

# THE SPEEDS OF CORONAL MASS EJECTION EVENTS

J. T. GOSLING

*University of California, Los Alamos Scientific Laboratory, Los Alamos, N.M. 87545, U.S.A.*

and

E. HILDNER, R. M. MacQUEEN, R. H. MUNRO,

A. I. POLAND and C. L. ROSS

*High Altitude Observatory, National Center for Atmospheric Research,\* Boulder, Colo. 80302, U.S.A.*

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**Abstract.** The outward speeds of mass ejection events observed with the white light coronagraph experiment on Skylab varied over a range extending from less than  $100 \text{ km s}^{-1}$  to greater than  $1200 \text{ km s}^{-1}$ . For all events the average speed within the field of view of the experiment (1.75 to 6 solar radii) was  $470 \text{ km s}^{-1}$ . Typically, flare associated events (Importance 1 or greater) traveled faster ( $775 \text{ km s}^{-1}$ ) than events associated with eruptive prominences ( $330 \text{ km s}^{-1}$ ); no flare associated event had a speed less than  $360 \text{ km s}^{-1}$ , and only one eruptive prominence associated event had a speed greater than  $600 \text{ km s}^{-1}$ . Speeds versus height profiles for a limited number of events indicate that the leading edges of the ejecta move outward with constant or increasing speeds.

Metric wavelength type II and IV radio bursts are associated only with events moving faster than about  $400 \text{ km s}^{-1}$ ; all but two events moving faster than  $500 \text{ km s}^{-1}$  produced either a type II or IV radio burst or both. This suggests that the characteristic speed with which MHD signals propagate in the lower (1.1 to 3 solar radii) corona, where metric wavelength bursts are generated, is about  $400$  to  $500 \text{ km s}^{-1}$ . The fact that the fastest mass ejection events are almost always associated with flares and with metric wavelength type II and IV radio bursts explains why major shock wave disturbances in the solar wind at 1 AU are most often associated with these forms of solar activity rather than with eruptive prominences.

## 1. Introduction

The dynamic nature of the outer solar corona has been revealed in recent years by improved techniques of observing the corona from the ground (e.g., Smerd and Dulk, 1971; Dunn, 1971; DeMastus *et al.*, 1973; Hansen *et al.*, 1974) and from spacecraft (e.g., Stone, 1974; Stewart *et al.*, 1974a, b; Koomen *et al.*, 1974; MacQueen *et al.*, 1974a; Gosling *et al.*, 1974; Hildner *et al.*, 1975a). Viewed in optical wavelengths, disturbances in the outer corona often take the form of mass ejections in which outward moving material (of the order of  $10^{15}$ – $10^{16}$  g) appears to escape from the Sun. Such events are commonly associated with other forms of solar activity, particularly eruptive prominences and (less frequently) flares accompanied by surges and sprays; about 30% of the time they generate metric wavelength type II and/or IV radio bursts (Gosling *et al.*, 1974; Munro *et al.*, 1976). Despite their association with eruptive prominences and flare sprays, coronal

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mass ejections are considerably larger than their  $H\alpha$  counterparts, travel at different speeds, and consist primarily of material originally residing in the lower corona (Hildner *et al.*, 1975b; Poland and Munro, 1976). MHD bow waves form around the material ejecta which compress the ambient corona ahead of the ejecta and deflect the ambient corona from the ejecta's outward path; at times these bow waves can be detected by their effects on nearby coronal structures (e.g., Gosling *et al.*, 1974; Hildner *et al.*, 1975a).

Speeds measured for coronal mass ejections already reported in the literature vary from less than  $100 \text{ km s}^{-1}$  (Hildner *et al.*, 1975b) to greater than  $1200 \text{ km s}^{-1}$  (Stewart *et al.*, 1975a); however, no systematic study of ejection speeds, their variation with height, and their correlation with other forms of solar activity has been reported. It is our purpose here to present the results of such a study for the mass ejection events observed with the white light coronagraph experiment aboard Skylab.

## 2. The Observations

### A. GENERAL

The High Altitude Observatory's white light coronagraph experiment on Skylab was designed to observe photospheric light scattered by the K-(electron) and F-(dust) coronal components within a 3.2 degree field of view centered on the Sun in broad band (3700–7000 Å) white light. Sequences of pictures taken in both polarized and unpolarized light were obtained throughout the 8 month mission. Descriptions of the instrument and its operating modes have been published elsewhere (MacQueen *et al.*, 1974a,b).

An example of a mass ejection event observed by the coronagraph is shown in Figure 1. This is one of several photographs taken on 27 October 1973 following a large flare at N20 E55. At least sixty-six similar events (most of them not flare-associated) were observed during the Skylab mission. The temporal coverage obtained for these sixty-six major events varies widely. For seven events the frequency of observations was sufficiently high that the speeds of the leading edges of the ejections can be determined as functions of height in the solar atmosphere. For nineteen events we have only enough photographs to determine the average outward speed within the field of view of the instrument. For the remainder of the sixty-six events usually no more than one sequence of photographs was obtained which shows the leading edge of the ejection. Lower limit estimates of the speed can be obtained for twelve of these latter events based upon the time lapse from either the previous sequence of photographs or from the start of the suspected surface or limb event (e.g., flare or eruptive prominence). No meaningful estimates can be obtained for the remaining twenty-eight major events either because surface or limb associations are unknown or because the time lapse between successive sequences of pictures was too long.

The leading edge of a mass ejection event is usually well defined (see, e.g., Figure 1), and its displacement with time can be readily measured to determine

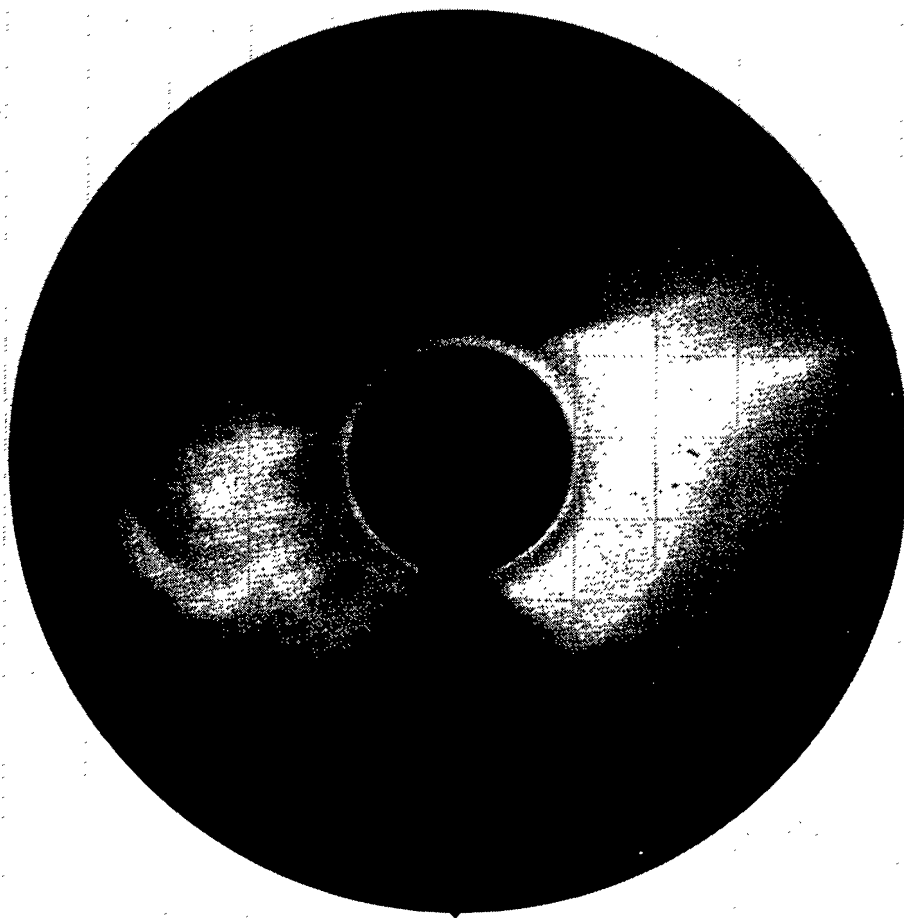


Fig. 1. A mass ejection event photographed at 1659 UT on 27 October 1973 following a large flare at 1543 UT at N20 E55. North is at the top and east is to the left. The field of view of the photograph is six solar diameters. The sun is obscured by the occulting disk at the center, whose effective diameter is 1.5 solar diameters. Diffraction rings appear around the periphery of this disk, and the shadow extending downward from it is caused by a pylon supporting the occulter. The faint annulus at about 3 solar diameters is an instrumental artifact. The very strong radial gradient of coronal radiance has been attenuated by vignetting within the instrument and by dodging the print.

the speed of ascent. The speeds of other portions of an event are more difficult to obtain because inhomogeneities are usually not present that are identifiable from one frame to the next. The speeds used in this paper, with one exception, refer to the centers of the leading edges of the ejections. Because the centers of the leading edges appear to travel faster than any other portion, their speeds may not be representative of all of the material within these disturbances. On the other hand, the speed of the leading edge of a mass ejection is probably intimately associated with metric radio burst generation and is an important factor in determining the ejection's subsequent propagation in the solar wind to large heliocentric distances.

The speeds used in this paper have been determined from direct measurements of the displacements of the leading edges of the disturbances (of an inferior feature in the case of the 15 January 1974 event) as seen projected against the plane of the sky (i.e., perpendicular to the Sun–Earth line). They have been corrected for motions out of this plane for those events having known

associations with surface phenomena (e.g., the event of 27 October 1973 illustrated in Figure 1). In these cases we assume that the motion is radially outward from the site of the surface phenomena. Corrections of this nature exceed 10% in only five cases, because the instrument is most sensitive to events near the plane of the sky.

Estimates of the errors involved in our speed determinations are somewhat subjective and vary from event to event depending upon the sharpness of the leading edges of the ejections and the time lapse between photographs. Typically, uncertainties in the individual speed determinations presented here range between  $\pm 25$  to  $\pm 75$  km s<sup>-1</sup>.

## B. SPEED DISTRIBUTIONS AND ASSOCIATIONS WITH SOLAR ACTIVITY

The number distribution of speeds observed, in intervals of 100 km s<sup>-1</sup>, is displayed in the upper panel of Figure 2. (For events where the speed clearly varied with height, we have taken the speed to be that measured at a heliocentric distance of 4 solar radii.) The events had speeds ranging from less than 100 to greater than 1200 km s<sup>-1</sup>, with the average being close to  $470 \pm 50$  km s<sup>-1</sup>. Approximately equal numbers of events had speeds above and below the average value, but the distribution is not normal about the average. Seventy percent of the events had speeds exceeding the escape velocity at 6 solar radii (the outer edge of the field of view of the coronagraph).

Examination of the data suggests that the speeds of mass ejection events are loosely correlated with the type of H $\alpha$  activity associated with them; events associated with flares usually have speeds greater than the speeds of those events associated with eruptive prominences. Henceforth we designate these coronal events as FLA and EPL events respectively. The distinction between FLA and EPL events is occasionally unclear for several reasons. For example, flare sprays seen on the limb in H $\alpha$  often resemble eruptive prominences, and minor H $\alpha$  brightenings in the chromosphere often accompany eruptive prominences (filaments). However, for all of the events placed in our EPL category there were no flares reported in close time coincidence with the H $\alpha$  eruptions. Of the events placed in our FLA category, virtually all of the flares had an associated H $\alpha$  mass ejection (i.e. spray or high velocity dark filament), but except for three infall-impact flares, all of the flares occurred prior to or simultaneous with the H $\alpha$  mass ejection. Further, all but one of the flares in the FLA category were Importance 1 or greater, suggesting that only the larger flares are effective in producing coronal mass ejection events (Munro *et al.*, 1976). Two of the events placed in the FLA category (15 September 1973 and 17 January 1974) are presumed to have originated in flares on the back side of the Sun. Both events appeared to originate from regions which were highly active when seen on the disk; in addition, extremely high ionization states were observed in the 17 January spray (Tousey, 1976), suggestive of a flare origin. Our associations with solar activity have been derived from the *Solar-Geophysical Data* prompt and comprehensive reports

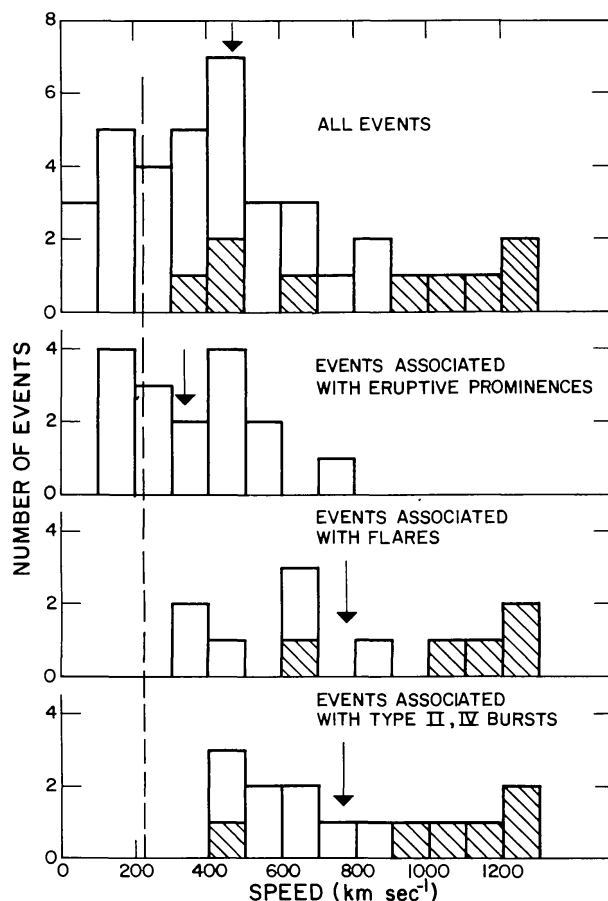


Fig. 2. The number distribution of measured speeds of the leading edges of mass ejection events (top panel) and the number distributions of speeds for mass ejection events associated with eruptive prominences, flares, and Type II and IV radio bursts (lower panels). As discussed in the text, there were no flares reported in close time coincidence with the prominence events; however, virtually all of the flare events had associated  $H\alpha$  eruptive activity. The cross-hatch pattern is used when the assigned speed is only a lower limit estimate. The arrows indicate average values; the vertical dashed line indicates the gravitational escape velocity for material at a heliocentric distance of six solar radii. The flare and radio burst events have much higher average speeds than do the events associated with eruptive prominences.

issued monthly by the National Oceanic and Atmospheric Administration (NOAA) as well as from materials supplied to the experimenters by the NOAA solar forecasting center during Skylab mission operations at Johnson Space Center.

The second and third panels of Figure 2 display the number distributions of speeds for EPL and FLA events respectively. The two speed distributions are distinctly different; all but one of the EPL events had speeds less than  $600 \text{ km s}^{-1}$ , the average being  $330 \pm 40 \text{ km s}^{-1}$ , whereas all FLA events had speeds greater than  $360 \text{ km s}^{-1}$ , the average being  $775 \pm 110 \text{ km s}^{-1}$ . This difference in speed distributions is qualitatively similar to that observed for  $H\alpha$  eruptive prominences and flare sprays. For example, Warwick (1957) and others have noted that  $H\alpha$  eruptions associated with flares (i.e., flare sprays) are distinguished from  $H\alpha$  prominence eruptions primarily by their higher speeds ( $670$  versus  $100 \text{ km s}^{-1}$ ). See also Kleczek (1964) and references therein.

The association of coronal mass ejection speeds with metric wavelength type II and IV radio bursts (RB events) is documented in the bottom panel of Figure 2. The number distribution of observed speeds for all RB events is similar to that for the FLA events; however, not all of the RB events had obvious flare associations. In particular, several of the faster EPL events produced type II or IV radio bursts (e.g., the events of 10 June 1973 (Hildner *et al.*, 1975a) and 21 August 1973 (Poland and Munro, 1976)). All but two mass ejection events with speeds greater than  $500 \text{ km s}^{-1}$  produced metric wavelength type II or IV radio bursts, or both. No mass ejection event with speed less than  $400 \text{ km s}^{-1}$  produced a radio event. Although our statistics are poor, the fastest mass ejection events tended to produce type II, IV burst pairs; single type II or IV bursts tended to be associated with mass ejection events with intermediate speeds ( $400\text{--}700 \text{ km s}^{-1}$ ).

### C. SPEED-HEIGHT PROFILES

In the absence of any force other than gravity, material moving upward in the corona will decelerate. Previous studies of the trajectories of individual mass ejection events have not, however, revealed any such decelerations (e.g., Gosling

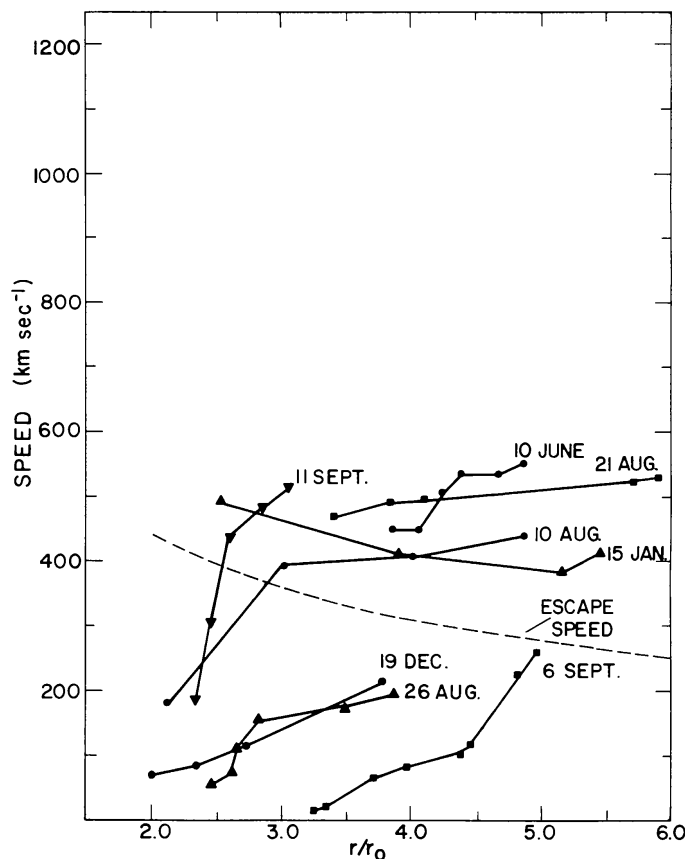


Fig. 3. The speeds of the leading edges of seven mass ejection events observed by the Skylab coronagraph as functions of heliocentric distance. Each point is plotted at the mid-height of the interval used to determine it. The lines connecting points aid in following particular events; their discontinuous nature almost certainly arises from measurement uncertainties, which typically range from  $\pm 25$  to  $\pm 75 \text{ km s}^{-1}$ . (The profile for 15 January refers to a bright feature internal to the ejection.) The January events occurred in 1974; all the rest were in 1973.

*et al.*, 1974; Hildner *et al.*, 1975a, 1975b). In fact, the leading edges of the events previously studied all accelerated with increasing height, suggesting that propelling forces, presumably magnetic or pressure gradient in origin, continued to act at relatively large (2–6 solar radii) heliocentric distances. Figure 3 shows that this behavior was common to a number of the events observed by the Skylab coronagraph; all but two of the events for which speed-height profiles can be constructed appeared to accelerate as they moved outward from the sun. The only exception is that of 15 January; in this case, the speed versus height profile drawn corresponds to a feature within the transient rather than to its leading edge. For seven events the observed velocity-height trajectories are roughly consistent with that expected for constant acceleration for which case the speed increases in proportion to the square root of the height above the solar surface.

### 3. Discussion

Although flare sprays and eruptive prominences often have a similar appearance in  $H\alpha$  when projected above the limb of the Sun, Tandberg-Hanssen (1967) and Smith (1968) find flares and eruptive prominences to be distinctively different physical phenomena. Evidence was presented in the previous section which suggests that the coronal counterparts of these chromospheric phenomena are also different. In particular, flare associated (FLA) mass ejection events move considerably faster through the corona than do eruptive prominence (EPL) associated events (775 vs 330 km s<sup>-1</sup> on the average), suggesting that FLA events are more impulsive than EPL events.

MHD bow waves form in front of coronal mass ejections (e.g., Gosling *et al.*, 1974; Hildner *et al.*, 1975a); these waves serve to compress and deflect the ambient corona ahead of the ejection. These bow waves are usually detected by their effects on nearby coronal structures. (We are definitely not suggesting that the bright loop-like leading edges of ejections are bow waves.) When the speed of an ejection exceeds the characteristic speed at which MHD signals propagate in the expanding corona, the bow wave must become a shock. According to Wild *et al.*, (1963) and others, metric wavelength type II bursts are generated by shocks traveling outward through the corona; similarly, according to Dulk and Smerd (1975), the explanation of some type IV bursts demands shocks for these disturbances also. Thus, the fact that events in this study which traveled at speeds less than 400 km s<sup>-1</sup> did not produce type II or IV radio bursts, whereas most all that did traveled faster than 500 km s<sup>-1</sup>, suggests strongly that the characteristic speed with which MHD signals propagate in the lower corona must be about 400 to 500 km s<sup>-1</sup>. (This neglects the small expansion speed of the ambient corona, i.e., solar wind at low coronal heights.) Most EPL events probably do not generate metric wavelength type II or IV bursts because their speeds, particularly in the height range of 1.1 to 3 solar radii where metric wavelength bursts are

generated, are not greater than the characteristic speed of the corona. On the other hand, the speeds of FLA events generally exceed  $400 \text{ km s}^{-1}$ , and consequently these events often do produce type II and IV bursts. (The foregoing discussion has implicitly assumed that type II or IV bursts are generated as soon as the bow wave running in front of a mass ejection becomes a shock. However, there have been suggestions in the literature that the shock must have a Mach number greater than about 1.6 to produce a type II burst (see e.g. Smith, 1972; Zaitsev, 1969). If so, our estimates of the characteristic speed of the corona are too high by about 60%.)

We have previously reported on a large coronal mass ejection event which followed a flare, generated metric wavelength type II and IV bursts, and produced a major shock wave disturbance in the solar wind at 1 AU (Gosling *et al.*, 1975). Similarly, statistical studies have established a reasonably strong correlation between shock wave disturbances in the solar wind at 1 AU and major solar flares accompanied by metric wavelength type II and/or IV radio bursts (e.g., Hundhausen, 1972a; Chao and Lepping, 1974). The results of our present study are consistent with the results of the earlier studies. Major solar wind disturbances near 1 AU are seldom associated with EPL events because, in general, these mass ejections do not travel fast enough relative to the ambient solar wind to perturb strongly the flow of the wind. In fact, the speed versus height profiles of EPL events in the height range 2–6 solar radii do not differ greatly from that expected for the ambient solar wind (compare the profiles of Figure 3 with that given in Parker, 1963, p. 75). On the other hand, many FLA and most RB events have speeds close to the Sun that are far greater than that expected for the ambient expansion. Consequently, the bow waves of these events are shocks both close to the Sun and near 1 AU so long as they do not experience significant decelerations in their transit outward. Both observations and theory suggest that these decelerations should usually be slight (e.g. Gosling *et al.*, 1975; Hundhausen and Gentry, 1969).

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