PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Phil. Trans. R. Soc. Lond. A 1980 **297**, 605-620
doi: 10.1098/rsta.1980.0236

Phil. Trans. R. Soc. Lond. A **297**, 605–620 (1980)
Printed in Great Britain

Coronal transients: a summary

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Observations with orbiting coronagraphs have illuminated the role of coronal mass ejections in solar activity, and raised a number of questions concerning their origin, the nature of the forces driving the coronal material, and their signature in interplanetary space. Current models of the ejection process – including propagation of loops as a result of azimuthal field gradients, ring currents or a build-up of magnetic pressure from below – are summarized, as are magnetohydrodynamic codes intended to stimulate transient conditions. Metric radio observations, can, in principle, distinguish the relative role of the magnetic field in the ejection process; observations to date are surveyed. It is concluded that at present, no compelling evidence is available to distinguish between transient driving mechanisms, but future observations of the corona and interplanetary medium may resolve the present ambiguity.

1. INTRODUCTION AND OVERVIEW

During the past five years, transient coronal disturbances have become recognized as an important manifestation of activity on the Sun. This recognition is a result of the advent of sensitive space coronal measurements of the white light coronal form (Howard *et al.* 1976; MacQueen *et al.* 1974), but suspicions of the coronal participation in solar activity were evident from observations made with ground-based K-coronameters (see, for example, Hansen *et al.* 1974), even before the development of orbital coronagraphs. The relatively large white light coronagraph on Skylab, with its high sensitivity and the ability to observe to within 1 $R_{\odot}$ of the solar limb, provided the most comprehensive view of the solar corona yet achieved, albeit at the phase of the solar cycle near solar minimum activity. Most of the inferences concerning coronal transient behaviour have devolved from study of the Skylab results; in the present discussion I shall rely heavily on those data and attempt to summarize the major properties of coronal transient events. It is now appropriate, however, to go beyond a summary of observational results and outline initial thoughts and models of the solar phenomena revealed by orbiting coronagraphs. However, it is important to stress that the results and inferences are based upon a restricted data set obtained at one phase of the solar cycle; whether or not they apply to other periods of the cycle is a matter for speculation, awaiting resolution by other data sets.

One principal result from the space coronagraph observations has been the identification of a broad range of coronal disturbances, encompassing the previously suspected responses to large solar flares, 'medium'-energy events associated with smaller flares and eruptive prominences, and finally, events at the lower limit of sensitivity of the observations. It is the medium to low energy events that have previously been undetected, and their energy and presence on a relatively frequent basis require modification of past ideas of solar activity.

The observations indicate that it is particularly appropriate to reexamine the role of coronal activity as a diagnostic for the flare process and its potential impact on coronal evolution. With regard to the flare process, it has been clearly established that the kinetic energy of the coronal material ejected from near the flare site represents a major energy component in the flare or eruptive process. That is, the kinetic energy associated with the ejection generally exceeds the total radiative energy output of the flare. Although this has been known to be so for large flares (see §V), it is apparently also true of a wide variety of flare energies. It has thus become clear that this energy must be accounted for in the development of theories of the flare/eruption mechanism. On the other hand, the role of coronal transients as disrupters of the evolution of coronal forms is yet uncertain. It is currently unclear if, despite the high frequency and significant energy of the average coronal perturbation, there results any substantive change in the long-term evolution of the global coronal field. Specifically, MacQueen & Poland (1977) have examined the evolution of equatorial coronal forms and evidence for transient involvement in this process during the Skylab period. They found that even though transients exhibited a similar character and occurred more or less uniformly throughout the period of approximately 9 months for which observations were available, changes in the coronal structure (as evidenced by changes in the periodic nature of the coronal radiance signal resulting from long-lived forms rotating through repeated limb passages) appeared to occur in a rather discrete, sporadic manner. They concluded that, at least during the observational period, the long-term evolution of equatorial coronal forms proceeded unimpeded by transient coronal behaviour. There is, however, contrary evidence, at least on a local scale. One specific example involves the formation of a large-scale coronal streamer as a direct result of the transient ejection of 14–15 September 1973 (Dulk *et al.* 1976). The restructuring of the corona following that transient caused the formation of a dense coronal streamer which was observed over several subsequent solar rotations; thus the form became a more or less stable coronal feature, and as such represented at least one example of a substantial change in the coronal magnetic field as a result of transients.

Yet another aspect of the role of transient behaviour concerns the relative contribution of transient mass ejecta from the Sun to the 'steady-state' flow of the solar wind; we can crudely estimate that contribution in the following way. Rust *et al.* (1979) have summarized the average properties of coronal transients as observed from Skylab (see §II) and found that the average mass ejected from the Sun is on the order of 5×10^{15} g. If it is assumed that the ejection process continues for a period of approximately 4 hours, then each transient event contributes a mass flow of *ca.* 3×10^{11} g/s over the period of approximately one-sixth of a day. On the other hand, if we extrapolate the (inecliptic) average proton flux density appropriate to the low speed solar wind (Hundhausen 1972) into 4π sr, this flux density corresponds to a mass flow of *ca.* 10^{12} g/s; Feldman *et al.* (1977) show that this mass flow is appropriate as a bulk flow parameter for the solar wind, i.e. low and high speed streams. Hence, these simple arguments lead us to estimate a total contribution of approximately 5% to the bulk solar wind mass flow as a result of coronal transients, based upon an observation period near solar minimum. From a correlation between observed sunspot number and frequency of transients during the brief Skylab period, Hildner *et al.* (1976) conjectured that the frequency of transient events might increase by as much as 3–4 times at solar maximum period. If this is so, then the transient mass flow contribution relative to that due to the solar wind during the maximum period of solar activity may increase to as much as 15–20%.

In sum, as a diagnostic for the solar flare/eruptive process, as a potentially significant influence in the evolution of the coronal magnetic field, and as a potentially significant contributor to the mass loss from the Sun, coronal transients have assumed an important and relatively new role within the spectrum of processes of solar activity.

At present, a number of important and yet unresolved questions have arisen concerning the nature of the ejection process and the subsequent passage of plasma and fields into interplanetary space. In the subsequent sections, following a brief summary of the observed properties of mass ejections, I shall attempt to point out some of the present uncertainties in the interpretation of the coronal phenomena and their interplanetary passage.

II. Summary of properties

During the Skylab mission period, approximately 110 coronal transients were recorded by the High Altitude Observatory white light coronagraph during its 227 days of observations. Of the 110, nearly 80 transients are identified as mass ejection events, i.e. events for which mass is observed to leave the field of view of the coronagraph (Munro *et al.* 1979). Even though transient occurrence has been seen to correlate with the variable sunspot number during the Skylab period (Hildner *et al.* 1976), transients occur more or less uniformly in time (MacQueen & Poland 1977), and the frequency of all observed transients (e.g. mass ejections and 'rearrangements') can be estimated well, merely from the total numbers observed, i.e. 110 transients per 227 days = 0.48 transient per day. As noted by Hildner *et al.* (1976), if corrections are made for instrument duty cycle and the fact that limb coronal observations are sensitive to only about one-half of the coronal 'sphere', the solar rate of production of all types of transients during the Skylab period is about one transient per day. Munro *et al.* (1979) have summarized the association of solar surface phenomena with transient ejecta during the Skylab period, and conclude that 40 % of the transients are associated with flares, 50 % are associated with eruptive prominences solely (without flares) and more than 70 % are associated with eruptive prominences or filament disappearances (with or without flares).

More subjectively, Munro (1977) has classified the appearance of mass ejection transients observed during the Skylab period; the most dominant type is that of the outwardly expanding loop, or loops, a class comprising nearly one-third of all those observed. Clouds or amorphous blobs constitute the next most common type, about one-quarter of all ejections observed. The remainder defy specific classification.

The overwhelming majority of the mass that makes up the ejection has been determined to originate in the low corona. This conclusion follows, first, from the excellent agreement between the observed linear polarization of the mass ejection and that predicted of Thomson scattering by free electrons (see, for example, Poland & Munro 1976; Hildner *et al.* 1975). Secondly, where observations of the Hα ejecta from flare and eruptive sites are available at similar times as the space-borne coronagraph observations, it is found that the white light feature and the Hα material are not superimposed: the white light features invariably lie 'ahead' (at greater distances from the limb) of the cooler ejecta (Hildner *et al.* 1975; Schmahl & Hildner 1977). Finally, in one case the outward progression of a low-lying coronal loop visible in soft X-rays was correlated at a later time with the appearance of an expanding white light loop high in the corona (Rust & Hildner 1976). It is important to stress that the estimated mass of the ejected material is far in excess of that attributable to flare ejecta seen in Hα or the mass of most prominences; the evidence alone indicates that the likely origin for the ejection is from a relatively dense coronal form (loop or loops), and/or from a substantial coronal volume overlying the eruption site.

Rust *et al.* (1979) have summarized the observed speeds and computed masses and energies for 24 Skylab events for which sufficient data exist. Table 1 displays their results. We note that flare-associated events typically involve larger mass and higher speeds than eruptive prominence-associated events. Thus, the kinetic energy estimates for flare-associated events generally exceed those for eruptive-associated occurrences. Note, however, that the events potential energy dominates in all cases. Gosling *et al.* (1976) have drawn attention to the fact that for the flare events the average speed for the ejection is 775 km s^{-1}, while eruptive-associated events have an average speed of only 330 km s^{-1}; they also find that type II or type IV metric radio emissions generally occur only for events whose speeds are greater than about 400 km s^{-1}.

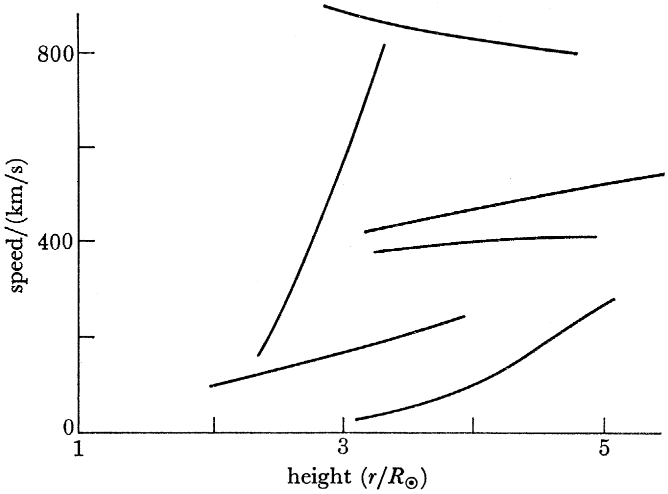

Figure 1. Schematic, smoothed representation of material passage speed with height for the range of events measured from Skylab observations. See Hildner (1978).

Of major importance is the measurement of the speed of the ejection event through the observed height range: the acceleration. Gosling *et al.* (1976) determined the speed variation for several events; the results have been supplemented and corrected in Hildner (1977). For the ten events for which adequate data exist, all but two show acceleration over the height range 2–3 to 5–6 $R_\odot$. The remaining two events show constant velocity and a slight deceleration, respectively. Thus, in general, we expect that the 'average' transient event exhibits a rapid acceleration to near 2 $R_\odot$ above the solar limb, followed by a slowing and approach to nearly constant velocity by, say, 6 $R_\odot$ from the Sun's centre (see figure 1).

Several other studies of transient phenomena are of interest at this point: Kahler *et al.* (1978) have shown that there exists a good association between prompt proton events and mass ejection transients during the Skylab mission period. They have suggested that the extreme local disruption of the coronal magnetic field resulting from the ejection provides an escape route for protons to interplanetary space. Also, they hypothesize that the acceleration of the protons (to the 4–10 MeV energy range) may occur high in the corona, in contiguity with the ejecta, as opposed to near the flaring site. Finally, Jackson & Hildner (1978) have discovered the presence of a faint, broad region of enhanced electron density bordering the brighter white light ejecta identified initially as the transient ejected mass. These regions – designated 'forerunners' – generally blend into the background coronal radiance 1–2 $R_\odot$ above the transient leading edge; their inclusion as part of the ejection process may raise transient mass estimates by as much as 25% and their existence implies either that a larger volume of the corona is perturbed by the transient driving force or that the coronal disturbance actually precedes the surface event (Jackson 1979).

III. Models of ejecta

Following the collection of the observational results summarized in the preceding section, some initial attempts have been made to produce elementary models that might illuminate the physical mechanisms responsible for the propulsion of the material from the Sun. Motivation for the initial analytical attempts has derived from two central observational results: first, the fact that the ejecta seem to follow trajectories implying a continued force on the material (excluding gravity) far from the Sun and, secondly, the result that nearly one-third of the transients observed during the Skylab period could be described as outwardly moving loops. The first result implies the presence of a driving force of substantial duration, acting over large spatial scales. Specifically, it should be stressed that the velocity–time curves for the several events for which this could be determined imply a substantially different trajectory from that expected ballistically. The second result has permitted theorists to concentrate their explanations on a relatively simply geometrical form: an expanding loop system.

Mouschovias & Poland (1978) and Anzer (1978) have formulated conceptually similar analytical models in attempting to describe the outward propagation of single loop structures. In the former work, the transient driving force is derived from the presence of an azimuthally confined loop of magnetic flux; the gradient of this azimuthal field provides the net outward force. Mouschovias & Poland find that the observed broadening of the loop as it moves outward could be accounted for by the presence of a longitudinal component of the field in the loop. They claim that the relative field component magnitudes are related by the criterion that $1.4\,B_1 > B_{\mathrm{az}} > B_1$ in order that there be present a net outward force and yet at the same time the pinch instability be avoided. Under these circumstances they predict that as the loop rises, its width at the top portion should increase in proportion to the distance from the Sun's centre: in good agreement with measurements from one well observed event. On the other hand, their predicted behaviour for the variation of the radius of curvature of the loops' top portion with distance from the Sun is substantially different from the measured variation: a fact that they claim might be accounted for if the (unknown) retarding force due to the background coronal field were to be included. Their model assumes the continued presence of the required components of the magnetic field in the loop; no attempt is made to suggest how the required twisting continues during the outward propulsion of the loop event. A conceptually similar view has been advanced by Anzer (1978). He proposed that the outwardly expanding loop, subjected to gravitational attraction, is driven by a global ring current. His predicted curves of velocity against height (or time) agree, at least qualitatively, with the general form inferred from observations (figure 1). Thus, if ring currents can be produced in the corona with a sufficiently fast time scale, an adequate driving force may be present to propel the loops outward. Recently, van Tend (1979) has extended the concept of Anzer to include conditions for the onset of the transient from an equilibrium state wherein the current circuit is prevented from expansion by gravity.

Pneuman (1979) has examined another approach: the possible role of magnetic pressure in driving loop transient events. He has noted several potentially restrictive concepts in the model of Mouschovias & Poland; these include (*a*) the azimuthal field is restricted to a narrow range, as noted above, and (*b*) the pitch angle of the twist must be greater than 45°, which requires, for a typical-sized transient, approximately 8–10 complete twists of the loop along its length. Such twisting has not been seen in either the white light coronal transient photographs (but of course might be present below the limit of resolution of *ca.* 7000 km) or in X-ray or eclipse observations of low-lying magnetic loops.

In suggesting magnetic pressure as a transient driving force, Pneuman notes that if the magnetic field under a coronal helmet structure is increased by even a small amount beyond its equilibrium value, a transient event with the observed characteristics may result, provided that the driving field expands with the transient. How can this new underlying field be produced? He suggests several possibilities, including: (*a*) the emergence of new underlying flux; (*b*) a lateral motion of magnetic field from the sides of the helmet towards the neutral line where it could reconnect, forming isolated loops of magnetic field; (*c*) an uplifting of the prominence under the helmet due to some internal instability.

Pneuman has computed an analytical model of a simple two-dimensional flux loop, driven by increased magnetic pressure from below. He finds that the loop width increases linearly with distance and time, while the velocity approaches a constant value at large distances. As noted previously, both results qualitatively fit the observed parameters. All of the above results are similar in that they ignore the gas pressure in the event and assume dominance of the magnetic field.

On the other hand, Dryer and colleagues (e.g. Steinolfson *et al.* 1978; Dryer *et al.* 1979) have examined the coronal mass ejection phenomenon with a rather different view. They have assumed that mass ejections may best be described in the fluid continuum approximation, e.g. a fully interactive magnetic field and plasma. Their models use nonlinear, two-dimensional magnetohydrodynamic numerical simulations of the propagation of energy through pre-existing magnetic field topologies. Of crucial importance in their studies is the nature of the 'pressure pulse' that provides the driving force for the evolution of the magnetohydrodynamic waves. The precise character of this impulsive force must often be assumed, and the input parameters varied arbitrarily until a 'match' with observations found. But in one recent case (Dryer *et al.* 1979), the input pulse employed was that deduced from an enhanced emission measure observed with broad-band filters in the soft X-ray spectral region. The computed shock wave and contact surface behaviour was identified with the observed transient properties; specifically, the white light transient is thought to be simulated by a region of enhanced density produced by a shock wave and also from the ejected plasma originating within the pressure pulse. Calculated speeds, masses and energies are found to agree reasonably well with the observed quantities. Steinolfson *et al.* (1979), has employed similar modelling techniques, but has used as the driving force new magnetic flux emerging from the solar surface and interacting with a pre-existing magnetic field. This approach therefore represents a fluid continuum counterpart of the Pneuman magnetically dominated model. Steinolfson *et al.* allow the emerging flux to increase by *ca.* tenfold and calculate the response of a pre-existing coronal field to that change; a shock is formed and moves outward through the corona, more or less independently of the emerging flux. Unlike for the pure pressure pulse driving force, material is trapped inside the contact surface and is subsequently compressed and heated.

This latter material, it is suggested, may provide a source for the generation of X-rays. Again, we note that the calculated properties of the outwardly moving material at least are qualitatively in agreement with observed transient properties.

How, then, do these initial efforts in modelling coronal transient behaviour compare, and how do they reproduce the observed behaviour of the mass ejection events? It should immediately be noted that the model of Mouschovias & Poland (or Anzer) aspires to describe the steady-state passage of the loop ejection, on the assumption that an azimuthal component of the magnetic field exists and meets certain conditions over rather extended periods of time. Pneuman's effort, on the other hand, does provide a logical framework for the initiation of the event and, like the Mouschovias–Poland effort, at least qualitatively predicts the form of the velocity against height (time) observed. It is clear that the relative roles of the initial parameters in Pneuman's model are crucial; it remains to be determined if the assumed values constrain the problem unduly. All of these works also predict a change in width of the leading edge of the transient loop with time which qualitatively agrees with measurement of one event; but observationally, more such measurements should be carried out – on data already acquired – to determine how crucial this agreement is. As noted above, the magnetohydrodynamic code approach to the transient description also qualitatively describes the gross features of events. As yet, the effects of ignoring the third dimension in such models is unclear. The present restriction of a pressure pulse injection at the coronal base to two dimensions may constrain the model unduly. Unfortunately, the observational evidence available for accurate specification of the third dimension of transients is not definitive; it does, however, point to the conclusion that transients are generally planar (Sime 1979, personal communication). If this is proved to be so, it may become difficult to reconcile a pressure pulse input to such a geometry without the inclusion of unnecessarily – and arbitrarily – strong lateral pressure gradients in the ambient corona. In some other areas, present efforts in magnetohydrodynamic codes require improvements; this is particularly true of the role of the ambient magnetic field in these models. At the risk of oversimplification, it may be stated that the models call for unreasonably large ratios of thermal to magnetic pressures far from the solar limb ($r > 2R_\odot$), and apparently require – or at least strongly prefer – open magnetic regions overlying the transient region (Wu *et al.* 1978). The latter requirement may be in conflict with observations (although no systematic study of the pre-transient magnetic field topology has been attempted).

IV. The role of the magnetic field

It is clear from the preceding summary that there exists a substantial dichotomy in models of transients with regard to the role of the magnetic field present in transients. On the one hand, magnetic fields are believed to dominate the transient structure, either through the presence of a gradient in the azimuthal component of the magnetic field across the loop structure, or the generation of ring currents providing a driving force for the expulsion of the structure, or through compression of an upwardly rising arcade system (or loop) of untwisted field. On the other hand, two-dimensional numerical simulation models suggest that the force of expansion or expulsion results from the generation of a pressure pulse at the coronal base. In these latter cases, the magnetic fields present provide only a 'background' to the transient effect which may modulate (albeit strongly) the characteristics of the outward expulsion process but which is not fundamental to the expulsion process itself.

Is it possible for observations to differentiate between these widely divergent views? For example, it is known that the presence of continuum radio emission in the metric wavelength range is indicative of either (harmonic) plasma emission or gyrosynchrotron radiation; the continuum radio emission therefore depends upon both the density of the emitting region and the magnetic field present there. The combination, then, of spatially resolved metric continuum radio emission observations and white light coronal observations – which are sensitive to coronal density alone – allows the possibility of measurement of the magnetic field strength in the emission region (it should be immediately noted that no information is available on the geometry of the field so deduced).

Several correlations of radio emission and coronal disturbances have been carried out with varying degrees of certainty in their spatial and/or temporal correlation. They are summarized below.

Stewart *et al.* (1974*a*, *b*) have examined two seemingly homologous events for which there exist K-coronameter, metric radio and satellite coronagraph results. The first event studied consisted of a complex array of flare spray, type II, stationary and moving type IV radio bursts, and for this event radioheliograph observations (C.S.I.R.O., Culgoora) were available. The type II burst emissions were found to be roughly coincident with the leading edge of an amorphous density enhancement observed by the OSO-7 coronagraph, while the moving type IV emission appeared at similar heights as the Hα spray material but displaced laterally by approximately 0.2 $R_\odot$. Finally, the stationary type IV emission was even further laterally removed – approximately 0.4–0.5 $R_\odot$ – from the Hα material. From the estimates of the density jump across the shock identified with the generation of the type II emission and the magnetic field strength estimated from applying the Rankine–Hugoniot relations across the shock (thus obtaining an estimate of the Alfvén speed), we find that the ratio, β, of the thermal energy density of the plasma to its magnetic energy density, relevant to near the leading edge of the cloud, is on the order of 10^{-2} to 10^{-3}. The second event studied by Stewart *et al.* (1974*b*) was in many ways similar to the first event; again there was present type II emission which could be projected to be roughly coincident with the leading edge of a 'cloud' observed by the OSO-7 coronagraph, and moving type IV emission. However, the spatial coincidence of the type $\mathrm{IV_m}$ emission and Hα ejecta is less convincing. Also, K-coronameter evidence (H.A.O., Mauna Loa) was available and indicated low coronal changes at nearly the same time as the white light cloud was observed in the outer corona by the satellite coronagraph.

Kosugi (1976) has examined the relation between metric observations of type II and IV emissions and white light observations obtained from OSO-7 (Brueckner 1974), and found that the height–time plots of the compact plasma clouds observed with the orbital coronagraph fit well with the extrapolated lines of the height–time plots of the moving type IV bursts. The complex event examined also exhibited stationary continuum emission and type II emission; the latter preceded the appearance of the continuum emission, and apparently corresponded to a shock propagation speed of at least *ca.* 1700 km $\mathrm{s^{-1}}$. Kosugi interprets the type II and continuum emission as being relatively independent of the dominant mass ejection process associated with the dense, compact blobs.

Dulk *et al.* (1976) have examined a loop transient event during the Skylab period for which metric continuum emission was observed and Skylab orbital coronagraph results obtained. Temporal simultaneous data were obtained only late in the event when the continuum emission was localized near the foot-points of the outwardly expanding loops; however, the early radio emission in the event could be placed near the leading edge of the loop by extrapolation of the motion of the loop backward in space and time (*ca.* 2 $R_\odot$ and *ca.* 30 min, respectively). Dulk *et al.* estimated that the region of emission of the early continuum burst was typified by a β of approximately 10^{-2} to 10^{-1}, depending upon the precise location of the burst relative to the brightest loop structure. The density enhancement, deduced on the basis of either gyrosynchrotron or harmonic plasma emission, was found to be compatible with the actual density deduced from the coronagraph results; Dulk *et al.* also found that the infrared magnetic energy density was marginally larger than the kinetic energy density in the fastest moving portion of the transient – the leading edge of the loop – but dominant everywhere else.

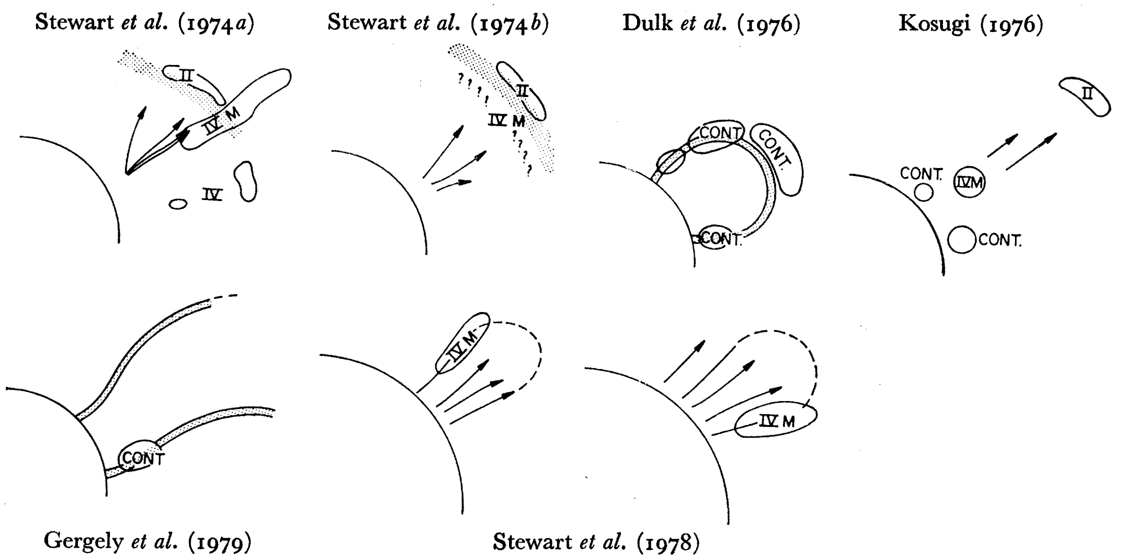
Stewart *et al.* (1974*a*)
Stewart *et al.* (1974*b*)
Dulk *et al.* (1976)
Kosugi (1976)
Gergely *et al.* (1979)
Stewart *et al.* (1978)

FIGURE 2. Schematic views of observations of metric radio emission and coronal/chromospheric material passage through the corona.

Another event during the Skylab period has been examined by Gergely *et al.* (1979). In this case, the radio emission was observed simultaneously with orbital coronagraph results and seen to be cospatial with the lower portion of one of the observed secondary white light loops. The radio source showed no dispersion of height with frequency and hence was attributed to gyrosynchrotron emission; the magnetic field deduced on this assumption was on the order of 2–4 G (0.2–0.4 mT) at 2 $R_\odot$ from the Sun's centre. From this estimate of the magnitude of the magnetic field and the measured electron density, Gergely *et al.* found $\beta \approx 1$ in the lower loop leg.

Finally, Stewart *et al.* (1978) have examined two eruptive prominence events that featured moving type IV emission; they found the emission to be coincident with Hα material blobs observed at the limb. Although no direct density measurements were obtained, they have estimated the kinetic energy density and magnetic energy density present in the radio-emitting region under the various assumptions of (*a*) fundamental plasma emission, (*b*) second harmonic plasma emission, (*c*) incoherent gyrosynchrotron emission, and (*d*) amplified gyrosynchrotron emission. For each case they found the magnetic energy density exceeded the kinetic energy density and a β in the range 10^{-1} to 10^{-3}.

I have attempted to summarize these various observations schematically (if imperfectly) in figure 2. The solid arrows represent the paths of Hα ejecta, the stippled areas (either outlined or not) indicate the extent of white light coronal material, and the regions giving rise to the metric radio emission are signified with enclosed areas. The reader is cautioned that the views represent my own interpretation of the measurements in that the observations, which in many cases covered extended periods of time, have been represented at a single time, with the inferred positions of radio bursts and density enhancements placed according to the best estimate of the sequence of events. If these few observations are indeed properly represented, several points are then suggested as generalizations.

(*a*) Type $\mathrm{IV_m}$ bursts apparently arise from plasmoids associated with Hα-emitting ejecta only; they do not correspond to any portion of the *coronal* mass ejections. Thus, we should regard considerations of magnetic fields and energy densities based upon type $\mathrm{IV_m}$ bursts as more indicative of the state of the material of the plasma and fields in the ejected chromospheric/prominence matter than in coronal plasma.

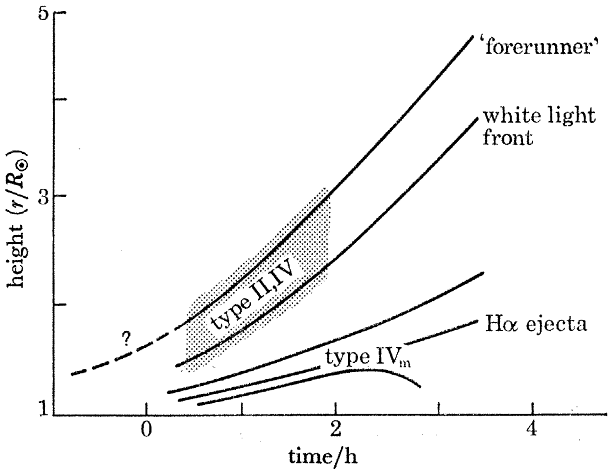

Figure 3. A hypothetical sequence of events for a mass ejection event, with placement of metric II, IV and $\mathrm{IV_m}$ bursts relative to ejected material, displayed as a height–time diagram.

(*b*) Continuum metric bursts seem to occur frequently in association with one of the legs of the outwardly expanding 'loop' coronal mass ejection. The radio emission thus observed apparently originates from gyrosynchrotron emission due to mildly relativistic electrons contained within the expanding loop. The emission appears at low coronal heights (less than $2R_\odot$) because it is there that $f \sim 2f_\mathrm{p}$, where f_p is the local plasma frequency. These bursts thus refer to the coronal condition of the loop leg(s), where the densities vary substantially from those in the loop leading edge and also vary with time (cf. Anzer & Poland 1979).

(*c*) Shocks occur in front of or coincident with the leading edge of the coronal mass ejection, for those events where the ejection speed exceeds that of propagation of magnetohydrodynamic signals in the corona by some amount. Smith (1972) and Zaitsev (1969) have suggested that type II bursts should occur when the Mach number for the shock exceeds 1.6. We thus conclude that the presence of type II bursts in conjunction with fast coronal mass ejections is most probably indicative of the state of the ambient corona in front of the ejection proper, at an appropriate 'stand-off' distance for the shock.

(*d*) Finally, we are left with evidence of the presence of continuum radio emission in the region of the leading edge – i.e. that studied by Dulk *et al.* (1976). It seems likely that this emission originates, as one alternative suggested by Dulk *et al.*, as a result of local acceleration of electrons in the vicinity of the white light front. Although the energies required to produce gyrosynchrotron emission (less than about 0.5 MeV) are considerably less than those required to explain prompt proton events (Kahler *et al.* 1978), it is attractive to speculate that for some events similar conditions may lead to the acceleration of both electrons and protons.

In sum, at present the only observations seemingly directly relevant to the question of the range of the plasma, β, in the *coronal* mass ejection are those of Gergely *et al.* and Dulk *et al.* The former measurements are not, however, relevant to conditions appropriate near the loop leading edge; the latter measurements suffer from the uncertainties resulting from the extrapolation, but with these reservations indicate that in the coronal loop a low β is appropriate. Nonetheless, it is fair to state that at present there is insufficient evidence to claim with certainty that coronal mass ejections are magnetically controlled (low β). It thus remains for clarification of this fundamental issue to look to future observations, and to predictions of more sophisticated models.

The above interpretation of the sequence of events composing mass ejection events is summarized in figure 3. Trajectories of (chromospheric) plasmoids giving rise to type $\mathrm{IV_m}$ radiation are indicated as following the overlying (coronal) white light front; some Hα-emitting material may ultimately return to the solar surface. Type II and/or type IV emission is shown as originating in the general area of the (coronal) forerunner and white light front; the precise location(s) cannot now be identified. Also uncertain is the time or height of origins of the forerunner.

V. INTERPLANETARY CONSEQUENCES

The response of the interplanetary medium to large flare events at the Sun is well known (Hundhausen 1971, 1972); the subsequent formulation of substantial shocks from which the mass and energy of the event can be estimated has been documented for dozens of events. The comparison of these energy estimates with the estimated radiative and particle output has resulted in the statement (Hundhausen 1972) that the shock wave apparently carries away at least one-half of the flaring energy. Gosling *et al.* (1975) identified a coronal origin of much of the mass ejection of 7 September 1973 associated with a 2B flare, and showed quantitative agreement between estimates of the mass and energy of this coronal transient and similar estimates derived from a subsequent interplanetary shock wave observation. In addition, Wu *et al.* (1976) modelled the interplanetary passage of an event associated with 2B and 1F flares, observed with the OSO-7 coronagraph and recorded by interplanetary probes. As a result of these studies, it is now clear that large flares affect a substantial volume of the overlying corona, with subsequent propagation of a major shock wave into interplanetary space.

What about the interplanetary passage and signature of the 'new' realm of lower energy, frequent events identified from the Skylab observations? Munro *et al.* (1978) have noted that the volume of corona affected by a surface event is apparently proportional to the energy of that event, i.e. large flares influence a larger coronal volume than do smaller flares. The large number of medium-energy events observed at the time of the Skylab mission, in fact, were of rather restricted latitudinal extent, with only the largest exceeding 65° latitudinal extent (Hildner 1978). (Only the latitudinal extent can be directly measured with coronagraph observations; the third dimension must be inferred from symmetry arguments, polarization measurements or other estimates.) Generally, transients subtend a *smaller* solid angle in progressing from 2 to $6R_{\odot}$ (Hildner 1978), perhaps under the influence of lateral pressure forces. In any event, in developing a hypothesis for the appearance of the events in interplanetary space, we might expect that, if the interplanetary modulation of both large and smaller energy transient events were similar, the spatial extent of the medium or low energy events would be substantially smaller than that of the large flare associated shocks previously studied.

A second signature of these events would be, of course, an enhanced density, either in the form of actual mass ejected, or the passage of a compressional wave. Since near-Sun coronal density enhancements of tenfold to fiftyfold are measured from the coronagraph results, we might expect that, despite the expansion of the material during passage, substantial density enhancements would be present as a signature of the outward passage of the ejecta.

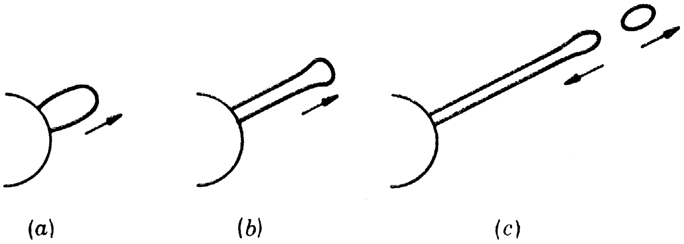

Figure 4. A suggested scenario for the 'disconnection' of coronal mass ejection loops from the Sun. The loop is initially observed in the intermediate corona (*a*); continuing outward, it is constrained in the low corona by lateral forces (*b*); finally the outer portion is pinched off (*c*). The connected loop returns to the Sun, while the disconnected bubble continues outward into interplanetary space.

As noted in the previous section, the magnetic field present in the interplanetary event is even more a subject of conjecture. However, the results of Dulk *et al.* (1976) may be used to estimate this quantity if it is assumed that the one event studied therein is representative of all transients of similar nature – e.g. loop events of kinetic energy *ca.* 2×10^{30} erg (2×10^{23} J). Dulk *et al.* found that the metric continuum observations could be interpreted (in a self-consistent way with the white light observations) as arising from a region of magnetic flux density $B \approx 1$ G (1 mT) at $2R_{\odot}$. If it is assumed this is an 'average' value for the field over the white light loop (of cylindrical cross section $1R_{\odot}\times0.2R_{\odot}$), we would infer a flux *ca.* 10^{21} G cm^2 (10^{17} T cm^2) present in each transient. Then, if similar transients occur at a rate of roughly once per day, in only 100 days a total flux of *ca.* 10^{23} G cm^2 (10^{19} T cm^2) would be expected to permeate the interplanetary medium – a total that is roughly equivalent to the net interplanetary flux, if the background 5γ field is assumed to be distributed over 4π steradians at 1 AU. Thus, it might be concluded that transients may be responsible for substantial modifications to the observed interplanetary magnetic flux – modifications which, however, apparently are not observed. One alternative to this 'paradox' is to suggest that, in fact, transients do not carry out distended fields to 1 AU, but rather are subject to a reconnection process such as that schematically illustrated in figure 4. If this picture is correct, the interplanetary (1 AU) signature of transients may, in fact, be a closed magnetic structure, of enhanced field. It should immediately be noted that no 'returning loops' have been identified from space coronagraph results, a fact that can be explained if the loops have been reduced in density sufficiently to render them invisible above the background K and F corona. This hypothetical picture of transients in interplanetary space then calls for events of more limited extent than those associated with large flare events, of enhanced density and magnetic field within a 'closed' field region, and of frequency *ca.* 1 per day during solar minimum.

Gosling *et al.* (1977) have identified the presence of enhanced density regions in the solar wind and have suggested that these regions are the interplanetary manifestations of coronal transients, particularly those associated with eruptive prominences. These regions occur when the bulk flow speed of the wind is either decreasing or approximately constant. The properties (e.g. flow speed, proton and electron temperature, magnetic field strength, α-particle:proton ratio) of these regions are similar to those of the low-speed solar wind except that the density is enhanced approximately four or fivefold over that of the low speed wind. The regions, labelled non-compressive density enhancements (n.c.d.e.), often (38% of 41 well defined examples found over the period 1971–4) show magnetic field reversals. Gosling *et al.* assumed, for want of better information, that the areal extent of the n.c.d.es included a region extending 30° in longitude and 90° in latitude. The radial extent of the event was determined from the observed average speed and duration (*ca.* 350 km s^{-1} and 11 h, respectively) to be on the order of 1.4×10^7 km, i.e. $20 R_\odot$. Their picture, then, is of a thin, extended shell wherein the mass is found to total *ca.* 10^{16} g and energy *ca.* 3×10^{31} erg (3×10^{27} J). They compare these values with the average properties of coronal transients (see table 1) and claim 'reasonably good agreement'.

TABLE 1. AVERAGE PROPERTIES OF MASS EJECTION EVENTS

	flare associated (8 events)	e.p l. associated (14 events)	all (24 events)
mass/(10^{15} g)	8.2	3.0	4.7
speed/(km s^{-1})	672	420	474
kinetic energy/(10^{30} erg†)	7.6	0.9	3.1
potential energy/(10^{30} erg†)	17	3.4	8.0

From Rust *et al.* (1979).
† 1 erg = 10^{-7} J.

The observed properties of n.c.d.es do, of course, match well one aspect of our hypotheses concerning the interplanetary appearance of transients – namely the requirement for enhanced density. The frequency of n.c.d.es also appears to be compatible with that of white light transients. However, the fact that n.c.d.es show no magnetic field enhancement, but sometimes exhibit field reversals analogous to those expected from the passage of closed magnetic structures, is contrary to our expectation of enhanced fields at 1 AU. Whether this in itself is evidence counter to that outlined for magnetic dominance of transient events is not yet clear. At present, however, the non-compressive density enhancement is the only suggestion so far put forward with evidence for a signature of the medium-to-low-energy coronal transient phenomenon.

VI. SUMMARY

The role of transient activity within the corona is now recognized as an important manifestation of solar activity: the coronal mass ejection is an important, and likely dominant, consumer of the energy budget of the flare process; coronal transients may prove to be important through the disruption and subsequent reformation of the global coronal magnetic field; and the coronal mass ejections may prove to contribute a small but significant amount to the mass loss of the Sun, particularly at solar maximum.

In contrast to the massive, extended coronal events associated with large, energetic solar flares, most transient mass ejections are of lower energy and are associated with eruptive prominences or particularly with flares (of various energies) exhibiting mass motions. Most importantly, the trajectories of mass ejections generally imply acceleration – or at least constant velocity – far from the limb of the Sun. This implies the presence of an extended, long-acting force of the ambient coronal medium. At present, the nature of this force is in dispute: there has appeared no definitive test to distinguish whether magnetic field gradients control the event, or if the field is a more-or-less equal participant in the ejection process. In fact, within the broad spectrum of types of ejection events – loops, amorphous blobs, etc. – there may be present an equally broad spectrum of participation of the magnetic field, or, indeed, other driving mechanisms such as wave pressure. To assess more quantitatively the role of magnetic forces requires additional future observations and interpretation of spatially resolved metric radio bursts, simultaneously with the density profiles obtainable from coronagraphs. Hopefully, these observations will illuminate the role of acceleration of electrons (and protons) in and around the mass ejection, and thus clarify, for example, if the gyrosynchrotron process is the cause for the metric radio emission and the process (stochastic acceleration by turbulent shocks?) or processes by which protons may be accelerated, and later appear near Earth.

Clearly, our present knowledge of the interplanetary passage of transients is rudimentary. Near-solar observational searches may prove fruitful in searching for evidence of the hypothetical processes outlined in the previous section. Particularly, Faraday rotation observations promise to be of great aid, if these can be obtained at the same times as outer coronal imagery: Levy *et al.* (1969), Schatten (1970), Pinter (1973) and, more recently, Bird *et al.* (1977) have presented evidence for the presence of Faraday rotation 'transient' events, where significant variations are observed, over time scales of hours, in the line-of-sight integral of electron density and transverse magnetic field to which Faraday rotation measurements are sensitive. It is a yet unproved supposition that such events are, in fact, the same as white light coronal transients – direct observations of a white light event, followed by the more outer coronal sensing of the Faraday rotation variation, are thus needed to verify the association. Since the white light observations provide an estimate of the geometry and electron density for the event, the Faraday rotation measurement may be interpreted more directly than usual, and the magnetic field component determined.

Radio scintillation measurements have, for the most part, proved to be a disappointment in so far as transient information is concerned, due principally to the limited temporal and angular coverage brought about by the paucity of suitable radio sources, and also as a result of the low signal:noise present in the observations of a single event. Sime (1976) has reported the tentative observation of several 'transient' events with the scintillation technique: this results show that one potential benefit from the technique is the assessment of the three-dimensional extent of the event, if suitable radio sources are available. Sime was able to deduce the volume of influence for several events during 1973 – before the Skylab period – despite the low signal:noise ratio of the observations.

In developing a picture of the passage of transients through the interplanetary medium, measurements of the density distribution far from the solar surface will be of great use. Such measurements, possible with phase-lag techniques (see, for example, Edenhofer *et al.* 1977), could show the expansion of the density structure of the transient event through the outer corona, where observations with coronagraphs are impractical. The combination of phase-lag and Faraday rotation measurements present on Helios 1 and Helios 2 provided a powerful tool for the examination of the near-solar state of transient ejecta, if such ejecta could have been identified with solar coronal imagery.

In sum, a number of interplanetary experiments are well suited to examine the nature of the interplanetary passage of transient phenomena, but as yet, these experiments have not been in operation at the same time as coronagraphic observations of the Sun. It can be hoped that by the time of the approaching solar maximum period, and after, this situation will not occur.

Much of the work concerning transient phenomena has resulted from the efforts of colleagues at the High Altitude Observatory: R. H. Munro, E. Hildner, A. I. Poland and, in the past, J. T. Gosling. A number of the ideas expressed herein are a result of discussions with the above colleagues and T. Holzer, D. Sime and A. J. Hundhausen; in addition, the author thanks T. Holzer for his comments concerning the manuscript.

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

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