THE KINEMATICS OF SOLAR INNER CORONAL TRANSIENTS

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Abstract. The kinematic properties of a dozen 'loop-like' coronal transients have been examined over the range 1.2–2.4 $R_\odot$ from Sun center. Values and trends of transient geometry, including radial height, lateral width at maximum extent, distance from loop top to height of maximum width, and lateral width at a fixed height above the instrument occulting disk at 1.2 $R_\odot$, are given. Radial and lateral speeds of expansion are tabulated, and range from 60–900 km s^{-1}, and 10–500 km s^{-1}, respectively. Flare-associated events are found to exhibit the highest speeds, and show little acceleration with height; on the other hand, eruptive-associated events exhibit large accelerations (some in excess of 50 m s^{-2}). This clear discrimination between flare and eruptive-associated events suggests that two different physical processes are present; it is suggested that flare-associated events result from an impulsive, localized input to the corona. On the other hand, accelerated, eruptive-associated events are subjected to appreciable net forces over radial heights of one solar radius (or more) above the solar limb. It is conjectured that the pressure gradient forces responsible for the generation of the solar wind may play an important role in accelerating these latter events.

1. Introduction

Coronal activity was discovered with ground-based *K*-coronameter observations by comparing daily variations. These variations were usually recognized as significant reductions in the line-of-sight coronal signal (Hansen *et al.*, 1974). Orbital coronagraph results revealed the variety of the phenomena, and showed that changes in the coronal form over spatial scales of several solar radii could occur over temporal periods of an hour or less (Brueckner, 1974; MacQueen *et al.*, 1974; Gosling *et al.*, 1974). In these latter studies, the term 'coronal transient' was coined to denote this activity and the term 'mass ejection' employed to describe those events where significant quantities of coronal material left the Sun (or at least moved beyond the field of view of the observing instrument). By now, numerous examples of solar coronal transient activity have been collected during differing phases of the solar cycle. It is clear from the high frequency of the events and their properties – mass, energy, volume – that transients are an important aspect of solar activity.

Space-borne externally occulted coronagraphs are limited to observing well above the solar limb; inner limits of the fields of view of such instruments typically range from 1.5 to 3.0 $R_\odot$ (from Sun center). In addition, the vignetting characteristics of these experiments usually only permit observations above several tenths of a solar radius beyond the inner limit. Thus, much of the current information on the properties of coronal activity has been derived from observations of the corona from heights greater than 2 $R_\odot$ from Sun center.

The recent development of an improved ground-based *K*-coronameter system (Fisher

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et al., 1981a) permits, for the first time, rapid-time response observations of coronal activity down to heights of 1.2 $R_\odot$. The instrument has completed nearly two years of observations from its site on Mauna Loa, Hawaii, and has recorded the characteristics of a number of mass ejection transients in the *inner* corona. Some specific aspects of several of these inner coronal events have been reported (Fisher and Poland, 1981; Fisher *et al.*, 1981b; Low *et al.*, 1982); it is the purpose of the present work to study the kinematic properties of a number of loop (or bubble)-like events. The goal of this report is to employ these inner coronal observations to specify the form of such transients as an aid to modelling efforts, and to deduce some properties of the transient propelling forces.

2. Observations

We have employed results from twelve of the better-observed loop (or bubble)-like transient events obtained within the period February 1980 to December 1982. The principal selection criterion used is that of completeness of the observational set – which has restricted the number of events studied substantially, despite the fact that transients are common phenomena. Indeed, orbiting coronagraphs – one on the Air Force P-78 satellite (Sheeley *et al.*, 1980) and one on the NASA Solar Maximum Mission (House *et al.*, 1981) – have observed transients during this period with a frequency encompassing 0.5–2 events per 24 hr (Howard *et al.*, 1982; Hundhausen *et al.*, 1983). Generally the complete sets of *K*-coronameter data resulted when the events were recognized in real time by the observers. It would be expected, therefore, that the selected events are biased towards those events where large changes of density occurred, or to those events relatively near the 'plane-of-sky'. In either case the observed quantity – the product of polarization and brightness of the Thomson scattering from coronal electrons – is enhanced. Finally, the selected events will also be biased against slow transients; these events involve radial speeds of only about 10 km s^{-1} and hence are difficult to recognize in real time (Garcia *et al.*, 1983). In fact, none of these very slow events are included in our sample. The events selected for study are summarized in Table I; specific characteristics will be discussed in the following sections.

Two-dimensional gray scale images of the coronal polarization-brightness product are produced by the *K*-coronameter; for the images studied herein we have produced prints of the images depicting the transient progress through the instrument field of view. Each of the transients studied exhibit the characteristic loop or bubble-like appearance of many transients. Figure 1 shows this shape in a schematic way, and indicates the parameters which have been measured directly from the photographic prints for each of the images depicting the transient passage. The shape of the transient is determined from the measurement of four quantities – h, w, a, and b, denoting the radial height, lateral width at maximum extent, distance from loop top to height of maximum width and lateral width at a fixed height near the transient base, respectively. The speeds of expansion of these features can then be determined, since the time of each image is known accurately.

TABLE I

Inner coronal transient parameters

Event	PA	Activity	t_i/t_f	h_i/h_f	a_i/a_f	α_i/α_f	R_i/R_f	$\dot{b}_i/\dot{b}_f$	$\dot{h}_i/\dot{h}_f$
(DOY/year)	(°)	–	(UT)	($R_\odot$)	–	–	–	(km s^{-1})	(km s^{-1})
46/1980	215°	eruptive	19:16 20:16	1.74 2.22	0.24 0.36	0.9 1.4	1.0 1.5	40 30	60 130
181/1980	250°	flare	18:26 18:42	1.53 2.37	0.12 –	? 1.1	0.9 1.7	460 40	580 580
218/1980	70°	eruptive	18:25 19:35	1.42 2.29	0.09 0.30	1.1 1.6	1.3 3.7	20 50	60 280
235/1980	280°	flare	17:45 17:50	2.05 2.23	0.33 0.45	2.2 2.0	3.5 4.3	0 0	340 340
84/1981	290°	flare	20:43 20:58	1.29 >2.41	0.03 0.52	0.4 >1.0	0.4 >2.1	770 0	890 ?
114/1981	80°	eruptive	21:34 21:49	1.72 2.20	0.24 0.66	0.9 0.9	0.9 1.1	140 ?	340 ?
155/1981	80°	flare	17:46 17:57	1.45 2.05	0.18 >0.9	0.5 0.6	0.7 0.8	1030 300	650 810
241/1981	120°	eruptive	19:41 20:05	1.54 2.26	0.24 0.48	0.6 0.9	0.7 1.2	90 110	110 630
349/1981	275°	flare	19:49 20:08	1.42 2.20	0.15 0.45	1.0 1.3	1.0 1.9	260 110	570 460
175/1982	330°	eruptive	19:39 20:04	1.26 1.58	0.30 0.51	0.5 1.2	0.5 1.2	? 238	120 190
178/1982	295°	u/k	18:18 18:31	2.40 2.55	0.45 –	? ?	1.5 1.5	? ?	340 370
191/1982	70°	eruptive	18:27 20:00	1.38 2.30	– –	1.4 1.8	1.4 2.9	100 100	75 320

Measurements and calculations to determine the above quantities and their time rate of change have been carried out for each image – or image pair – available for the transients studied. In this manner, a history of the (evolving) shape of the event, and the speeds involved, has been determined under the assumption that all motion occurs in the plane of the sky. The accuracy of the derived parameters is principally dictated by the accuracy with which the quantities h, w, a and b can be measured; and this depends, in turn, on the contrast of the event relative to background. In some cases (events of 46/1980 and 84/1981, for example) the shapes are easily discernible, and the

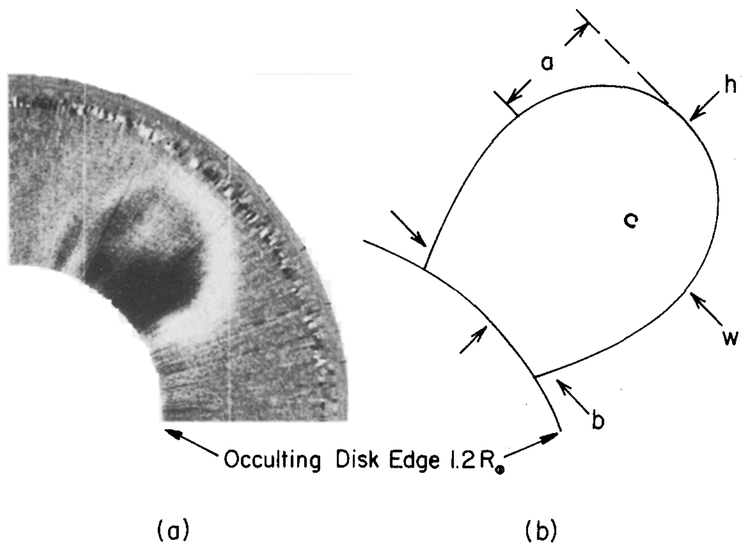

Fig. 1. The schematic shape of loop-like coronal transients. The measured parameters are indicated.

measurements are accurate to about 5–10%; in other cases (early in the events of 241/1981 and 181/1980) the contrast is poorer, and the accuracy of measurement is on the order of 15%. It is probably the case that the derived speeds do not involve errors proportional to the formal measurement errors above, for a substantial fraction of those errors may be attributed to uncertainties in defining the transient edge, and measurements of one frame relative to a previous tend to be consistent. Because of high concentrations of volcanic debris present in the Earth's atmosphere, data from the summer of 1982 yield speed estimates which are more uncertain. Noise levels in the raster images are such that an accuracy of 30% is typical for the events of 175/1982, 178/1982, and 191/1982. For other events, we estimate that the speeds are accurate to about 20–25%, and variations within this error should be ignored. These uncertainties preclude the possibility, for example, of an accurate comparison between a high-speed transient and a ballistic behavior; however, they are not so large as to obscure the detection of transient acceleration through the corona, at least in the case of the slower events. Further comments on the accuracy of the transient speed determination are contained in Section 4.

Although certain trends are evident, and will be discussed below, the measured parameters show substantial variations between events. Measured lateral movements encompass the range from 0.16 to 0.36 $R_\odot$; loop (or bubble) heights have been examined over the height range 1.3 to 2.4 $R_\odot$; while transient widths at maximum vary from 0.025 to 0.40 $R_\odot$. The parameter a has values ranging from 0.03 to 0.9 $R_\odot$. Speeds deduced from the temporal evolution of the parameters vary widely: $\mathrm{d}b/\mathrm{d}t$ ranges from 10 to 500 km s^{-1}; $\mathrm{d}w/\mathrm{d}t$ ranges from 10 to 700 km s^{-1}; and $\mathrm{d}h/\mathrm{d}t$ ranges from 60 to 900 km s^{-1}.

3. Transient Properties and Associations

First, we consider the behavior of the form of the transients with time. In Figures 2(a) and (b) we present plots for each of the transients, of the behavior of α $(=h/w)$ and $R(=h/b)$ as functions of time, measured from that of initial observation. These geometric parameters reflect the evolving shape of the lower coronal transient; the parameter α reflects the 'aspect ratio' of the expanding loop (or bubble), while the parameter R is an indication of the relative role of outward expansion of the event and the lateral expansion at the lowest observable height in the corona. Note, however, that the measurements are made relative to the instrument occulting disk; no correction has been applied to the parameter h to account for the extrapolation to the solar surface, or for large departures from the plane of sky. Note also in the figure that the measurements correspond to the plotted points; these points have been connected with lines to facilitate comparisons. From Figure 2(a) we note that at the time of initial observation the parameter $\alpha > 1$ in only three cases; thus initially most transients exhibit as much lateral as radial motion. For all events, except that of 235/1980, α increases with time, indicating the dominance of the radial extension in the events. The parameter R shows a similar behavior; at the time of first observation R is somewhat larger than α (since in general $b < w$) and increases thereafter. One event – 235/1980 – has $R > 3$ at the outset and has not been plotted. The association of these events with observed solar surface activity will be discussed below; in the meantime note that Figures 2(a) and (b) include labelling (F) of those events associated with flares. All other events are associated with mass motion at the limb – typically eruptive prominences. Note that no particular systematic differences in the loop geometry between that associated with flares or eruptives seem to emerge, although there seems to be a weak tendency for flare-associated events to take on larger values of R late in the event than those associated with prominence eruptions. This appears to be a reflection of the higher average radial speed of flare-associated events, discussed below.

All events show increasing values of the parameter a as the event evolves; the actual values of a do not allow any means to discriminate between types of events. Initial values of a range from 0.03 to 0.45 $R_\odot$, and final values encompass the range 0.30 to greater than 0.9 $R_\odot$.

Now let us examine the time rate of change of the parameters. Figure 3 illustrates the radial speeds of the transient events, $\mathrm{d}h/\mathrm{d}t$, plotted as a function of the observed distance from Sun center. These data seem to indicate a clear delineation between flare- and non-flare-associated events. Specifically, flare-associated events are observed to exhibit systematically higher speeds, with those speeds being more-or-less constant. In fact, there seems to be little difference between the observed speeds versus height for flare-associated events and that of a projectile exhibiting a ballistic behavior, represented by the curve labelled 'escape speed' in Figure 3 (the present measurements are not accurate enough to address this issue quantitatively). On the other hand, eruptive prominence-associated events are typified by lower speeds, and observable accelerations. Indeed, the events of 241/1981 and 218/1980 exhibit accelerations in excess of 50 m s^{-2}. We will return to the speed characteristics in Section 4.

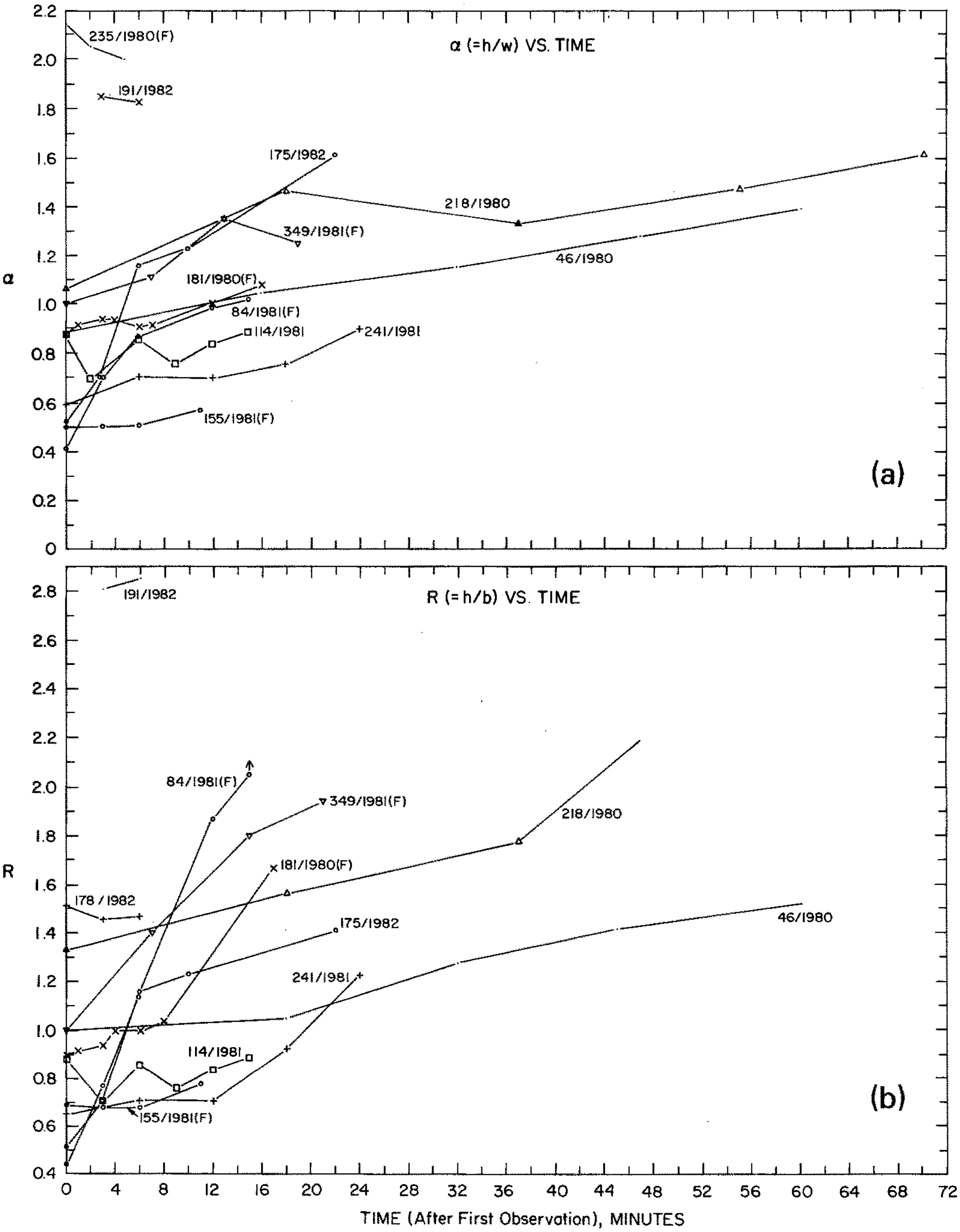

Fig. 2. (a) The parameter $\alpha = h/w$ as a function of time, measured from that of initial observation; (b) Same as (a) for $R = h/b$.

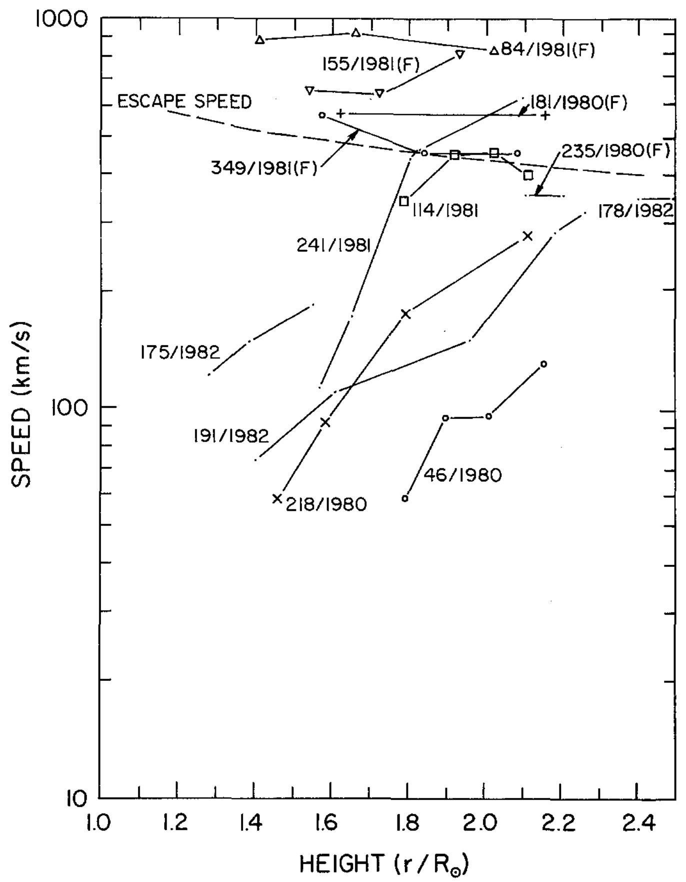

Fig. 3. The radial speeds of transients vs height.

In Figure 4 we show the speed of lateral displacement ($\mathrm{d}B/\mathrm{d}t$) of the transient base as a function of the lateral displacement ($b/2$). The speeds determined encompass the range from 10–500 km s^{-1}; it should be noted that these speeds are not merely the result of an apparent increasing separation of the loop foot-points as the event emerges from behind the occulting disk. Rather, most events appear in the initial observations fully formed, with definable w and b. Unlike the situation with radial speeds, there seems to be no apparent correlation of the magnitude of speed with type of association. As the transient evolves, the speed of lateral expansion generally decreases. (The events of 46/1980 and 218/1980 appear to be exceptions; in both cases the speed remains between 10–20 km s^{-1} throughout the period of observation). However, note that the strongest decelerations occur for those events correlated with flare activity (155/1981; 349/1981; 84/1981; 181/1980).

The associations of solar activity with the transients studied herein have been determined principally from examination of correlative data (NOAA, 1980, 1981) and correlative observations from the Mauna Loa site. In the latter case, an instrument designed

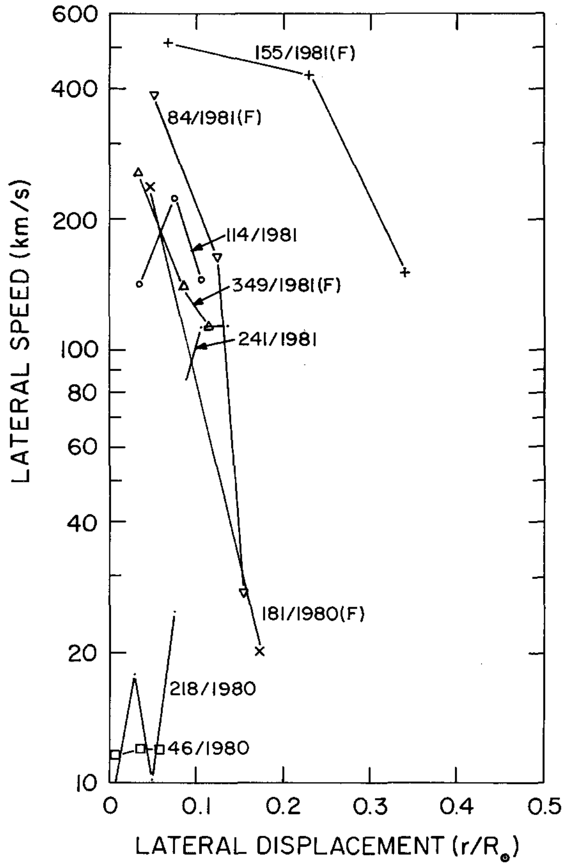

Fig. 4. The lateral speed of transient separation as a function of displacement.

to monitor limb activity in Hα (Fisher *et al.*, 1981a) is particularly useful, since all the events exhibit Hα mass motion. In certain cases, the assignment of activity to an event is ambiguous. For example, the event of 155/1981 has been associated with flaring activity behind the east limb, on the basis of the presence of type II metric radio emission just prior to the transient observation, and a small, faint (flare) spray at the appropriate position angle observed by the prominence monitor. The case of the event of 241/1981 is interesting. Examination of the disk image on the prominence monitor film shows that prominence activity and then the transient event occurred some 11 min *prior* to an optical flare at S 29 E 75–80, for which significant 1–8 Å X-ray enhancement (M1) was recorded by the GOES satellite sensors (*Solar-Geophysical Data* Report). Thus, this event is taken to be eruptive-associated. Table I presents the results of the search for associations for all the events studied. Unlike outer coronal results, where a substantial fraction of events are unassigned, we are able to specify associations for each event with some confidence. Probably, this is a result of: (a) the more localized (to the plane-of-sky) nature of the polarization-brightness product, thus reducing the ambiguity of the surface extrapolation; (b) the significantly smaller spatial and temporal extrapolation to the surface needed for the inner coronal observations; and (c) the availability of concomitant Hα limb observations for each event.

The values of the measured transient parameters, for the times of initial and final observation, also are presented in Table I.

4. Discussion

At the time of initial observation, we see that it is generally the case that the transient base width, b, is on the same order as the height of the loop. Even though the initial observation may occur some minutes after the transient appearance, it is clear that significant lateral movement of the transient typifies this initial stage. Low *et al.* (1982) have previously noted this fact in their study of the event of 218/1980 – an eruptive prominence associated dark transient event. Also, early in the events' evolution the speed of lateral motion is of the same order as that of the radial motion. However, later in the events' history, the speed of lateral movement generally decreases.

As noted earlier, the parameters α and R generally increase, dictated by the combination of increasing radial speed (for eruptive prominence-associated events) and decreasing $\mathrm{d}b/\mathrm{d}t$ and $\mathrm{d}w/\mathrm{d}t$ with time. From Figure 2(b) we see that flare-associated events show the steepest behavior of the parameter R with time, although the events of 155/1981 and 241/1981 are exceptions.

The radial speed vs height plot, Figure 3, suggests the clearest delineation between classes of events. Flare-associated events trend toward the highest speeds, and show more-or-less constant speeds with height. On the other hand, eruptive prominence-associated events clearly exhibit accelerations. This result supplements that reported for outer coronal events by Gosling *et al.* (1976), later refined by Hildner (1977). Using outer coronal speed vs height results from the Skylab era, those workers were unable to identify an event's cause, although they did show that flare-associated events tended to have higher speeds than eruptive-associated events. It appears that these inner coronal measurements offer a new diagnostic tool for transient study, and further, suggest that there is a fundamental difference between flare- and eruptive-associated events.

We suggest that these new results are consistent with the following hypotheses: flare-associated events arise from an 'impulsive' input (which is observationally constrained to act over spatial scales less than 0.2 $R_{\odot}$, and over times less than a few minutes) in the low corona; the transient then propagates outward through the corona; eruptive-associated transients are subjected to an observably *significant* net propelling force over extended distances and times, causing their acceleration outward from the solar surface. Note, however, that one cannot conclude that the force per unit mass acting on the transient ejecta is less for flare-associated events than for eruptive-associated transients, for the presence of an acceleration of on the order of 50 m s^{-2} – typical of that seen in eruptive-associated events – cannot be distinguished in the case of the high-speed flare events. That is, we cannot exclude the possibility that net forces of similar magnitude act both on flare- and eruptive-associated events well above the solar limb; if this is the case, the only difference between the two types of events would arise from the 'input' conditions.

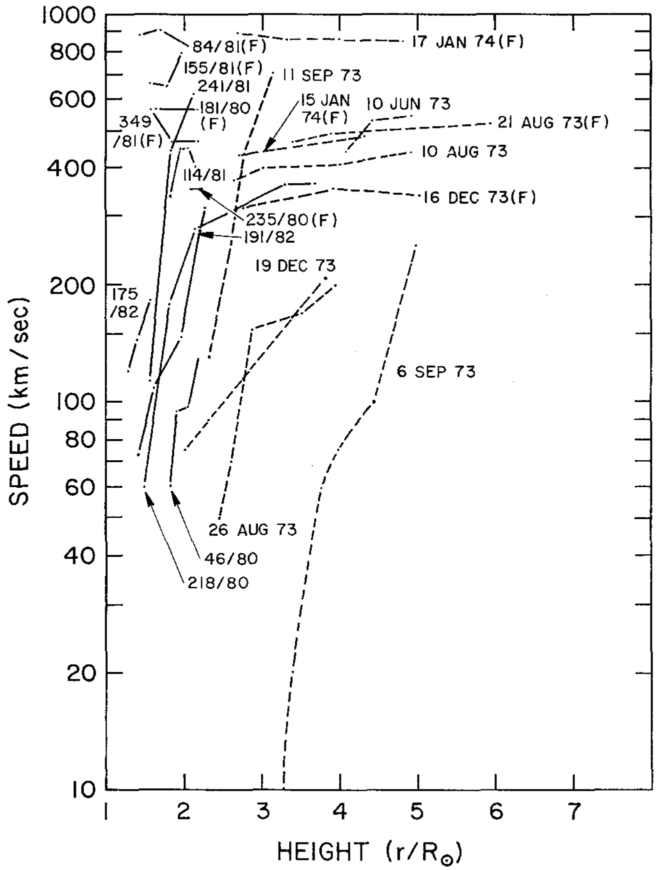

Fig. 5. Radial speeds of transients, including measurements from the Skylab coronagraph and from the SMM coronagraph/polarimeter (218/1980).

With these ideas in mind, we reexamine the speed vs height results from the Skylab coronagraph. Those results (Gosling *et al.*, 1976; Hildner, 1977) are shown in Figure 5, combined with the present data. Two additions to the previously described data have been made. Firstly, the 10 August, 1973 event data includes a new measurement at 2.65 $R_\odot$, of 375 km s^{-1}. Also, the inner coronal results of the event of 218/1980 have been extended by inclusion of measurements in the outer corona, from the coronagraph/polarimeter on SMM. Also, in cases where the association with surface activity could not be differentiated between flares or eruptive we have assumed the former dominates. When viewed in the context developed in the present work, the outer coronal results now reveal similar traits; flare events show more or less constant speeds with height and eruptive-associated events exhibit accelerations. The evidence of the event of 218/1980, together with the general trends of the inner coronal data, suggests that eruptive-associated events frequently show reduced acceleration with increasing height – a fact which has hampered our past ability to discern trends from the outer coronal data alone.

The behavior of the transient base region early in the event appears to be in disagreement with that currently predicted by models of the progression of a compressive wave through the corona resulting from an impulsive input. In the latest in a series of papers describing the results of magnetohydrodynamic modelling efforts, Wu *et al.* (1982) present results wherein the lateral expansion speed of a non-planar wave is ten times less than the 'lifting' speed. For the first time low coronal observations are now available which allow a direct comparison with the model; this comparison shows to a significant disagreement in that early in the event observed speeds of lateral motion are approximately equal to the radial speed.

Having suggested that we can now discriminate between flare- and eruptive-associated transients on the basis of the observed inner coronal radial speeds, we may ask if the observed behavior of the events offers additional clues concerning the nature of the net propelling force. A number of workers have suggested that a prime candidate for the driving force of the transient is the magnetic field. Low (1981) has suggested that coronal transients may arise from magnetic field loops (or arcades) buoyantly driven following the spread, by photospheric motions, of the coronal magnetic field footpoints. The Low *et al.* (1982) study applied these ideas to the event of 218/1980 included in the present survey; thus, the concept is at least consistent with the range of parameters we have determined for the inner coronal behavior of transients. Based upon observed properties of outer coronal transients, Mouschovias and Poland (1978), Anzer (1978), and Pneuman (1980) have each advanced various magnetically-controlled situations as potential transient driving forces. Their ideas have been applied to outer coronal loop-like geometries, irrespective of the initiating agent (flare or eruptive). However, since each study has attempted (successfully) to match 'speed vs height' profiles which exhibit significant acceleration, their work, in the present context, should now be viewed only to the case of eruptive-associated events.

As opposed to these magnetically-dominated driving forces, we suggest that the observed speeds and accelerations of eruptive-associated inner coronal transients may be a result only of bulk forces similar to those responsible for the near-solar wind. More restrictively, we suggest that an important (and perhaps dominant) force involved in the transit of eruptive-associated events may be that which causes the expansion of the solar wind. The suggestion is based upon two factors: (a) the speed of the eruptive-associated events is of the same magnitude as that predicted for solar wind flow at similar heights, given reasonable base conditions; and (b) the magnitude of the acceleration of these events is also comparable to that predicted for the solar wind, given appropriate input conditions.

For comparison, Figure 6 includes the curves of speed vs height for only the eruptive-associated events, and for a steady-state, isothermal near-solar wind. These latter curves are computed from the expression

$$u^2 - u_c^2 \ln(u^2/u_c^2) = u_c^2 + 2q \ln(r/r_c) + 2GM_0(1/r - 1/r_c) \tag{1}$$

(Parker, 1964), where $r_c = GmM/2qkT$ and $u_c = (2kT/m)^{1/2}$ are the critical radius and speed, respectively. The curves illustrate the solar wind speed behavior for the cases

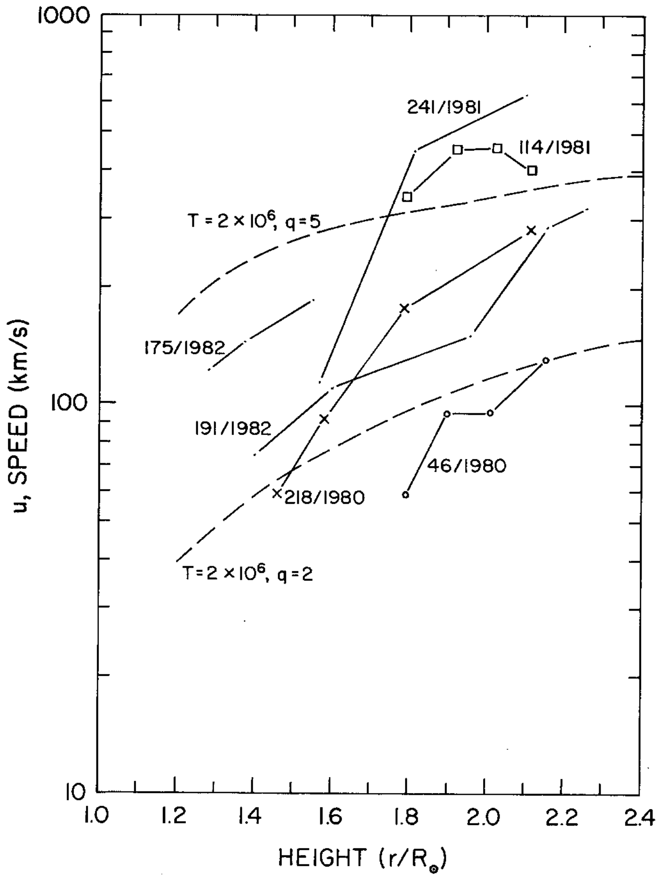

Fig. 6. Radial speed vs height for all inner coronal eruptive-associated events, and solar wind speeds for a steady-state, isothermal corona of temperature 2×10^6 K, and areal divergence factors of 2 and 5, respectively.

where the base temperature is 2×10^6 K, and where the areal magnetic field divergence is 2 (radial) and 5, respectively. For these cases, the critical speed is 181 km s^{-1}, and the critical radii 2.9 $R_\odot$ and 1.2 $R_\odot$, respectively. This comparison shows that the magnitude of the predicted solar wind speed is comparable to those of eruptive-associated transients at similar heights. The transient acceleration, however, seems to be greater than that given by these simple cases. Several possibilities exist for reconcilling this difference. Firstly, the acceleration could be the result of the presence of an additional, non-solar wind force. Next, solar wind expansion forces could dominate, but be modified by the inclusion of height-dependent geometrical effects (i.e., in a simple case, transition, at appropriate heights, from a lower to a higher value of q in the above expression). Thirdly, the sudden presence in the corona of a density enhancement (transient material) will enhance the normal pressure gradient responsible for the wind flow, thus producing an enhanced force and resultant acceleration. A final possibility may involve the addition of energy or momentum to the flow of the solar wind above the coronal base. Recently, Holzer and Leer (1980), Leer and Holzer (1980), and Leer *et al.* (1982) have studied the effects of such energy or momentum addition on the properties of the solar wind flow at 1 AU; the inner coronal effect is, however, less clear, and requires study. Munro and Jackson (1977) have shown that, in order to reconcile the observed polar coronal hole density with an inferred particle flux, a speed in excess of that derived from an isothermal radially flowing solar wind is required. This in turn dictates the 'effective temperature' increase with height – which finally requires that the outflowing material either be heated or momentum be added well above the coronal base. In the present case, in order to match the observed speed vs height profile, we would require that the acceleration of the solar wind be enhanced between 1.5–2 $R_\odot$, a region which may be either above or below the critical point – at least relative to the simple isothermal case considered above.

It should be stressed that we do not suggest that the values of the isothermal solar wind parameters presented in Figure 6 are unique; rather, they are presented only as representative and reasonable. In sum, we suggest that eruptive-associated events may involve nothing more than release of low-coronal ambient fields from the solar surface, thence allowing the fields and entrained material to partake of – and perhaps enhance – the bulk solar wind expansion. If this process dominates the flow of the transient, then no hypotheses concerning driving forces originating from particular orientations of the magnetic field would appear to be necessary.

5. Conclusion

Observations of the behaviour of the properties of coronal transients in the low corona permit valuable clues as to their nature. Particularly, the behavior of the transient speed as a function of radial height indicates, for the first time, that there is a definite distinction between flare- and eruptive-associated events, thus suggesting that there is a qualitative difference between the nature of the initial transient input – at least over the spatial and temporal scales relevant to these inner coronal observations.

The properties of the events sampled herein set practical constraints for continued (and future) efforts to model loop (or bubble) transient behavior; in particular, we hypothesize that the observations suggest that flare-associated transients differ from eruptive-associated events in the nature of the initial spatially and temporally localized input. More precise measurements of the speeds of both types of events may permit upper limits to be placed on the presence of accelerations in flare-associated events; then, questions concerning the nature of the net forces involved may be addressed. Present evidence, however, permits the suggestion that eruptive-associated coronal material may be released and entrained within the flow of the solar wind.

Although loop (or bubble) events represent a minority of all transient events in the corona, still they remain as potentially the most simple (!) and easily understood representatives of the transient phenomena. As such, explanations for their behavior which are *quantitatively* consistent with the principal observed quantities should remain a high priority for theoretical investigations.

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