Proceedings of ICRC 2001: 3435 © Copernicus Gesellschaft 2001

ICRC 2001

The role of CME dynamics in production of ∼10 MeV protons

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Abstract. During January 1997 – June 1998, the Large Angle Spectroscopic Coronagraph (LASCO) aboard the Solar and Heliospheric Observatory spacecraft (SOHO) registered 670 coronal mass ejections (CMEs). We compare two groups of the 300–800 km s^{-1} CMEs: (i) (very) gradually accelerating CMEs with acceleration below $10\ \mathrm{m\ s^{-2}}$, and (ii) impulsively accelerating CMEs with acceleration $a > 20\ \mathrm{m\ s^{-2}}$ near the Sun, continuing then with the constant speed across the LASCO field of view. An association of those CMEs with solar energetic particle (SEP) events is studied using the data of the energetic particle experiment ERNE also aboard SOHO. There were no SEP events registered in association with the first group CMEs, whereas about 8% of the second group CMEs produced an enhancement in the ~ 10 MeV proton flux at SOHO. This result along with a number of additional tests supports an idea that production of SEPs by the moderate speed CMEs depends not only on the final speed but also on the magnitude of acceleration that CME experiences during its liftoff. The SEP-producing CMEs are typified by impulsively accelerating CMEs accompanied by soft X-ray flares and coronal shocks.

1 Introduction

A modern paradigm of cause and effect in solar-terrestrial physics emphasizes the role of CMEs in producing major solar energetic particle (SEP) events (Reames, 1999). The correlation between SEP intensity and CME speeds was presented by Kahler et al. (1984) and updated by Reames (2000). The correlation is reported for the 2 MeV and 20 MeV peak proton intensities associated with CMEs in the speed range from ~ 200 to $\sim 2000\ \mathrm{km\ s^{-1}}$, with correlation coefficients $\sim 0.6 - 0.7$. The correlation is related to the steep enhancement in the peak intensities observed when CME speeds exceed $\sim\ 750\ \mathrm{km\ s^{-1}}$. Reames (2000) argued that the correlation coefficient $\sim\ 0.6 - 0.7$ is surprisingly high, taking into account that many factors are not considered. Kahler et al. (1999) pointed out that a considerable scattering in that correlation suggests that factors other than CME speeds play significant roles in the production of SEP events. Among others, the CME acceleration value was suggested to be a candidate factor affecting production of SEPs. Kahler et al. (1999) considered 17 poorly covered CMEs within the 650 to 850 $\mathrm{km\ s^{-1}}$ speed range, but the data were not sufficient to argue *pro* or *contra* a distinction between accelerating versus constant speed profiles.

We have performed a statistical study of relation between the acceleration that CME experiences during its liftoff and production of SEPs. We employ CME observations by the LASCO coronograph (Brueckner et al., 1995) and ~ 10 MeV proton intensities measured by the ERNE instrument (Torsti et al., 1995), both on the Solar and Heliospheric Observatory (SOHO) spacecraft. In what follows we present results of analysis of several hundreds CMEs registered during the 1.5 year period beginning in January 1997 (see CME lists at http://lasco-www.nrl.navy.mil/lasco.html).

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2 Data Analysis

Lists showing the first appearance times and characteristics of CMEs detected in the SOHO LASCO C2/C3 images during January 1997 – June 1998 contain 670 records (St.Cyr et al., 2000). In 542 cases it was possible to find polynomial fits to the CME height-time data in the 2–30 $R_\odot$ field of view using the data reduction method described by Hundhausen et al. (1994) and St.Cyr et al. (1999). The first order (const. speed) fits are valid in 450 cases. The quadratic (constant acceleration) fits work in 92 ejections. In the latter case both the acceleration value and the final value of the CME speed are listed in the tables. We employ this set of polynomial fits to test a hypothesis that production of SEPs depends not only on the CME velocity, v, but also on the acceleration, a.

In the case of function of two arguments, $f(a, v)$, the a-

dependence must be studied at a fixed value of v. Otherwise an implicit dependence via the velocity, which is in itself dependent on acceleration, $f(v(a))$, might be mistaken for the explicit dependence $f(a, v = \mathrm{constant})$. This reasoning is equally valid for a statistical study, with the correction that values v and a must be replaced with a set of bins in those variables. Width of the bins is dictated by the statistics available. We adopt 3×3 bins in the velocity-acceleration plane. There are three bins in v: (V1) $v < 300$ km s^{-1}; (V2) $300 < v < 800$ km s^{-1}; and (V3) $v > 800$ km s^{-1}. For the three bins in acceleration we employ: (A1) a subclass of accelerating LASCO CMEs with $a < 10$ m s^{-2} (note that in all registered cases $a > 2$ m s^{-2}); (A2) a subclass of accelerating LASCO CMEs with $a \geq 10$ m s^{-2} (note that in the middle velocity-bin 85% of them have $a < 20$ m s^{-2}); and (A3) constant-speed LASCO CMEs, which experience a strong acceleration below $\sim 2-4$ $R_\odot$. The estimated lower limit for the acceleration of the latter group CMEs is $20\ \mathrm{m\ s^{-2}}$. A poor statistics of accelerating CMEs in the high velocity range, V3, and the low expectation of SEP production by the low velocity CMEs in the V1 range send us in a search for the a-dependence in the V2 range only.

In an effort to observe even not very strong effect of acceleration we initially selected CMEs most separated in a, groups A1 and A3. Then the A2 group was also employed. Thus we start with comparison of the SEP-event occurrences in association with two groups of CMEs: **1)** V2_A3, constant speed CMEs with speed values in the range from 300 km s^{-1} through 800 km s^{-1}; and **2)** V2_A1, gradually accelerating CMEs in the same speed range with the acceleration value $a < 10\ \mathrm{m\ s^{-2}}$. We have 253 CMEs of the first type and 43 CMEs of the second type. Hereinafter the first type CMEs are termed *impulsive*, and the second type CMEs are termed *gradual* for short, despite this definition of the classes does not exactly coincide with the definition by Sheeley et al. (1999).

The CME associated SEP-events were selected using the ERNE $\sim 1-100$ MeV proton data. In the first stage of selection we find all significant enhancements in the 6.4–12.7 MeV proton channel. Then the neighboring energy channels are used (i) for revealing simultaneous increases in different energy channels, which obviously are of a local origin and should be dropped, and (ii) for refining solar injection time of the first protons observed above the background. In the last stage an association of the SEP event with a CME is established, if the first proton injection time does not differ by more than 3 h from the first appearance time of a CME. The search has revealed 19 SEP-associated CMEs. It turns out that all SEP-associated CMEs are impulsive. None of gradual CMEs was accompanied by ~ 10 MeV proton event in ERNE.

We also studied association of different groups of CMEs with (i) soft X-ray flares, (ii) Hα flares, (iii) metric type II radio bursts, and (iv) type IV bursts, as listed in Solar-Geophysical Data with no respect to a burst magnitude. The association of a solar event (i–iv) with the CME is established if in the 1.5 h vicinity of the first appearance time of CME we find

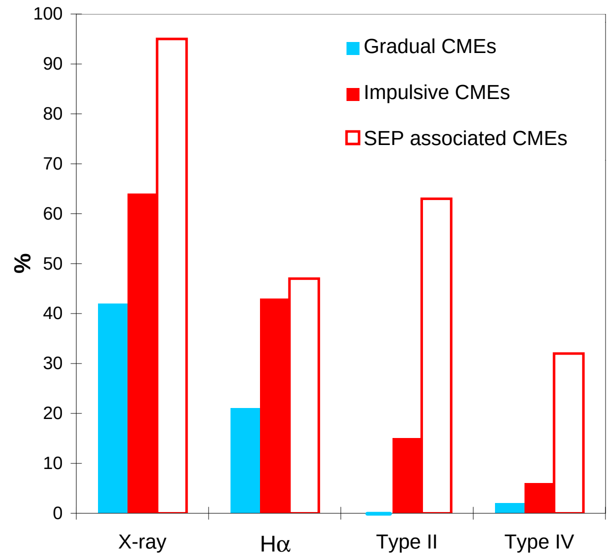

Fig. 1. Percentage of CMEs associated with soft X-ray and Hα flares, type II and IV radio bursts for the different CME groups. Total statistics are 43, 100, and 19 for the gradual ($a < 10$ m s^{-2}) CMEs, impulsive CMEs, and SEP-associated CMEs, respectively. The 100 impulsive CMEs have been selected by a random number generator from the total 253 impulsive CMEs.

at least one of the following times of the solar event: start or maximum time of the soft X-ray flare, start time of the Hα flare, start time of the radio type II/IV burst. Different associations are summarized in **Fig. 1** for all gradual CMEs, for all impulsive CMEs, and also for the impulsive CMEs associated with proton events (SEP-producing CMEs).

3 Discussion

Our search revealed $n_i = 19$ SEP-associated CMEs among the total $N_i = 253$ impulsive CMEs, whereas no SEP-associated CMEs ($n_g = 0$) were found among $N_g = 43$ gradual CMEs. To check whether this is by a random chance or not, one can employ a statistics

$$\chi^2 = (n_i N_g - n_g N_i)^2 [N_i N_g (n_i + n_g)]^{-1} \qquad (1)$$

at one degree of freedom (Bolshev and Smirnov, 1983). This criterion verifies a conclusion that probabilities to observe SEP events in association with impulsive CMEs and in association with gradual (< 10 m s^{-2}) CMEs are significantly different. The straightforward calculation of χ^2 yields the Estimated Confidence Level ECL $= 93\%$[1].

[1]The estimate may be also done in less rigorous but more transparent manner. At probability $P = 19/253$ estimated from the statistics of impulsive CMEs, the probability of the event that no SEP enhancement has occurred in 43 trials is $(1-P)^{43} = 3.5\%$. Hence, a probability to observe a SEP event in association with gradual CME is significantly less than that for impulsive CMEs, at ECL $\approx 96.5\%$.

We have compared gradual CMEs with acceleration $a < 10\ \mathrm{m\,s^{-2}}$ and impulsive CMEs, both in the speed range $300 \le v \le 800\ \mathrm{km\,s^{-1}}$. The comparison reveals a significant difference in association of the two groups of CMEs with ~ 10 MeV proton events. The gradually accelerating CMEs did not produce SEP events, while about 8% of impulsive CMEs were associated with SEP events at SOHO. Note that the latter percentage accounts only for the SEP events observable at a given solar longitude. The longitude-integrated probability should be significantly higher, most likely $> 70\%$, because the average size of the impulsive CMEs is only $77°$. Note that for gradual CMEs with $a < 10$ m s^{-2} the mean size is $93°$ (see also Appendix). The difference is revealed between frequencies of the SEP-event occurrences in the V2_A1 and V2_A3 CME bins, at the confidence level $\mathrm{ECL} = 93\%$. In additional sets of calculations, we tested sensitivity of the result to the biases in the CME speed/size distributions, to the choice of the bin boundaries, and to the V2_A2 data-bin employment. All these factors were found to have a minor impact on ECL (Kocharov et al., 2001).

Previously reported correlation between SEP intensities and CME speeds finds its counterpart in a speed dependence of probability to observe SEP event in association with a given CME. This is evident from comparison of the event statistics in different velocity bins, V1_A3 *vs.* V2_A3 *vs.* V3_A3. In the medium velocity bin V2_A3 we find 19 events per 253 CMEs, whereas there are 14 SEP events per 38 CMEs in the high speed bin V3_A3, and only one event per 159 CMEs in the lowest speed bin V1_A3. Thus the percentage of SEP events per one CME rises from less or about 1% for the low speed CMEs, $< 300\,\mathrm{km\,s^{-1}}$, to almost 40% for high speed CMEs, $> 800\,\mathrm{km\,s^{-1}}$.

The χ^2-test revealed significant distinctions also between the CME→flare associations (**Fig. 1**). Degrees of association in different pairs, gradual/impulsive/SEP-associated CMEs *vs.* X-ray/type II bursts, are significantly different at ECL= 85.0–100.0%. We find that the moderate-speed impulsive CMEs associated with SEPs are also highly associated with X-ray flares and type II radio bursts. Thus, the typical SEP-producing CME is that impulsively accelerated at heliocentric distances $< 2-4\ R_\odot$ in association with soft X-ray flare and coronal shocks. We would like to stress that we do not examine association of flares and SEPs. Our statistics is related to the association of different groups of CMEs with X-ray flares and type II/IV radio burst. Among others, we have considered a group of CMEs which were accompanied by SEP events at SOHO. It turns out that these SEP-producing CMEs are highly associated with X-ray flares, despite only a small portion of flares is associated with SEP events.

In early 1980s, MacQueen and Fisher (1983) studied 12 CMEs and found that flare-related CMEs moved at constant speeds, whereas prominence-related mass ejections accelerated. A more comprehensive study that determines accelerations for CMEs based on SMM and Mauna Loa observations confirms that conclusion (St.Cyr et al., 1999). Recent investigations with LASCO (Sheeley et al., 1999) suggest two principal types of CMEs: gradually accelerating CMEs and impulsive CMEs. Impulsive CMEs, often associated with flares and Moreton waves, move uniformly across the LASCO field of view. Hence, CMEs of this kind should experience a strong acceleration when getting a full speed during a short period below $\sim 2-4\ R_\odot$.

Kahler et al. (1999) proposed the CME acceleration value as a candidate factor affecting production of > 20 MeV protons, because “an accelerating CME may produce a shock later than a CME with a constant speed”. Based on this kinematics-type explanation and on the result of the present statistical study, a question should be raised as to why it is so crucial for shock to appear close to Sun. In this respect two reasons might be considered: (i) a constant-speed shock maintains high Mach numbers predominantly close to Sun, and (ii) a seed particle/wave population for the (moderate-speed) CME-shock acceleration is available only near the Sun. We see no arguments in favour of the first item over the second one, because Alfvén speed does not decrease towards the Sun.

On the other hand, Torsti et al. (2001a,b) analyzed the May 9, 1999, May 27, 1998, and December, 28, 1999 SEP events associated with impulsive CMEs with speeds 540 km s^{-1}, 880 km s^{-1}, and 512 km s^{-1}, respectively. The case studies support a kind of ‘closed-chain scenario’ that an early rise of CME triggers the flare which in its turn starts a continual proton acceleration culminating later at the CME-driven shock in the interplanetary medium. The first proton acceleration is triggered by the coronal counterparts of CME but followed by the long-term acceleration at the CME-driven shock in the interplanetary medium. It was suggested that the first acceleration may provide a seed population for the second one. It is possible that different seed populations may dominate in different eruptions, or in the same eruption but observed at very different solar longitudes.

We have studied SEP production by the 300–800 $\mathrm{km\ s^{-1}}$ CMEs, and conclude that data in hand support the following

1. The near-Sun dynamics of CME is a significant factor contributing to the intensities of ~ 10 MeV proton events.

2. A typical SEP-producing CME experiences fast acceleration close to Sun in association with soft X-ray flare and coronal shocks.

3. The CMEs (very) gradually accelerating across the 2–30 $R_\odot$ field of view with acceleration 2–10 $\mathrm{m\ s^{-2}}$ are less likely to produce > 10 MeV SEP events.

These results indicate that at least in the moderate speed range the near-Sun dynamics of CME, its acceleration, accelerating force, and corresponding force applied to solar corona, must be further considered as a significant factors affecting production of solar energetic particles along with the CME final speed. The joint analysis of the LASCO and ERNE data-sets brings out one more promising direction for the SEP-CME investigations.

Acknowledgements. The ERNE team thanks Academy of Finland for the grant. The SOHO is an international cooperation project between ESA and NASA.

Appendix A CME angular width

With the intent of estimating projection effects, consider CME as a cone, letting $\phi/2$ be the angle between the axis of the cone and the generatrix of the cone. Denote the angle between the axis of the cone and the perpendicular to the plane of sky by θ. One can see that the (full) angular width of the cone projection onto the sky plane, $\phi_\perp$, is in the form

$$\phi_\perp = 2\arctan\frac{\sin(\phi/2)}{\sqrt{\cos^2(\phi/2)-\cos^2\theta}}, \tag{A1}$$

at $\phi/2 \le \theta \le 180° - \phi/2$; otherwise $\phi_\perp = 360°$. After averaging over the directions of the cone axis we get the average angular width of the cone's shadow on the sky plane:

$$\langle\phi_\perp\rangle = 180°\Big(1+\sin\frac{\phi}{2}-\cos\frac{\phi}{2}\Big). \tag{A2}$$

If the CME average width in the projection plane, $\langle\phi_\perp\rangle$, is know, one can estimate the cone angle using the expression coming from Eq. (A2),

$$\phi = 90° + 2\arcsin\Big[\frac{1}{\sqrt{2}}\Big(\frac{\langle\phi_\perp\rangle}{180°}-1\Big)\Big]. \tag{A3}$$

Then the CME solid angle can be also estimated.

For the goals of the statistical study, one may suggest that the ratio of the frequency of SEP events associated with impulsive CMEs to the frequency of SEP events associated with gradual CMEs is proportional to the ratio of solid angles of corresponding CMEs (Kocharov et al., 2001). However a correction for the actual difference in $\langle\phi_\perp\rangle$ of impulsive *vs.* gradual CMEs, $77°$ *vs.* $93°$, is not very significant.

Note that the observed a-effect in production of SEPs might come through the width of the SEP producing region. Torsti et al. (1999) reported an observation of injection of > 10 MeV protons from a distant solar longitude in association with a coronal Moreton wave. A higher association of impulsive CMEs with coronal waves might result in a wider production cones for SEPs, despite the smaller mean angular size of impulsive CMEs as compared to the gradual ejections. The wider production-cone of SEPs may be also interpreted in terms of a wider angular spread of the seed particle population available for the CME bow-shock acceleration. For this reason, the a-effect seems linked to availability of the seed particle population, irrespective of whether the seed population is produced at/above the flaring region or at coronal waves far apart from the eruption center.

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