Coronal Mass Ejections and Solar Proton Events During the Great March 1989 Disturbances.

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Abstract: The great active region of March, 1989 was the most prolific in X-rays in the preceding 15 years and produced very large bright optical solar flares. The accompanying solar energetic particle event was one of the four most intense episodes since 1963, continuing for two weeks during which time there were several increases in flux, Here these increases in particle fluxes are compared to the major X-ray and optical flares and to the major CMEs in order to test the hypothesis that fast CMEs are needed to produce solar proton events, no matter how major the flare. Proton fluxes increased during the expected time intervals in the cases of three major flares accompanied by fast CMEs. In the case of one major flare without a CME and in the case of a slow CME there were no proton increases. However, there was an increase in proton fluence observed during the expected time for another major flare with no CME, in apparent disagreement with the hypothesis.

1. Introduction

The processes in which solar energetic particles are accelerated are still a matter of active research. Some workers emphasize the role that the shocks accompanying fast coronal **mass** ejections (CME) play in accelerating protons (cf. Gosling, 1993). Others hold that energetic particles with energies in the MeV range are accelerated both in the flare itself and

by the coronal mass ejection shock (Kallenrode et al., 1993). It was noted early that CMEs were associated with post flare loops (Sheeley et al, 1975) and metric type 11 bursts (Lin, 1970) and that these events were associated with proton events (Bruzek, 1964) and CMEs (Mum-o et al. 1979). This led to a model in which the type II burst was due to plasma turbulence in a detached shock moving ahead of the CME (Maxwell and Dryer, 1981) and the energetic protons were accelerated by the shock (Lee ancl Fisk, 1982, Acherberg and Norman, 1980). The relation between solar energetic protons and coronal mass ejections was studied more directly by Kahler et at (1978, 1984) who suggested that CMEs arc required for proton events.

In this paper we discuss a series of well observed major solar flare events from a single active center and the major CME events from the same center and study their relation to proton events observed at Earth. We test the hypothesis that fast CMEs are required to accelerate the protons by asking the following, questions:

1, Did all the major high velocity CME events in this related series result in proton enhancements?

2. Did any of the major flares not accompanied by CMES cause proton intensity increases?

2. **Proton Events**

A major series of solar proton events occurred in association with the March 1989 active region and was observed on the GOES-7 satellite. (See Joshi, 1993, for a description of the evolution of the active region and Kahler, 1993, for a description of the GOES particle detector.) The total fluence integrated over the entire episode of activity for particles with energies > 10 MeV was 2.3x109 particles/cm^2 (Zwickl, personal communication, 1989) making it one of the four most intense episodes since 1963 up until the date at which it occurred.

The proton observations for the March episode are shown in Figure 1. The proton flux in space was enhanced for 14 days and there was a series of increases followed by decays. The initial rise above background began slightly before midnight of March 7 to 8 and there were no enhancements in this series after March 22. The absolute fluxes shown in Figure 1 may be in error by perhaps 20% but that inaccuracy will not effect this analysis of the relation between CME and proton events.

3. CME Observations

During the passage of the active region across the solar disk, coronal mass ejections were observed from the High Altitude Observatory's coronagraph and polarimeter on the Solar Maximum Mission (SMM) spacecraft. These instruments gave a projection of the corona against the sky that covered the distance range from about 1.6 and 5 solar radii. (See MacQueen et al, 1980, Csoeke-poeckh et al., 1982, for descriptions of the instrument and its operation). A study of major solar flare events and coronal mass ejections associated with this center has been reported elsewhere (Feynman and Hundhausen, 1994). In that paper all the CMEs and solar flares that satisfied at least one of the following criteria were studied:

a) A clear and bright CME was observed at a position that could reasonably be associated with the active region.

b) An X-ray event classified as X3.0 or above took place somewhere on the Sun. (Category X is the highest flux category in use for X-ray flares. It indicates the flux is given in units of 10-4 W/m^2, so that, for example, the X-ray intensity for an X3,0 flare is 3.0x 10-4 w/m^2.)

c) An optical flare classified as 3B or above took place in the active region. (The B indicates the brightest category for flares and the 3 is a measure of its area 011 a scale of from 1 to 4. Class 4 flares arc very unusual.)

The six events that satisfied at least one of these trite] ia are listed in Table 1 which gives the date, the time at which the associated CME was observed, the classification of the X-ray flare and the position and importance of the optical flare. The final column indicates whether or not Type 11 radio emission was detected in associ at ion with the event (see Feynman and Hundhausen, 1994, for a detailed discussion of each of the events).

4. **Comparison of Proton Enhancements and CMEs**

Each of these 6 events will be compared with the proton data. We ask which of the flare/CME events arc associated with increases in the interplanetary proton fluences. To make these associations the expected delay time between the flare/CM13 and the proton event must be estimated. This delay time is strongly dependent on the longitude of the solar event. We usc the data on observed delay times to event onset for 30 MeV protons shown in figure 2 (from Barouch, 1971). In evaluating the flare-proton event assignment we also consider the time between onset and maximum for 20-80 McV protons collected by Van Hollebeke et al. (1975). See also Smart and Shea (1985). Events from east solar longitudes have very long delay times; whereas the delay times for west longitude events are much shorter, so that the associations for west longitude events are simpler to make. Because of this the three west longitude events will be discussed first.

On March 17 at 1731 UT (event 5 in tables 1 and 2) there was a X6.5 X-ray event and a 2B optical flare at N33 W60 (33 degrees North latitude and 60 degrees West longitude on the Sun). It was accompanied by a type 11 radio event and a well observed CME. At W60 this event was expected to be well connected to the Earth. In every respect this event was a classic candidate to cause a proton enhancement at Earth. The estimated time to onset from these longitudes ranges from less than 1/2 hour to 3 hours. The uncertainty is due to the scatter in the observed delay times shown in figure 2. The proton event expected on the basis of the shock acceleration hypothesis is clearly seen in the sudden rise of more than 2 orders of magnitude in the > 10 MeV flux which occurred on March 17 a short time after the flare (Figure 1).

This event is in nice contrast to event 4 (March 16) of Tables 1 and 2, The solar event consisted of two flares, a class X3,6, 2B at W47 and two hours later a class M2.4, 3B at W59. (For M class X-ray events the fluxes are expressed in units of 10-5 W/m^2, i.e. 1/1 O the size of the X class units). Again this event should have been well connected with the Earth with a delay time to onset of up to 3 hours and a rise time from onset to maximum of up to 7 hours. But in this case there was no significant CME so no proton increase was expected assuming increases are caused by CME shocks alone. The arrival window during which the event is expected (late on March 16) is indicated in Figure 1. It is clear that there is no proton enhancement, This observation is in agreement with the idea that CMES are required for energetic proton events.

The third event to be discussed is number 6 (March 18) of Tables 1 and 2. It was seen by SMM as a beautiful coronal mass ejection. Although there was an M4.4 X-ray event, no optical flare was identified. This may have been because the Sun had rotated so that most of the active region was behind the limb. ‘he onset expectations window of from 1 to 3 hours is shown on Figure 1 (March 18). The expected time from onset to maximum is 1 to 8 hours. No proton event is evident for this case although it is possible that the decay of the earlier event masked a small rise. The observed velocity of [he CME front was only 387 ±1O km/sec. Apparently the disturbance was not moving fast enough to produce a shock and turbulent region. This is consistent with its producing neither type 11 radio emission nor a proton event. Again the results agree with the concept that shocks produced by CMEs are required for proton acceleration.

The three East longitude events have considerably longer expected delay times to onset and rise times to maximum.

The first event observed from the active region occurred on March 6 when a spectacular CME appeared over the northeast limb of the Sun. The X-ray event was off scale for 27 minutes but was estimated to be Xl 5 (flux 1.5x 10-3 W/m^2) and the optical flare, at 69E, was of importance 3B. The CME was traveling so fast that it was seen on only one SMM observational. frame. No accurate determination of its velocity could be made but it was roughl y estimated to be about 1400 km/s (Feynman and Hundhausen, 1994). The delay time for a proton event onset on this limb of the Sun is both long and uncertain. From figure 2 wc estimate the expected onset time as 12 to 36 hours after the flare. The observed onset (Figure 3) is some time before 1800 UT March 7, which is well within the expected window, supporting the association between fast CM I Es and proton enhancements.

The next major is in apparent disagreement with the hypothesis. The flare (event 2 of tables 1 and 2) took place at 1538 UT March 9 at 1338 and was an X4.(), 413 event. Flares of importance 4B are very rare and this flare was one of the most intense optical flares ever observed. The estimated time delay to onset (figure 2) is 4 to 12 hours. This window is shown in figure 3. There is a rapid rise in flux during that period, The maximum is expected 7 to 20 hours after onset, and in fact a maximum takes place well within that interval. Thus both the rise and the maximum take place when they would be expected if they were produced by event 2 in table 1. But this flare was not accompanied by a coronal mass ejection. Not only was no CME seen but there was additional very strong evidence that no significant CME occurred (see Feynman and 1 lundhausen, 1994 for a very detailed analysis). A pre-existing slowly rising CME was not disturbed significantly. The X-ray event was narrow and peaked and the probability of a CME decreases with shorter lasting X-ray events (Sheeley et al. 1983). There were also no post flare loops nor was there a type 11 radio signal although both these phenomena are strongly statistically associated with CMEs. It was concluded in Feynman and Hundhausen that no mass ejection took place in association with the March 9 flare. Thus the increase in solar energetic protons during the time appropriate to the March 9 event is an unexpected result which seems to be at variance with the notion that shocks produced by CMES are required to produce energetic solar protons. These observations will be returned to in the discussion section.

The final event to be discussed is the flare/CME event of March 10 (event 3 of tables 1 and 2). The X4.5, 3B flare took place at E22 at 1922 UT and was accompanied by an extremely bright CME. This CME is believed to have been the cause of the enormous magnetic storm that began on March 13 (Allen et al., 1989). A rough est i mate of the lower limit of the CME velocity yielded 530 km/s (Feynman and Hundhausen, 1994). The velocity may have been considerably higher. This event was an excellent candidate for which to expect a solar proton enhancement. The expected arrival time was from 3 to 10 hours after the solar disturbance i. e. between 3/1() at 2200 UT anti 3/11 at 0500 UT. An inspection of the data in Figure 4 shows that protons began to art ive during the expected interval at about 2300 UT. New protons are especially obvious in the > 100 MeV range where an increase above background takes place for the first time in this episode of proton events. For the >10 MeV and > 30 MeV energy ranges the appearance of the new particles is seen in the change of slope from a decaying flux to a rising flux. Notice the change in spectrum between the fluxes on March 10 and March 11. The later fluxes have a harder spectrum in agreement with the variation of spectral index with source longitude reported by van Hollebeke et al. (1975). The maximum for the event is expected between 3 and 17 hours after onset in the 20 to 80 MeV range particles. There appears to be a change from a rising to a decaying slope just after 1200 UT on 11 March; well within the expected window. For this event then we have the expected result of a fast CME associated with an energetic proton event.

This completes the list of the proton fluxes associated with the six events chosen for special study in Feynman and Hundhausen, 1994. No other events that satisfied the criterion for being included in Feynman and Hundhausen, 1994 were observed during the passage of the active region across the solar disk.

5. Discussion and Conclusions

The results of the analysis are brought together in table 2. Except for event 2 the results are in agreement with the notion that fast CMES are required for the production of solar proton enhancements. Events 4 and 5 are an outstanding pair illustrating that agreement. Event 6 probably did not produce protons or type 11 emission because the velocity of the CME was somewhat low. The first and third events are also illustrations of protons being produced in events with CMEs. Event 2 however appears to disagree with the hypothesis that CMEs must be present to cause the acceleration of solar protons.

The contrast between the events 1 and 2 is outstanding. Event 1 has a CME, a long duration X-ray event, type II radio emission and post flare loops. Event 2 has no CME, a short duration X-ray event and no post flare loops (Feynman and Hundhausen, 1994). However, both events are apparently associated with increases in the >10 MeV and >30 MeV energy ranges. In event 2 we have a truly major optical and X-ray flare without a CME but with an apparent proton event. Because of the implications of this observation to theories of proton production, other explanations must be considered. Three possibilities present themselves:

1 -The increase in proton flux was actually part of a very late maximum associated with the first event.

2- The increase in flux was caused by a CME unrelated to the major active region and unaccompanied by an X-ray flare >3X.

3- The protons were accelerated by the flare itself. This would lead to the conclusion that solar proton events, although usually associated with CMEs, do not require CMEs.

Returning to the first question posed in the introduction wc have found that all of the high velocity CMEs in this series are associated with proton events. The answer to the second question is less satisfactory. This series of events contains examples of major flare events without CMEs that were also without proton enhancements, in agreement with the idea that CMES are needed to accelerate solar protons, However there. was also an increase in proton flux that began and maximized at the. proper times to be attributed to a major flare that was shown (Feynman and Hundhausen, 1994) not to have a CME. This observation presents a challenge to the hypothesis that 0111 y CMEs cause large proton enhancements at Earth.

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Figure Captions

Figure 1. Integral fluxes of solar protons March 8 to March 22, 1989 observed by GOES 7 (from Solar Geophysical Data, SESC PRF 70721 March 1989). Data is shown for the energies given on the right hand ordinate. The windows of expectation for the arrival of solar protons from the three west major flares and/or CMEs are shown as shaded regions.

Figure 2. lag times between flares and 30 McV solar proton events as a function of flare longitude. Figure from Smart and Shea, 1985, using data from Barouch et al., 1971.

Figure 3. The proton fluxes of March 6 to March 13,1989 showing the onset of the first proton event. The windows of expectation for the three east longitude flares or CMEs are shaded. The time axis is expanded relative to that shown in Figure 1.

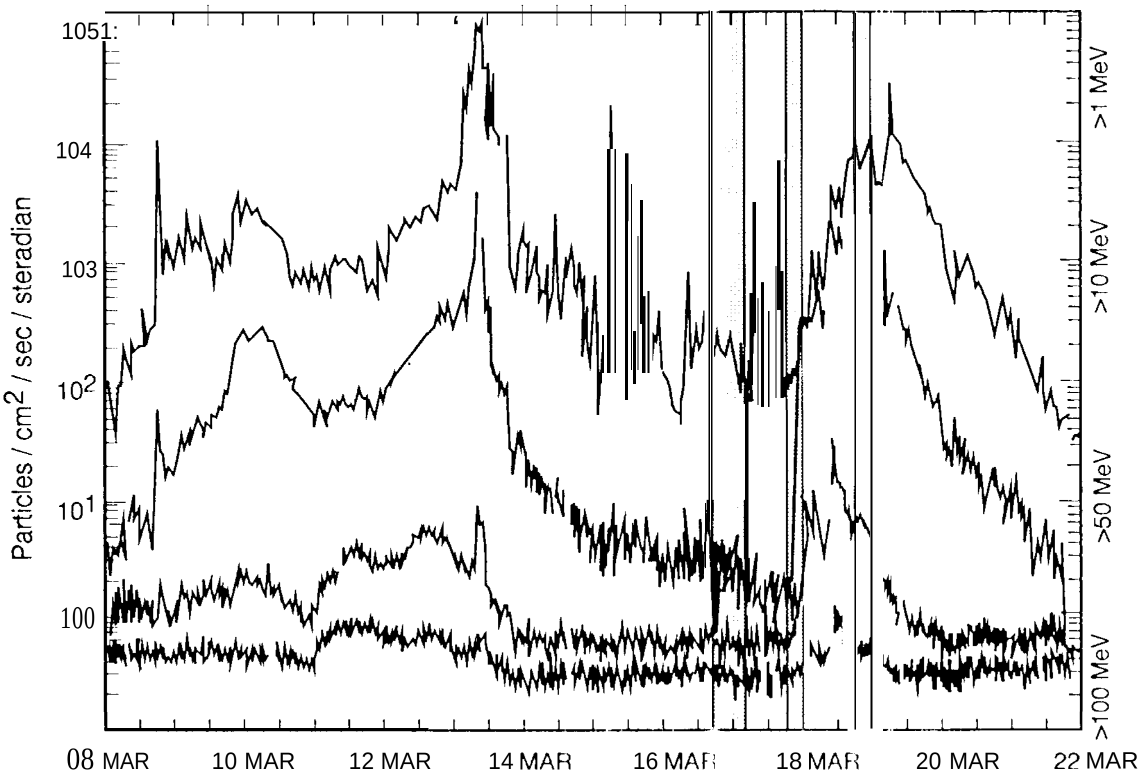
Table 1- Flares and **CMES**

Event	date	CME time ohs.	X-ray flare	Optical flare max class position	Type II ?
1	3/6	1412	X15	1405 3B N35E69	yes
2	3/9	----	x4	1538 4B N30E38	no
3	3/10	1922	x4.5	1922 3B N31E22	**yes**
4.	3/16	-----	X3.6 M2.4	1527 2B N36W47 1759 3B N31 W59	no
5.	3/17	1731	X6.5	17'37 2B N33W60	yes
6.	3/18	1856	M4.4	------------------	no

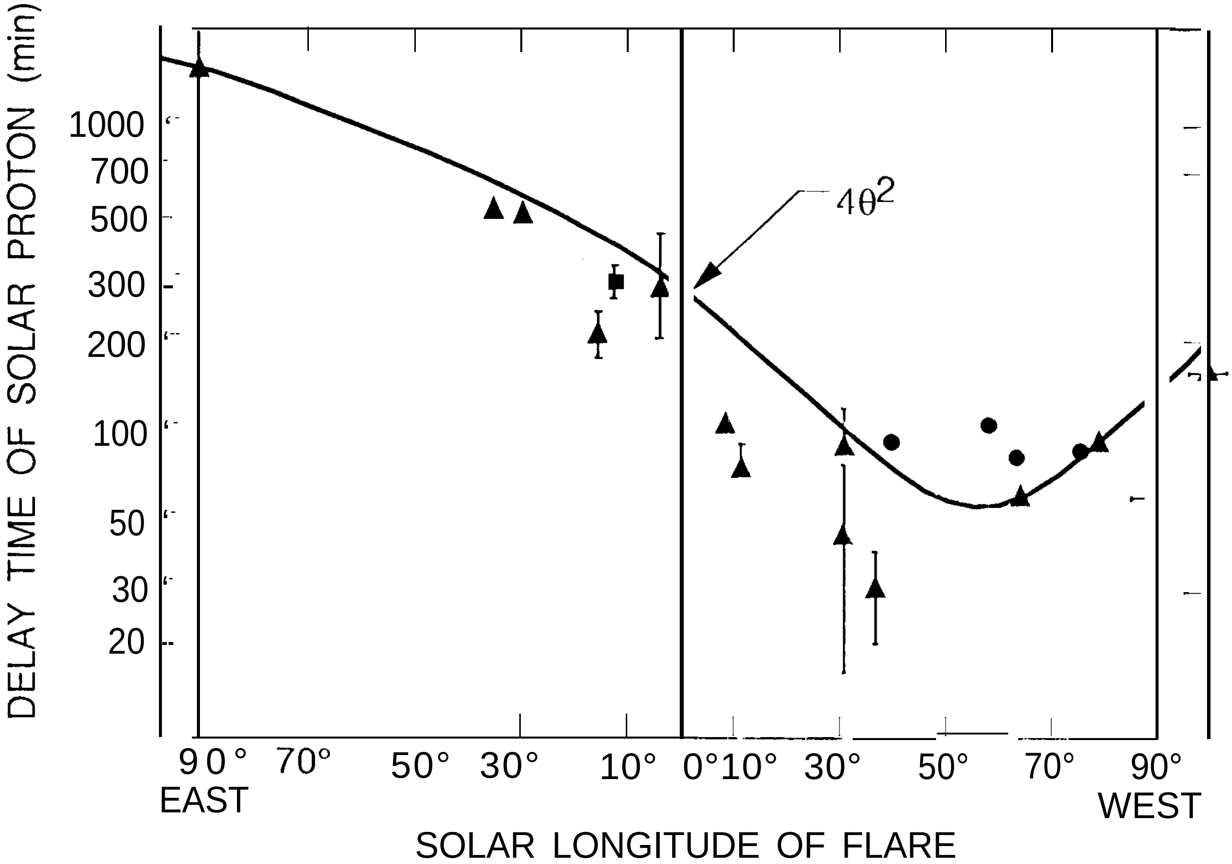
Table 2 -Proton Events and CMES

Event	Expected delay time to onset	Expected rise time to max.	Observations and remarks	CME?
3/6	12-36 hrs.	15-45 hrs.	Onset about 3/7 1800 U'I', maximum undetermined	Yes
3/9	4-12 hrs.	7 to 20 hrs.	Rise and broad maximum in expected time interval	No
3/10	3-10 hrs.	5 to 17 hrs.	Onset in expected interval maximum undetermined	Yes
3/16	o-3 hrs.	O to 7 hrs	No proton event	No
3/17	O-3 hrs.	O to 7 hrs	Sudden rise after about 6 hrs	Yes
3/18	1-4 hrs.	1 to 8 hrs	No change in ongoing event	Yes

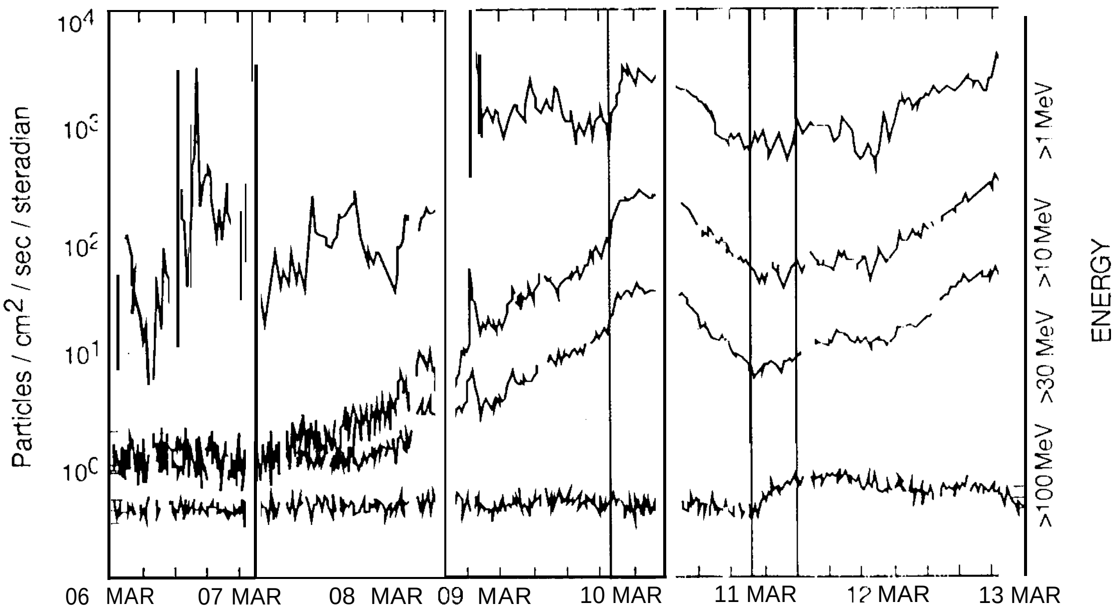
GOES PROTON INTEGRAL FLUX (5 min)



1989


DELAY TIME OF SOLAR PROTON (min)
1000
700
500
300
200
100
50
30
20
$4\theta^2$
90° 70° 50° 30° 10° 0° 10° 30° 50° 70° 90°
EAST
WEST
SOLAR LONGITUDE OF FLARE

GOES PROTON INTEGRAL. FLUX (5 rein)



1989