FORERUNNERS: EARLY CORONAL MANIFESTATIONS OF SOLAR MASS EJECTION EVENTS

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Abstract. Coronal ejection transients viewed with the white light coronagraph on Skylab are studied from the times of their very earliest manifestations for clues to their origin. Excess coronal mass with a configuration like that of the eventual transient is seen in twelve events prior to the transient's associated near-surface Hα eruption or flare. In seven of the events, data are adequate to observe the rates of outward mass motion of coronal material prior to their surface manifestations. The observations place severe constraints on different solar mass ejection mechanisms because they spread the process responsible for the ejection over a larger region of the corona and over a longer period of time than normally considered. The observations suggest the corona is an active participant in the ejection that begins with the acceleration of the outer portion of a preexisting structure and ends with the obvious surface manifestation.

1. Introduction

Recently, Jackson and Hildner (1978) have reported Skylab coronagraph observations of 'forerunners', rims of slightly enhanced density bordering the more dense portion of mass ejection transients (for a description of coronal transients see Gosling *et al.*, 1974). In this paper as before, the term forerunner is used to designate the portion of the mass ejection which is not ordinarily visible solely by inspection of individual Skylab coronagraph images: i.e. where subtraction of digitized images was necessary to obtain the position of the forerunner leading edge. Where both transient and forerunner are observed in the outer corona, the outermost edges of the forerunners maintain an approximately constant offset with time in front of the main portion of transients for the best observed events. By extrapolating the position of these edges back in time assuming a constant speed (the same speeds as those of the ejection transients) it is easy to show that forerunners should be present and moving outward in coronagraph images obtained before the start of the rapid outward motion of the associated near-surface Hα material or flare.

Evidence of coronal motions and other phenomena preceding solar flares and mass ejections abound in the literature. For instance, Hansen *et al.* (1971) reported a brightening in K-coronameter data at $1.5R_{\odot}$ from Sun center prior to an Hα spray and 80 MHz radio burst. Other pre-flare activity from filament changes, metric radio observations, outward arch structure motions, and off-band Hα changes have been

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reported by other observers (Smith and Ramsey, 1964; Wild, 1968; Bruzek and De Mastus, 1970; Martres *et al.*, 1977; Sheridan *et al.*, 1978; and Jackson *et al.*, 1978). Most of these reports describe only a single event, usually in a qualitative fashion. This generally attests to the difficulty of the observations.

In the following sections of this paper I show that in every mass ejection event that was well observed with both the Skylab coronagraph and Hα monitors there is evidence for an increase in observed brightness and thus an implied increase in electron density above $2R_\odot$ prior to the associated surface Hα eruption or flare. These observed coronal brightenings are documented for 12 events; their outer edges appear to be directly associated with the transient forerunner outer edges described by Jackson and Hildner (1978). These brightenings indicate that forerunner motion precedes the rapid motion of transient-associated surface ejecta in time as well as space. The observations indicate that mass ejections begin as rapid motion from the top or outside of pre-existing coronal material. In the discussion section, I present a speculative model based on the observations which describes how the existing corona evolves to an outward moving material ejection.

2. Data Analysis

Because this study is limited by a set of data selection criteria, only a small portion of the mass ejection transients observed by Skylab could be used. Most of the transients' surface associations are obtained from NOAA observations presented in Munro *et al.* (1979). Of the events with surface associations, extant coronagraph observations prior to the time of the associated surface event had to be available according to a variable time window which was longer for slower events. In addition, a coronagraph image had to exist that could be used to determine the extent of the transient forerunner rimming the main portion of the transient.

Thus, a subset of the 16 mass ejection events presented by Jackson and Hildner (1978) were chosen for more complete analysis. Although care was taken to choose the data set in a way that would not bias the sample of events to be studied, in reality, of the approximately 80 ejection transients observed from Skylab, less than half have surface associations (i.e., Munro *et al.*, 1979) and of these, 16 fulfilled the requirements of the data selection – a fairly large percentage of the total. Events with well observed surface associations failing the other selection criteria generally had a cadence of coronagraph images too slow for an extant observation in the time window prior to the surface manifestation of the event.

Coronagraph images prior to the surface manifestation of the 16 mass ejection events chosen for more complete analysis were digitized, subtracted point by point from an initial image, and the resultant images converted to excess columnar density. Digitally subtracted images are especially important in determining the extent of the transient forerunners because the edges of this material do not have steep density gradients and generally cannot be seen in individual photographs. Error in the determination of the positions of the forerunner outer edges and thus the errors for their height generally increased with increasing distance from the Sun for the best observed events.

The best documentation of Hα surface phenomena associated with Skylab transients is given for the 21 August event by Poland and Munro (1976), the 26–27 August event by Hildner *et al.* (1975), the 19 December event by Schmahl and Hildner (1977), and the event of 17 January 1974 by Webb and Jackson (1981). In these four events, the Hα material associated with the eruptive prominence is lower than the more massive outer part of the transient. Hildner *et al.* (1975) indicate that this spatial configuration is generally valid for all transients with associated eruptive prominences. The time evolution of the Hα eruption with respect to the forerunner outer edge is not presented in these papers.

For all of the 16 events, wherever possible, original data films from NOAA Hα monitors or such instruments as the Mauna Loa or Catania Hα coronagraphs were used to determine the apparent height vs time plots of the top of the Hα material or the time of the associated flare. Although prominence activity or surging may have been recorded prior to the eruption, the time of prominence eruption was determined as the onset of the lifting or disappearance of the major portion of this pre-existing Hα structure.

TABLE I
The events studied

Event	Data prior to Hα eruption	Pre-existing structure?
June 10, 1973	outward motion	yes
June 24	outward motion	yes
Aug. 9	outward motion	yes
Aug. 10	outward motion	yes
Aug. 13 (A; 05:56 GMT)	?	
Aug. 13 (B; 21:41 GMT)	mass increase	yes
Aug. 21	mass increase	yes
Aug. 26	outward motion	yes
Sept. 7	?	
Sept 10	mass increase	yes
Dec. 14	mass increase	yes
Dec. 16	?	
Dec. 19	outward motion	yes
Jan. 12, 1974	mass increase	yes
Jan. 17	?	
Jan. 21	outward motion	yes

Table I lists the 16 ejection events studied and summarizes the data available for these events. Excess coronal mass as indicated by a brightness increase above $2R_\odot$ prior to the Hα eruption is observed in 12 events and the quality of these observations is detailed in the second column of the table. For some events showing a mass increase only one useful coronagraph observation exists prior to the Hα eruption or else consecutive observations were not spaced far enough apart in time to determine an outward motion. These events are indicated by 'mass increase' in the table. The question marks '?' denote events with observations present from the original criteria, but data inadequate to show a mass increase (or decrease) prior to the Hα eruption.

The last column of Table I indicates which of the 16 transient events definitely appear to modify pre-existing structures (streamers). A 'yes' in this column indicates that these streamers are obliterated or significantly altered by the ensuing ejection when observed by the coronagraph shortly after the event. Three-fourths of the events in the table appear to modify pre-existing coronal structures. For the four events that are not labeled 'yes', an associated pre-existing structure may be present, and later obliterated, but observations of an isolated and later altered structure are not clear. Of the approximately 80 mass ejection transients observed during Skylab, two-thirds would have been labeled 'yes' using the above criteria. Only one faint transient (observed on 12 December) apparently arose in a region devoid of streamers and would have been labeled 'no'. Thus most transients appear to arise from and/or significantly alter pre-existing structures observed with the Skylab coronagraph. The 16 events chosen for study, on the whole better observed than most of the group members, are examples of and not exceptions to this general observation.

3. Results

Twelve of the 16 ejection events studied clearly show coronal brightenings above $2R_\odot$ from Sun center prior to the surface manifestations of their respective events. These coronal brightenings have the same spatial configurations as the eventual transients. Four of the 16 events are eliminated from the study for various reasons, but these data never contradict the above observations (there is no indication that a coronal mass increase is not present on some events just prior to the surface manifestation of the ejection). The 12 events which show these early coronal mass increases deserve more careful analysis.

Height vs time plots of the seven events that show outward mass motion prior to the Hα eruption are given in Figure 1 (the events labeled 'outward motion' in column 2 of table I). The errors given for the heights of the outermost material indicate the precision with which the average position of the $\sim+2\sigma$ density level of the forerunner outer edge most distant from Sun center can be determined. These errors are defined liberally to enable a comparison of events; they do not represent the higher degree of precision with which it is possible to trace the motion of the forerunner outer edge at a specific solar position angle for some events. Positions of the maximum excess density as defined in Jackson and Hildner (1978) and the top of the associated Hα prominence are also plotted.

Excess mass vs time plots for the same 7 events are displayed in Figure 2. The best observed events (i.e., 9 August, 10 December, and 21 January) show gradual excess mass increases for the same period that the forerunner outer edge is observed to

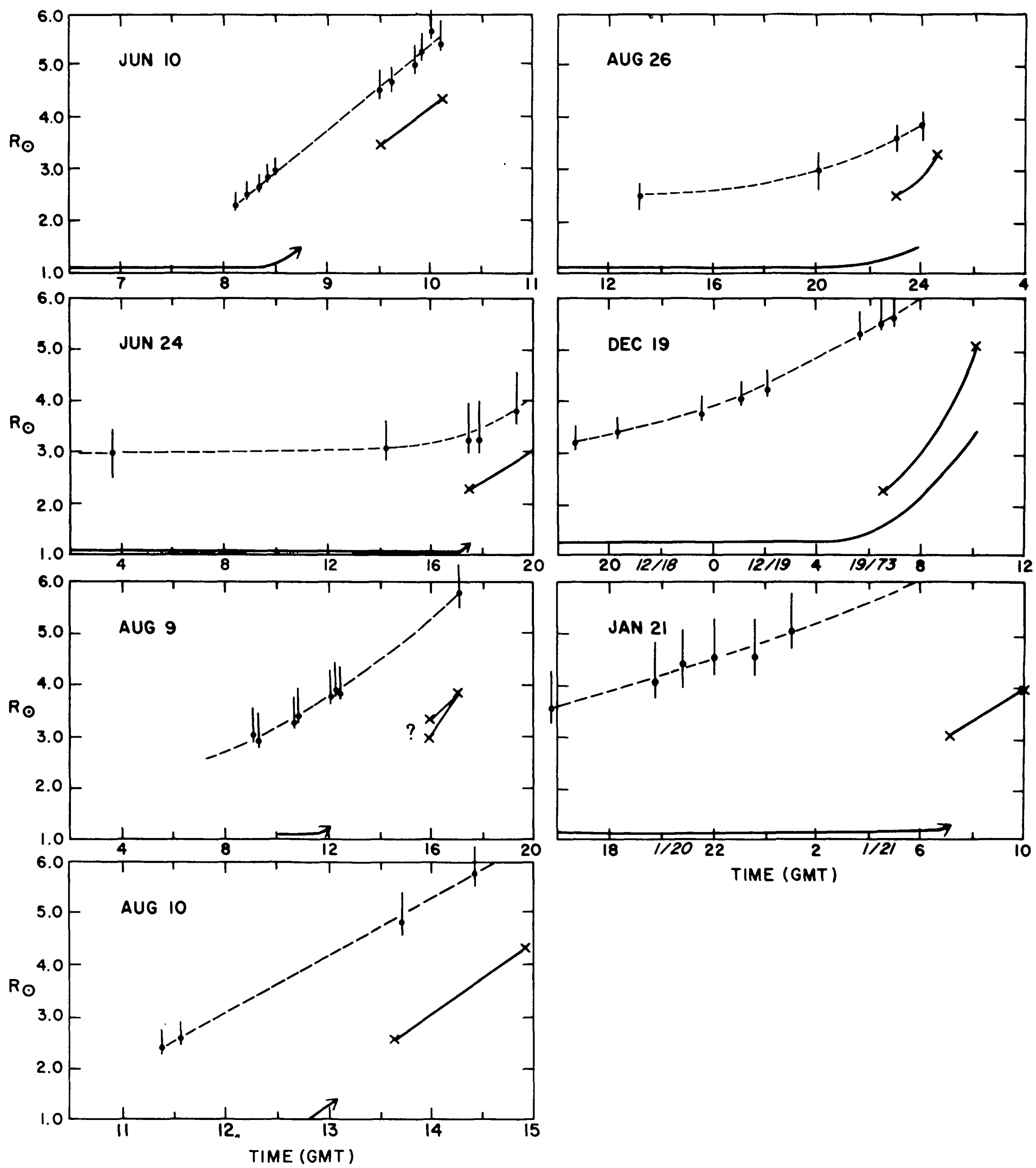

Fig. 1. Height vs time plots for the seven mass ejection events during the Skylab period that show outward coronal material motion prior to an associated Hα mass eruption. Data points indicate the availability of coronagraph images. Note that two different time scales are used. The dashed lines represent an interpretation of the motion of the forerunner. The solid lines terminated by ×'s indicate the position of maximum excess density at the top of the ejection transient. The near surface lines show the highest distinguishable feature of the associated Hα eruption.

move outward. This tends to confirm a gradual evolution as opposed to a series of discreet ejections for this material. For each event this early excess mass was determined from the smallest coronal area above $2R_\odot$ that would include the whole coronal mass ejection observed in its later stages. The errors plotted in Figure 2 were determined from measurements of subtracted images in regions adjacent to the

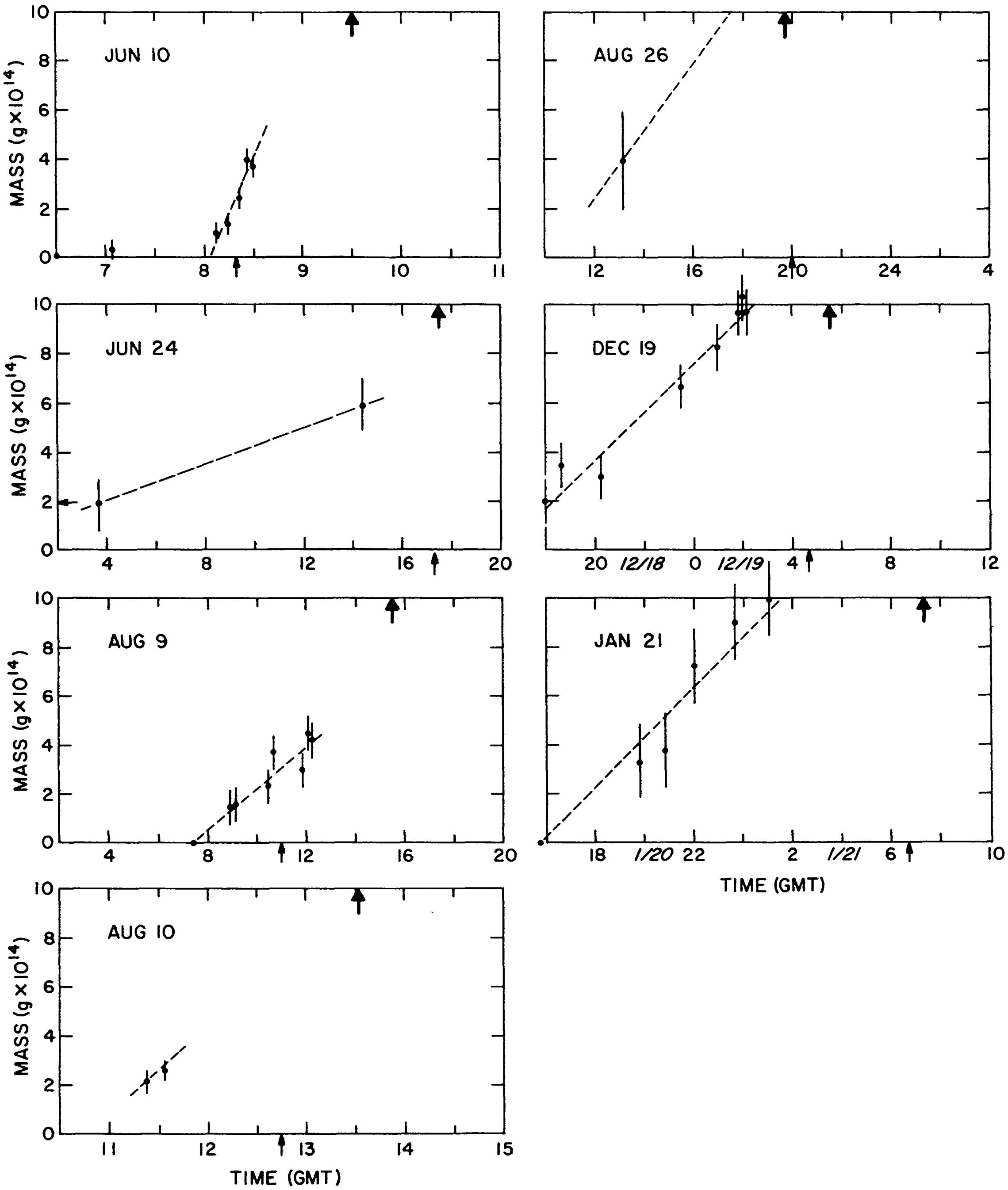

Fig. 2. Excess mass above $2R_\odot$ vs time for the seven mass ejection events depicted in Figure 1. The same time scales used in the previous figure are used above. The dashed lines represent an estimate of the approximate mass increase indicated by the individual observations of each event. Large arrows pointing off-scale at the top of each event give the time of the next coronagraph image showing excess mass. Arrows at the bottom of the individual event figures give the time of the onset of rapid outward motion of Hα material. The mass scale is determined relative to the first frame (dot if on scale) in the sequence.

mass ejections from areas identical in size to those used to determine excess mass prior to the Hα eruption.

Observed brightness changes prior to the Hα surface manifestations of transients are not coincidental random coronal changes. The interpretation of any coronal brightness or mass change could be confused by solar rotation of streamers into the plane of the sky or fluctuations of streamers. However, determination event by event of the geometrical position of streamers (as in Munro and Jackson, 1977) within the transient mass area shows that the streamers observed in these regions were either too close to the limb or rotating away from it and could not cause the observed mass increases. There were never any mass decreases observed immediately prior to ejection transients. In addition, large scale mass changes in evolving streamers are not large or frequent enough to be confused with the forerunners studied here. For instance, the brightness deviations with time from a simple streamer model at limb passage studied by Poland (1978) are many times too small to be interpreted as forerunners.

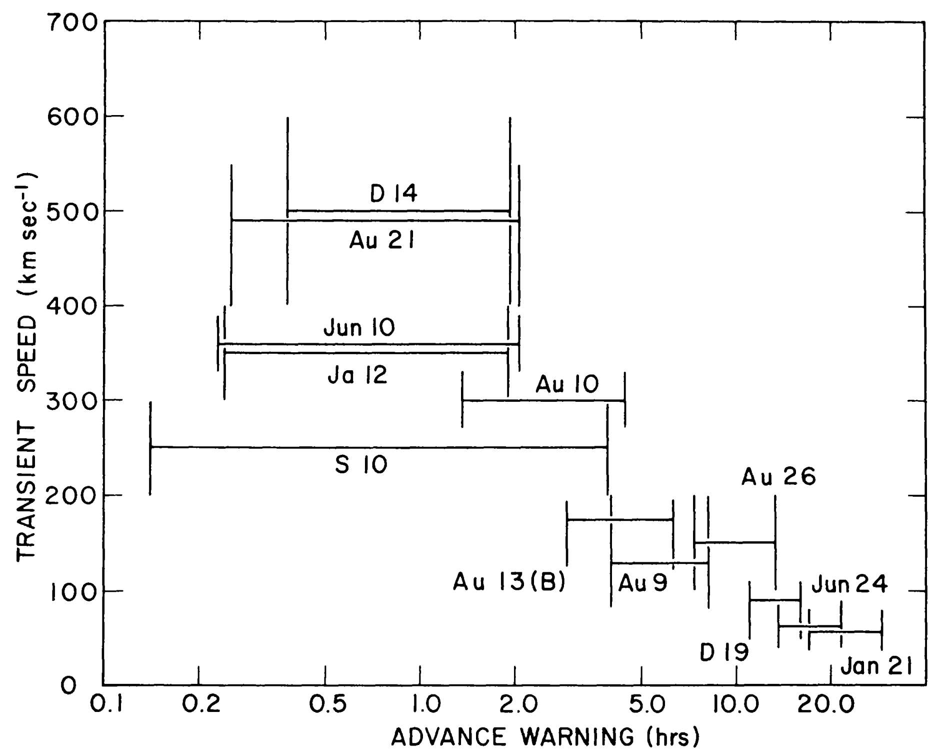

Fig. 3. Transient speed vs advance warning of the first evidence in coronagraph images above $2R_\odot$ of outward coronal motion prior to the times of Hα eruption.

The amount of advance warning of an impending Hα surface eruption from coronagraph observations is indicated by Figure 3. The figure shows the speed of the transient excess mass at $3R_\odot$ vs the advance warning of the first coronagraph observance of the excess coronal mass prior to the beginning of the Hα eruption or flare. The time errors are caused principally by the unavailability of coronagraph data showing the beginning of the coronal mass increase but also include error estimates for the times of the onset of the surface ejections. The left-hand extent of the time error bar indicates the time prior to the surface ejection that the forerunner is first observed. The right extent of the time error indicates the time prior to the surface ejection of an available coronagraph image not showing the forerunner.

The plotted maximum speed errors vary from transient to transient and represent the adequacy of coverage for each event. There is an indication in some events that the excess coronal material seen as a brightness increase prior to the Hα eruption begins motion from below $2.2R_\odot$ (i.e., Figure 1). Skylab coronagraph digital subtractions are restricted by stray radiance and the instrument occulting disk below $2R_\odot$. If the earliest mass motion for an event begins near or below this height, the time of the earlier mass motion will not be available from these observations. In general, the amount of advance warning is longer for slower events.

The similarities of different coronal transient-forerunner combinations are depicted in Figure 4 by plotting transient speed vs the difference between the time of the forerunner outer edge passage at $3R_\odot$ and the time of maximum mass passage of $3R_\odot$. For every mass ejection event plotted in Figure 4, the time the outermost edge passes $3R_\odot$ is obtained from observations of its position *prior to the event's Hα manifestation.* If outward mass motion prior to the Hα manifestation could not be measured and the outermost edge was not at $3R_\odot$, then the speed of the ensuing transient was used to extrapolate to the time of the edge's passage of $3R_\odot$. This is justified by observations of the best observed coronal transients where the forerunner outermost edges move outward with approximately the same speed as the most

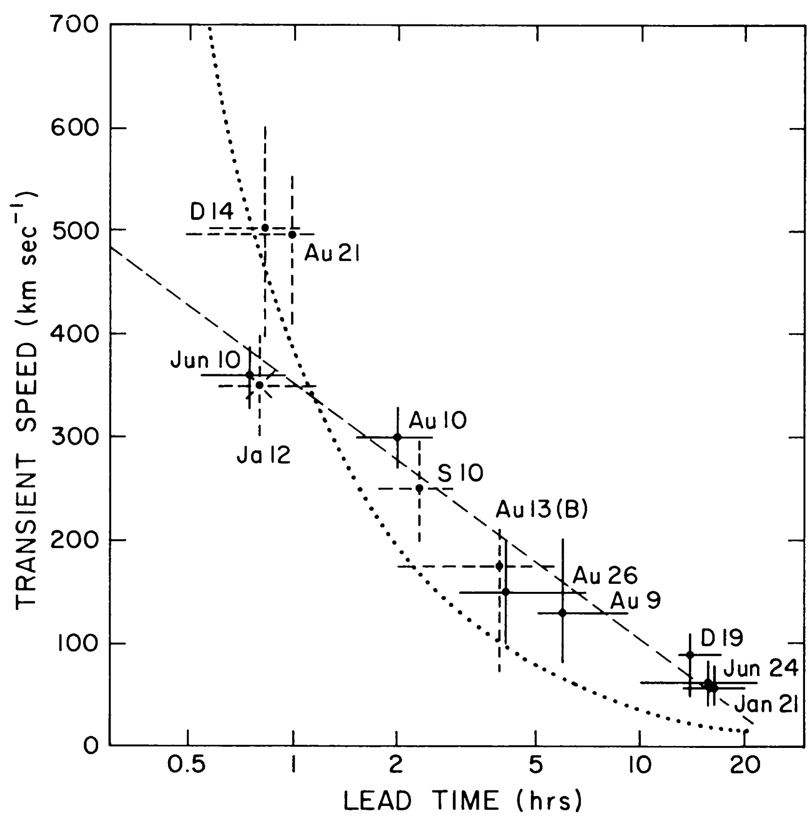

Fig. 4. Transient speed vs lead time for coronal material passage of $3R_\odot$. The speeds plotted are those of the transient excess mass at $3R_\odot$. Solid lines indicate events for which multiple images exist showing outward coronal mass motion prior to the surface Hα eruption. The diagonal dashed line is an indication of data continuity. The dotted line depicts the lead time of the hypothetical case of one structure $2R_\odot$ ahead of another where both maintain the same constant speed.

dense portions of the transients. Time errors in this figure represent the possible error in determining the $3R_{\odot}$ forerunner outer edge and transient maximum mass passage time. A plot like Figure 4 could be obtained for any set of ejection transients with adequate coronagraph data – not just those transients with excess mass observations prior to their surface associations. In particular, visual examination of additional slow speed ejection transients with adequate coronagraph data but not surface associations (four are available) show the same long lead times for the outermost edge passage of $3R_{\odot}$.

Thus, not only does this forerunner outermost edge have the same configuration and position angle as the eventual denser transient structure, but Figure 4 shows that the outermost edge is observed to move outward past $3R_{\odot}$ in the corona prior to the surface manifestations of the event in a very specific way related to the eventual speed of the dense portion of the transient. Thus, Figure 4 is one of the best indications, in lieu of continuous data coverage, that the early coronal brightness increases seen prior to the Hα surface manifestations of the events are indeed forerunners of the ensuing mass ejection transients.

If a coronagraph brightness increase was always present above $2R_{\odot}$ prior to an Hα eruption, it could not be used to predict Hα limb eruptions or flares with certainty. More than half of the coronal ejection transients observed (Munro *et al.*, 1978) have no apparent surface association. This is mainly because some of the events occur behind the solar limb and have unseen associated surface manifestations. It is also possible that some ejection events simply have no easily recognizable Hα surface association. Conversely, during Skylab several dozen eruptive limb prominences (EPL's) could not be seen as a mass ejection transient in the coronagraph. Three of the most extensive of these eruptions with adequate coronagraph coverage occurred on 30 August (EPL to $1.2R_{\odot}$), 10 September (EPL to $1.15R_{\odot}$), and 4 December (EPL to $1.3R_{\odot}$). (For more details on the last event, see Wagner and Demastus, 1977.) The corona above these three eruptive prominences was looked at in detail by digitally reduced coronagraph images. Apparent large-scale coronal change above $2R_{\odot}$ did not exceed 3×10^{14} g of additional mass. Thus, some rather extensive eruptive prominences are limited to the lower portion of the corona and do not produce a forerunner or transient above $2R_{\odot}$. Such eruptive prominences apparently do not lead to the escape of mass from the Sun; they do, however, pose constraints for the mass ejection mechanism of Steinholfson and Nakagawa (1977) and Wu *et al.* (1978) where forerunners are depicted as arising from hydromagnetic shocks propagating from the solar surface.

Only the 12 January 1974 event of the 12 events in Figures 3 and 4 has an associated surface manifestation which can definitely be classified as a flare seen on the solar surface as an Hα brightening. It is not surprising that the faster, flare associated transients in the 12 studied are undersampled compared to the Munro *et al.* (1979) Skylab observations where approximately one-sixth of the transients are flare associated. In general, flare associated transient ejecta have a higher speed than do non-flare associated ejecta (Gosling *et al.*, 1976), and thus an early mass increase is visible to the coronagraph for less time for flare associated ejecta (see Figures 3 and 4). Since only coincidental pre-surface manifestation coronagraph observations are available, there are fewer of these for faster events. The 12 January event does not appear spatially different from other non-flare associated ones. The forerunner outermost edge is seen at approximately $3.0 R_\odot$, 14 min prior to flare onset, and fits in well with the lead time values for other events in Figures 3 and 4.

The 12 mass ejection events of the original 16, when studied in more detail, support the basic conclusion of an outward motion of coronal mass prior to the Hα surface manifestation of the event. They show that this material is an early observation of the transient forerunner. The observations indicate that forerunners move rapidly outward preceding at least a portion of the mass ejections in time as well as space. Though only one of the 12 mass ejections studied is definitely flare associated, there is no distinction between it and the other events of approximately the same speed.

4. Discussion

These data indicate that energy is input to the corona causing an outward mass motion for time periods much longer than originally thought and prior to the obvious surface manifestations of the ejection event. In no case is it possible to directly measure material flow speeds within the transient forerunner. Observed is an unresolved brightening that extends to higher heights with time.

The data indicate a rapid outward motion of the existing corona (possibly of streamer structures) prior to the Hα eruption. Motion of the underlying Hα structure associated with the mass ejection events does not appear as a gradual acceleration from the time the forerunner is first observed. Most of the events have observations which show the Hα material accelerated to a speed comparable with the outward motion of the forerunner outer edge and transient maximum excess mass; the Hα material appears to accelerate to this speed in a very short time compared to the lead times of the events depicted in Figure 3. In Figure 5 I present a schematic interpretation of the observations. In this interpretation, the rapid outward motion of existing coronal material begins at successively later times at lower heights, starting with the first manifestation of the events in the high corona to the Hα ejection near the solar surface. The dashed and full lines in Figure 5 show the evolution of material at three locations in the corona, and the dotted line is a speculative position of the onset of rapid coronal motion as time progresses. The inserts at the bottom of Figure 5 depict the situation at three different times. Because it is impossible to observe faint coronal material below $2.0 R_\odot$ with the Skylab coronagraph, it is impossible to tell how the motion of heated coronal material between the top of the Hα eruption and $2.0 R_\odot$ proceeds with time. Thus, the dotted line in Figure 5 may not accurately represent the onset of rapid outward motion, but it serves to emphasize an entirely different viewpoint that may now need to be taken in interpreting solar ejection events. Hopefully, simultaneous low-corona obser-

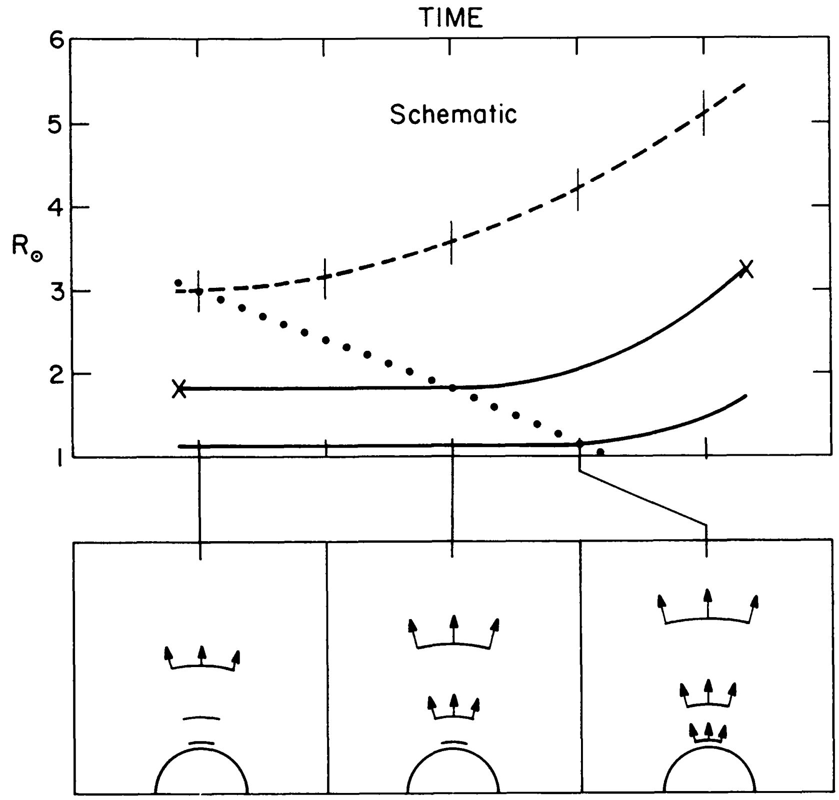

Fig. 5. Conjectural height vs time plot of the position of each height of the corona's rapid outward motion during a coronal mass ejection event. (For comparison, see the actual data plots of Figure 1). Schematic representations of the corona are shown at the bottom of the figure depicting the onset of rapid outward motion of existing corona at three different times. Rapid outward motion of the outer, higher part of the corona begins prior to the lower part. The dotted line indicates the locus of initiation of the rapid outward motion in existing material. The time axis is unlabeled, but from observations has an upper limit of about four hours per division and a lower limit of about one-quarter hour per division.

vations utilizing spatially overlapping coverage from future instruments will allow better observations of these effects.

5. Conclusions

In all Skylab coronagraph data where it is possible to observe the effect, there is a coronal mass increase seen shortly prior to the surface manifestation of the mass ejection event. The simplest interpretation of this early mass increase is one of an outward coronal structural motion associated with a later ejection of underlying material. The ability to predict large surface Hα eruptions or flares by this method is by no means absolute, but the feasibility of predicting at least a portion of these surface events is inescapable.

The concept should allow better understanding of the solar mass ejection process and solar flares. These observations place severe constraints on some of the mass ejection mechanisms that have been proposed because they indicate an energy input to the corona which manifests itself in a rapid outward coronal change that begins from the top or outside of pre-existing coronal material. The observations imply coronal foreknowledge of the impending surface manifestation of the mass ejection event. Future observations and theory must answer whether or not all mass ejection transient events, especially those at the extreme upper limit of mass and energy output, display this same behavior.

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