LA-UR -91-3546

LA-UR--91-3546

DE92 003857

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

Received 1991

DEC 03 1991

TITLE: In Situ Observations of Coronal Mass Ejections in
Interplanetary Space

AUTHOR(S): J.T. Gosling

SUBMITTED TO: Proceedings of IAU Colloquium 133, Iguazu, Argentina,
2-6 August 1991

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

MASTER

REPRODUCTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

IN SITU OBSERVATIONS OF CORONAL MASS EJECTIONS IN INTERPLANETARY SPACE

J. T. Gosling
Los Alamos National Laboratory
MS D438, Los Alamos NM 87545 USA

Abstract. Coronal mass ejections, CMEs, in the solar wind at 1 AU generally have distinct plasma and field signatures by which they can be distinguished from the ordinary solar wind. These include one or more of the following: helium abundance enhancements, ion and electron temperature depressions, unusual ionization states, strong magnetic fields, low plasma beta, low magnetic field variance, coherent field rotations, counterstreaming (along the field) energetic protons, and counterstreaming suprathermal electrons. The most reliable of these appears to be counterstreaming electrons, which indicates that CMEs at 1 AU typically are closed field structures either rooted at both ends in the Sun or entirely disconnected from it as plasmoids. About 1/3 of all CMEs have sufficiently high speeds to produce transient interplanetary shock disturbances at 1 AU; the remainder simply ride along with the solar wind. The frequency of occurrence of CMEs in the ecliptic plane, as distinguished by the counterstreaming electron signature, varies roughly in phase and amplitude with the 11-yr solar activity cycle. Near solar maximum they account for ~ 15% of all solar wind measurements, while near solar minimum they account for less than 1% of all the measurements. All but one of the 37 largest geomagnetic storms near the last solar maximum were associated with Earth-passage of interplanetary disturbances driven by fast CMEs; that is, CMEs are the prime link between solar and geomagnetic activity. However, more than half of all earthward directed CMEs are relatively ineffective in a geomagnetic sense.

The leading edges of coronal mass ejections, CMEs, have outward speeds at distances of several solar radii above the photosphere ranging from less than 50 km s^{-1} to greater than 1200 km s^{-1} [1,2]. When the speed difference between the leading edge of a CME and the ambient solar wind ahead exceeds the characteristic speed with which small amplitude pressure waves propagate, a shock should form ahead of the CME. At 1 AU typical solar wind bulk flow speeds are of the order of 400 km s^{-1} , while the sound and Alfvén speeds typically are each of the order of 50 km s^{-1} [3]. Thus CMEs with speeds in excess of $\sim 500 \text{ km s}^{-1}$ should usually drive shock wave disturbances in the solar wind, while slower ones should not. In fact, a nearly one-to-one correlation exists between large, fast CMEs detected by satellite coronagraphs and transient shock wave disturbances in the solar wind observed at roughly the same solar longitudes [4].

Transient interplanetary shocks thus serve as useful fiducials for searching for plasma and/or field anomalies by which one might uniquely identify CMEs in the solar wind. As illustrated in Figure 1a, an offset is expected between an interplanetary shock and the CME that drives it.

Fig. 1a (Left). A meridional cut through a hypothetical interplanetary shock wave disturbance driven by a fast CME as well as the corresponding radial variation of magnetic field strength along the centerline of the disturbance. Compression, driven by the relative motion between the CME and the ambient solar wind ahead, produces strong magnetic fields in a broad region extending sunward from the shock to well within the leading portion of the CME itself. The ambient magnetic field drapes about the CME [5] because CMEs generally originate in closed field regions in the corona not previously participating in the solar wind expansion. Note, particularly, that the shock and the CME are separated by an extended region of shocked ambient plasma. Adapted from [6].

Fig. 1b (Right). A sketch illustrating possible origins of counterstreaming halo electrons in the solar wind. Adapted from [7].

Figure 2a displays selected solar wind plasma data from the Los Alamos plasma experiments on IMPs 7 and 8 for an interplanetary shock disturbance observed in July 1977. Discontinuous increases in the proton density, temperature, and bulk flow speed near the start of the day on July 29 signal passage of the shock. Approximately 12 hours later a sudden and large increase in the abundance of He^{++} and a large decrease in proton temperature occurred. Such variations are often observed a number of hours after shock passage [8,9], and were the first anomalies identifying CMEs recognized in solar wind data. (Interestingly, this recognition predated the first good observations of CMEs by the OSO 7 and Skylab coronagraphs.) Note that the plasma identified as the

Fig. 2a (Left). Solar wind plasma measurements encompassing a shock wave disturbance on July 28, 29, 1977. From [10].

Fig. 2b (Right). A time series of 1-dimensional solar wind E/q spectra obtained within the CME on July 29, 1977. Tic marks on the left-hand vertical scale denote factors of 10 differences in counts. Adapted from [10].

CME in this event had a higher speed than the ambient plasma ahead of the shock, as would be expected if it were the cause of the shock. On the other hand, this plasma had a lower density than the ambient even though one of the things that characterizes CMEs in coronagraph observations is a high density. Examination of a large number of solar wind shock disturbance events reveals that CMEs in the solar wind at 1 AU typically do not have particularly high densities when compared to the surrounding solar wind. This suggests that CMEs experience greater expansion in transit to 1 AU than do typical solar wind plasma volume elements.

Figure 2b, which displays a vertically stacked time series of E/q spectra obtained by the IMP instrumentation, provides a more detailed examination of the July 29, 1977 CME, the onset of which is obvious at 1224 UT. The most remarkable aspect of the data is the sudden appearance within the CME at 1314 UT of a large spectral peak at an E/q value of 4.0 times that of the H^+ peak. This third peak was caused by He^+ , which has an m/q value of four times that of H^+ . Normally He^+ is quite rare in the solar wind, virtually all of the helium present being doubly ionized owing to the million degree temperature of the solar corona from which the solar wind arises. The exceptionally large He^+/He^{++} abundance (~ 0.3) measured for ~ 1 hr within the interior of the July 29, 1977 CME indicates a somewhat cooler origin for that particular volume of plasma. We, in fact, believe that that volume originated in a solar filament. However, the special nature of this particular observation cannot be overemphasized. This is by far the largest He^+

enhancement yet observed, although smaller He^+ enhancements have been detected in several other events [11,12]. Usually the helium within filament material ejected into the solar wind must become almost completely ionized as it passes outward through the corona.

Over the years a variety of plasma and field signatures have been identified, in addition to those above, that qualify as unusual compared to the normal solar wind but that are often observed a number of hours after passage of interplanetary shocks. Presumably they serve to identify at least portions of the CMEs driving the shocks. The most prominent of these signatures according to [7] are (1) helium abundance enhancements, (2) ion and electron temperature depressions, (3) unusual ionization states, (4) strong magnetic fields, (5) low plasma beta, (6) low magnetic field variance, (7) coherent field rotations, (8) counterstreaming energetic protons, and (9) counterstreaming suprathermal electrons. Most, but not all, of these characteristics are also found about equally often elsewhere in the solar wind where it is assumed that they serve to identify those CMEs with speeds that are too low to produce shock disturbances. It is worth emphasizing that relatively few CMEs at 1 AU exhibit all of these characteristics [13]. Further, some of these features are more commonly observed than are others. Our experience is that a counterstreaming flux of suprathermal electrons above ~ 80 eV is the most reliable signature of a CME in the solar wind at 1 AU. The following paragraph helps explain why the counterstreaming electron signature is so reliable.

Solar wind electrons above ~ 80 eV are commonly referred to as the “halo” population to distinguish them from the thermal electron population at lower energies. These electrons carry the solar wind electron heat flux, and are usually narrowly beamed along the interplanetary magnetic field in a direction pointed outward away from the Sun. As illustrated in Figure 1b, a unidirectional beam of halo electrons normally arises because field lines in the solar wind usually are “open” and are effectively connected to a hot source (the solar corona) at only one end. Counterstreaming of these electrons is usually taken to indicate that a field line is connected to a hot source of electrons at both ends. Thus, the counterstreaming halo electron events, which we associate with CMEs in interplanetary space, are commonly interpreted in terms of “closed” field structures such as the connected loop or disconnected plasmoid drawn in the figure. The closed field topology suggested by counterstreaming electron events is consistent with coronagraph observations, which indicate that CMEs generally originate in closed field regions in the solar corona not previously participating in the solar wind expansion [14]. Indeed, it is precisely because CMEs generally originate in closed field regions and because the halo electrons are so sensitive to field topology that counterstreaming electrons are such a reliable signature of CMEs.

Figure 3, which displays 3-dimensional views of 2-dimensional solar wind electron distributions measured by Los Alamos plasma instrumentation on ISEE 3, illustrates how counterstreaming electron events can be recognized in solar wind data. The electron distribution on the left is representative of what is normally observed in the solar wind, and contains an enhancement at energies above ~ 80 eV in the direction pointed outward away from the Sun along the interplanetary magnetic field. By way of contrast, the distribution on the right, obtained within a counterstreaming event, contains

Fig. 3. Solar wind electron distributions within the normal solar wind (left) and within a CME (right). An azimuth of 0 deg corresponds to flow away from the Sun. The small blip at the lowest energy is an artifact. Adapted from [15].

enhancements at these energies in the directions both parallel and antiparallel to the field.

We have scanned color-coded plots of electron angular distributions similar to those previously shown [7,15] in order to identify the counterstreaming electron events in the ISEE 3 / ICE plasma data that we associate with CMEs (ISEE 3 was renamed ICE in December 1983 after it was redirected toward an encounter with comet Giacobini-Zinner). At least 286 counterstreaming events have been identified in the interval extending from launch in August 1978 through December 1990. The average event duration was ~ 18 hours, corresponding to a radial thickness of about 0.2 AU. Approximately 1/3 of the events had sufficiently high speeds relative to the ambient solar wind to drive interplanetary shocks at 1 AU. The other events had no obvious associations with interplanetary shocks.

Figure 4a shows selected plasma and field data from ISEE 3 for a transient shock disturbance driven by a fast CME (identified by the counterstreaming signature). Note that the leading portion of the CME had a higher speed than that of the ambient wind ahead of the shock. The shock was, of course, a result of the interaction between the CME and the slower solar wind ahead. This interaction both accelerated the ambient wind and decelerated the CME, and the resulting compression produced a region of enhanced density, proton temperature, and field strength extending rearward from the shock into the leading portion of the CME itself. By way of contrast, Figure 4b shows selected plasma and field measurements encompassing a counterstreaming event that was not shock associated. Note that the bulk flow within the counterstreaming event was less than or comparable to that of the ambient solar wind ahead, which explains the lack of a shock association. In addition, it is clear that the counterstreaming event was a distinct plasma and field entity, distinguished by low plasma density, low proton temperature, moderately strong and steady magnetic field, low plasma beta, and field rotations at either end. This event illustrates that the magnetic field tends to be somewhat elevated

Fig. 4a (Left). Selected solar wind plasma and field measurements encompassing a shock wave disturbance driven by a fast CME. Adapted from [15].

Fig. 4b (Right). Selected solar wind plasma and field measurements encompassing a slow CME. Adapted from [15].

within CMEs in the solar wind at 1 AU even when there is no evidence for compression in interplanetary space. However, interplanetary compression is primarily responsible for the very strong fields commonly observed within shock events.

Although CMEs in interplanetary space, as distinguished by the counterstreaming electron signature, are usually distinct plasma and field entities such as the ones illustrated in Figure 4, in most respects they do not usually differ greatly from the ordinary solar wind. On a statistical basis, when compared with the entire body of solar wind data, the characteristics of these events that stand out the most are stronger field strengths, lower proton and electron temperatures, and lower plasma beta. This is illustrated by the plots shown in Figure 5, which compare the frequency of occurrence of these quantities in counterstreaming electron events with those for all of the ISEE 3 solar wind data for the 1978-1979 interval. As we have already noted, these events are usually not distinguished by abnormal plasma densities despite the fact that density is apparently one of the distinguishing traits of CMEs in coronagraph observations.

Analysis of coronagraph observations reveals that the occurrence rate of CMEs tends to track the solar activity cycle, as measured by (say) sunspot numbers [16]. From the coronagraph observations Kahler [17] has estimated that CMEs contribute $\sim 10\%$ of the

Fig. 5. Histograms of the relative frequency of occurrence of different values of proton and electron temperature (left) and magnetic field magnitude and plasma beta (right) within counterstreaming events and for the entire solar wind data set from August 1978 through December 1979. Adapted from [15].

solar wind mass flux in the ecliptic plane at solar activity maximum and $\sim 1\%$ near solar minimum. One test of the reliability of using counterstreaming electron events as signatures of CMEs in the solar wind at 1 AU would be to see if counterstreaming events exhibit a similar variation over the solar cycle. Figure 6a shows the percentage of the available solar wind electron data from ISEE 3 / ICE for which counterstreaming was observed on an annual basis from 1978 through 1990. For the most part, the annual variation in counterstreaming percentage varied smoothly as a function of the phase of the ~ 11 -yr sunspot cycle. Near solar activity maximums in 1980 and 1989 counterstreaming events accounted for $\sim 14.7\%$ of the available solar wind measurements. By way of contrast, near solar minimum in 1986 counterstreaming events accounted for only 0.7% of the available solar wind data. These percentages are comparable to Kahler's estimates noted above, although his estimates are for mass flux rather than for the percentage of time that CMEs pass a spacecraft at 1 AU. Yearly estimates of the numbers of CME events expected at a single point in the ecliptic plane (such as, for example, at ISEE 3 / ICE or at Earth) derived from both coronagraph observations and the ISEE 3 / ICE electron measurements are also in reasonable agreement [18]. The number of CMEs/yr at a single point in the ecliptic plane varies from about 70 events/yr at solar maximum to about 5-10 events/yr at solar minimum. Taken together, these

Fig. 6a (Left). Counterstreaming solar wind halo electron observations by ISEE 3 / ICE as a percentage of all the solar wind electron data, plotted on an annual basis. The counterstreaming percentages vary roughly in phase and amplitude with the 11-yr solar activity cycle as measured by sunspot numbers. Adapted from [18].

Fig. 6b (Right). Bar graph indicating the geomagnetic effectiveness of CMEs, shock disturbances, and shock/CME events passing Earth in the interval from August 1978 through October 1982 at the last solar maximum. The numbers in parentheses indicate the number of interplanetary events in each category. The different types of events are not mutually exclusive. From [6].

results provide further strong evidence that CMEs in the solar wind at 1 AU, including the many slow ones which do not produce transient interplanetary shocks, can usually be identified by the counterstreaming signature.

Finally, the high flow speeds and strong magnetic fields (often with strong southward components) associated with interplanetary disturbances driven by fast CMEs suggests that such events should often be quite effective in stimulating geomagnetic activity. Indeed, recent work with the ISEE 3 data indicates that fast CMEs are the crucial links between solar activity and large, nonrecurrent geomagnetic storms. For example, it has been shown [6,19] that all but one of the 37 largest geomagnetic storms in the August 1978 - October 1982 interval spanning the last solar maximum were associated with Earth-passage of solar wind disturbances driven by fast CMEs (as identified by the counterstreaming electron signature).

On the other hand, many CMEs and CME-driven interplanetary disturbances passing the Earth were relatively ineffective in stimulating major geomagnetic activity. One commonly-used measure of geomagnetic activity is the K_p index, which ranges from 0₀ up to 9₀ in 28 logarithmic steps. In what follows we have assumed that interplanetary events are geomagnetically effective only if they produce a geomagnetic disturbance with

$K_p > 4_+$. Figure 6b shows that only 44% of all CMEs and 53% of all transient shock disturbances (which we assume were driven by CMEs whether or not the CME itself was actually encountered directly), but 85% of all events in which the Earth encountered both a shock and the CME driving it in the 1978 - 1982 era were geomagnetically effective in this sense. Further analysis reveals that the geomagnetic effectiveness of these events was directly related to the associated flow speed, magnetic field magnitude, and strength of the southward field component. We have suggested [6] that the initial speed of a CME relative to the ambient solar wind ahead is ultimately probably the most important factor in determining if an earthward directed CME will be geomagnetically effective. A substantial speed differential appears to be essential for producing strong magnetic fields in interplanetary space via compression, and a large southward field component, the most important element in coupling solar wind energy to the Earth's magnetosphere, is more likely when the total field is strong.

Acknowledgment. This work was performed under the auspices of the U.S. Department of Energy with NASA support under S-04039-D. I thank the meeting organizers and NASA for travel support to the colloquium.

REFERENCES

1. J. T. Gosling, E. Hildner, R. M. MacQueen, R. H. Munro, A. I. Poland, and C. L. Ross, The speeds of coronal mass ejection events, *Solar Phys.*, **48**, 389, 1976.
2. R. Howard, N. R. Sheeley, M. J. Koomen, and D. J. Michels, Coronal mass ejections: 1979-1981, *J. Geophys. Res.*, **90**, 8173, 1985.
3. W. C. Feldman, J. R. Asbridge, S. J. Bame, and J. T. Gosling, Plasma and magnetic fields from the Sun, in *The Solar Output and Its Variation*, edited by O. R. White, Colorado Assoc. Univ. Press, Boulder, CO, p. 351, 1977.
4. N. R. Sheeley, R. A. Howard, M. J. Koomen, D. J. Michels, R. Schwenn, K.-H. Muhlhauser, and H. Rosenbauer, Coronal mass ejections and interplanetary shocks, *J. Geophys. Res.*, **90**, 163, 1985.
5. J. T. Gosling and D. J. McComas, Field line draping about fast coronal mass ejecta: A source of strong out-of-the-ecliptic magnetic fields, *Geophys. Res. Lett.*, **14**, 355, 1987.
6. J. T. Gosling, D. J. McComas, J. L. Phillips, and S. J. Bame, Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections, *J. Geophys. Res.*, **96**, 731, 1991.
7. J. T. Gosling, 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, Geophysical Monograph 58, Amer. Geophys. Union, p. 343, 1990.

8. J. Hirshberg, S. J. Bame, and D. E. Robbins, Solar flares and solar wind helium enrichments: July 1965-July 1967, *Solar Phys.*, 23, 467, 1972.
9. J. T. Gosling, V. Pizzo, and S. J. Bame, Anomalous low proton temperatures in the solar wind following interplanetary shock waves: Evidence for magnetic bottles?, *J. Geophys. Res.*, 78, 2001, 1973.
10. J. T. Gosling, J. R. Asbridge, S. J. Bame, W. C. Feldman, and R. D. Zwickl, Observations of large fluxes of He^+ in the solar wind following an interplanetary shock, *J. Geophys. Res.*, 85, 3431, 1980.
11. R. Schwenn, H. Rosenbauer, and K.-H. Muhlhauser, Singly ionized helium in the driver gas of an interplanetary shock wave, *Geophys. Res. Lett.*, 7, 201, 1980.
12. R. D. Zwickl, J. R. Asbridge, S. J. Bame, W. C. Feldman, and J. T. Gosling, He^+ and other unusual ions in the solar wind: A systematic search covering 1972-1980, *J. Geophys. Res.*, 87, 7379, 1982.
13. R. D. Zwickl, J. R. Asbridge, S. J. Bame, W. C. Feldman, J. T. Gosling, and E. J. Smith, Plasma properties of driver gas following interplanetary shocks observed by ISEE 3, in *Solar Wind 5*, NASA Conf. Publ., CP-2280, edited by M. Neugebauer, p. 711, 1983.
14. A. J. Hundhausen, The origin and propagation of coronal mass ejections, in *Proceedings of the Sixth International Solar Wind Conference*, edited by V. Pizzo, T. E. Holzer, and D. G. Sime, NCAR/TN-306+Proc, Boulder, CO, p. 181, 1988.
15. J. T. Gosling, D. N. Baker, S. J. Bame, W. C. Feldman, R. D. Zwickl, and E. J. Smith, Bidirectional solar wind electron heat flux events, *J. Geophys. Res.*, 92, 8519, 1987.
16. D. F. Webb, The solar cycle variation of the rates of CMEs and related activity, *Adv. Space Res.*, 11, (1)37, 1991.
17. S. Kahler, Observations of coronal mass ejections near the Sun, in *Proceedings of the Sixth International Solar Wind Conference*, edited by V. Pizzo, T. E. Holzer, and D. G. Sime, Tech. Note 306+Proc, p. 215, Natl. Cent. for Atmos. Res., Boulder, CO, 1988.
18. J. T. Gosling, D. J. McComas, J. L. Phillips, and S. J. Bame, Counterstreaming solar wind halo electron events: Solar cycle variations, *J. Geophys. Res.*, submitted, 1991.
19. J. T. Gosling, S. J. Bame, D. J. McComas, and J. L. Phillips, Coronal mass ejections and large geomagnetic storms, *Geophys. Res. Lett.*, 17, 901, 1990.

END

**DATE
FILMED**

01/15/92