\alpha_j}\, e^{\frac{-\alpha_j^2}{a^2} D_T\, t}\, \frac{1}{J_1\left(\alpha_j\right)} \int_0^a J_0\left(\alpha_j \frac{r}{a}\right) r\, d r$$

$$N(t) = N_0 \sum_{j=1}^{\infty} \frac{4}{\alpha_j^2}\, e^{\frac{-\alpha_j^2}{a^2} D_T\, t}$$

Thus, the mass fractionation is

$$\frac{N(t)}{N_0} = \sum_{j=1}^{\infty} \frac{4}{\alpha_j^2}\, e^{\frac{-\alpha_j^2}{a^2} D_T t}$$