MHD ASPECTS OF CORONAL TRANSIENTS

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1. INTRODUCTION

If one defines coronal transients as events which occur in the solar corona on rapid time scales ($\lesssim$ several hours) then one would have to include a large variety of solar phenomena: flares, sprays, erupting prominences, X-ray transients, white light transients, etc. Here we shall focus our attention on the latter two phenomena; solar flares have been discussed at great length in a recent Skylab workshop and IAU Colloqium No. 44 was devoted to the study of prominences. Coronal transients, in the narrower sense, were first seen with the instruments on board of Skylab, both in the optical and the X-ray part of the spectrum.

The X-ray observations in the range between 2 and 50 Å were described by Webb et al. (1976) and Rust and Webb (1977). They report a total number of 156 observed X-ray enhancements. Their general behaviour can be summarized as follows: most of them have loop-like structures with lengths between 50 000 and 500 000 km and an average diameter of 15 000 km. They last between 3 and 40 hours. The loops expand initially with velocities up to 50 km/s but slow down rapidly to 1-10 km/s. The estimated temperatures lie in range from 2 to 5×10^6K, the densities between 10^9 and 10^{10} cm^{-3}. The events which occur away from active regions are very often associated with the disappearance of an H_α filament. Their total thermal energy content is of the order of 10^{29} erg.

The white light coronal transients were first reported by Gosling et al. (1974). Detailed studies of many different aspects of these transients were performed and a good summary can be found in the paper by Hildner (1977). Due to the instrumental design of the coronagraph the white light events could only be seen from $\sim 1.6\ R_\odot$ to $6\ R_\odot$. This of course makes it hard to establish correlations between transients and phenomena which occur near the surface of the sun, where one assumes that transients originate. Like the X-ray transients many of the white light events (115) also show loop-like structures. The tops of these loops move rapidly through the field of view whereas their legs remain

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visible for several days. The width of the loops is of the order of several tenths of $R_\odot$. The densities decrease from ~2×10^7 cm^{-3} to ~5×10^5 cm^{-3} as the transients move from 1.6 to 6 $R_\odot$. The temperatures cannot be measured directly, but it has been concluded from polarization measurements that most of the material must be at temperatures higher than 10 000 K. The velocities are in the range 100 to 800 km/s, which is much higher than those of the X-ray transients; typical velocity curves are shown in fig. 1.

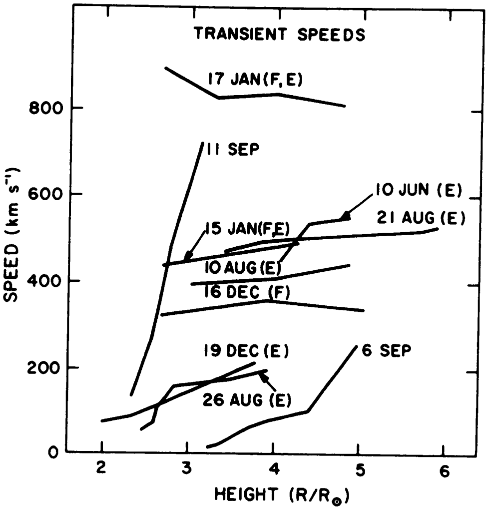


Fig. 1. Speeds of loop transients' leading edge versus height. Uncertainties in the velocity measurements range from ±50 km s^{-1} to ±100 km s^{-1}. All but the January 1974 events occurred in 1973. The letter *E* or *F* indicates that the ejection was associated with an eruptive prominence or flare, respectively. See Hildner (1977).

Most of the transients show little or no acceleration during their passage through the field of view. The energies associated with these motions are between 2×10^{30} erg and 7×10^{31} erg, and masses between 10^{15} g and 2×10^{16}g are ejected.

Rust and Hildner (1976) describe an event (13 Aug., 1973) for which both X-ray and white light data were available. Fig. 2 shows the relative positions of the loop structures, fig. 3 the temporal evolution. It should be noted that for this particular event accelerating X-ray structures are observed, whereas in general X-ray loops show a deceleration. Unfortunately there is a large data gap between 1.4 $R_\odot$ and 3.8 $R_\odot$. Therefore we cannot be absolutely sure that white light and X-ray event are identical. The masses estimated for both are comparable which speaks in favour of the interpretation that they are identical structures.

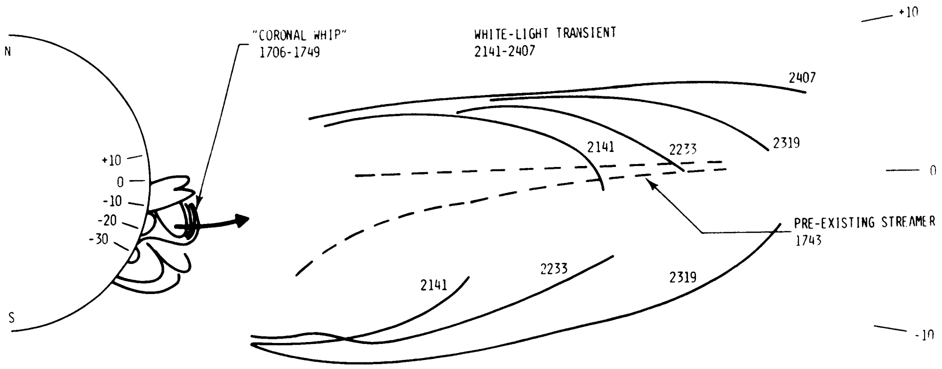


Fig. 2. Composite drawing of the mass ejection as deduced from the X-ray photographs and white light images. Heavy lines indicate the edges of the white light transient at the times indicated.

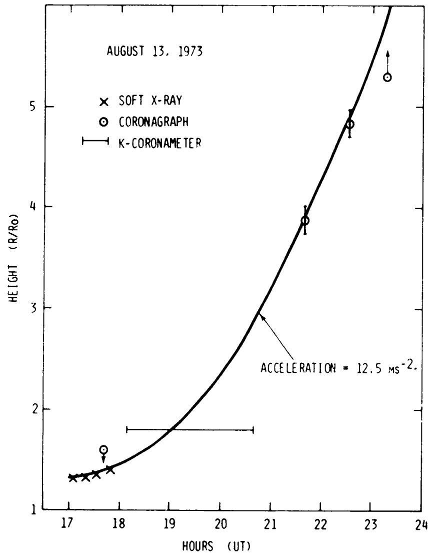


Fig. 3. Height vs time plot showing progress of the expanding X-ray arch in the inner corona and of the leading edge of the white light bubble in the outer corona. A curve for constant outward acceleration at 12.5 m s^{-2} appears to fit the points well; however, other curves with slightly different assumed start times could describe the event, too.

In order to understand the dynamics of coronal transients it is necessary to obtain information on the strength and configuration of the magnetic field in the corona. This information, however, is very indirect and the values derived are based on many assumptions. Dulk and McLean (1978) gave a review on the fields estimated in the corona, fig. 4. This diagram represents a composite of all kinds of different field estimates and shows a large scatter. For a radius of 1.1 $R_\odot$ e.g. one may deduce a field of 5 to 20 G.

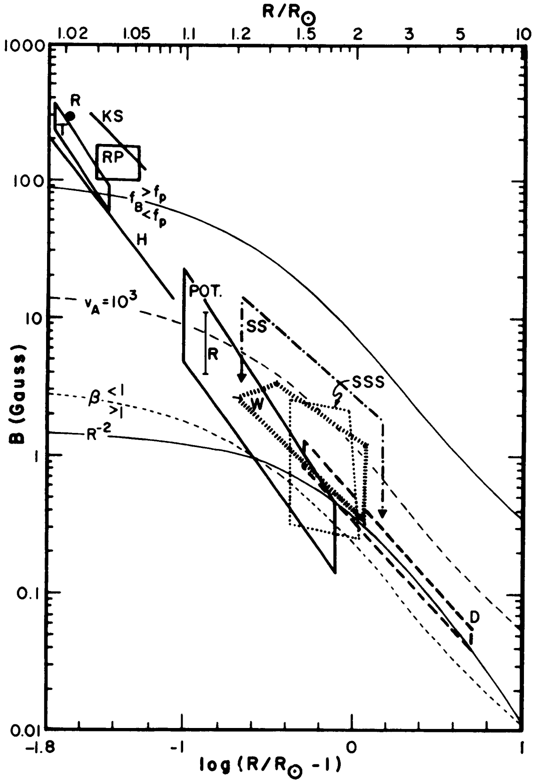


Fig. 4. Magnetic field strength vs height above active regions. A coronal density model twice that given by Newkirk (1967) or Saito (1970) for the equatorial corona at sunspot minimum has been assumed. (This assumption affects only the positions of boxes 'SS', 'SSS' and 'W', and the curves for $f_B = f_p$, $v_A = 10^3$ km s^{-1} and $\beta = 1$.) The various lines and boxes are identified in the text.

Dulk et al. (1976) and Gergely et al. (1979) derived estimates for individual transients. These are again very model-dependent. Dulk et al. found B = 3G at 1.8 $R_\odot$ and < 1G at 3 $R_\odot$, Gergely et al. give B ~2-4.5G at 2 $R_\odot$. The resulting magnetic pressure at 2 $R_\odot$, is of the order of 1 dyn/cm^2, whereas the gas pressure is less than 5x10^{-3} dyn/cm^2. This shows clearly that magnetic forces have to be taken into account in theoretical models.

2. THEORETICAL MODELS

The existing models can be devided into two groups. Models of the first group describe transients as single structures which move through the corona, the surrounding corona only providing the driving magnetic field, other interactions between corona and transient are not considered. The other approach is to assume that coronal transients are perturbations of a stationary corona caused by rapid changes at the lower boundary (i.e. the solar chromosphere). Models with gas pressure, temperature and magnetic pressure pulses are studied.

2.1 Models with single structures

Calculations based on the assumption that a transient is a large loop were presented by Mouschovias and Poland (1978). They started from the observation that loop-like transients show no (or only very small) acceleration during their passage through the field of view. They took a constant velocity which in their model implies that the magnetic forces exactly balance gravity. They used a helical field inside the transient. To avoid pinch instabilities of their configurations, they assumed that the ratio of the azimuthal to the longitudinal field is less than 1.4. On the other hand this ratio must be larger than unity to produce an outward force. Under the assumption that this ratio is constant in time they were able to deduce the evolution of the loop. They found that both the width of the loop and it's radius of curvature are proportional to the distance of the transient from the center of the sun. These results are in agreement with the observations made for the transient of 10 Aug., 1973, (see fig. 5). The results are not too conclusive when one takes into account the large error bars of the measurements. Another weakness of this paper is that it only considers the magnetic field inside the transient, leaving the surrounding field completely unspecified. But, of course, this field has eventually to provide all the driving.

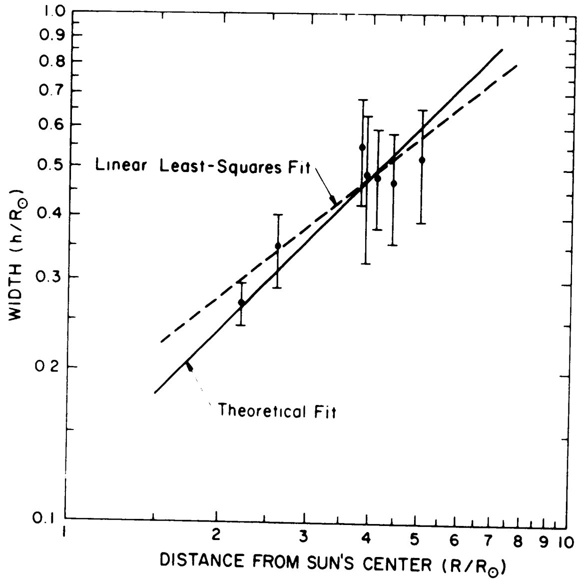
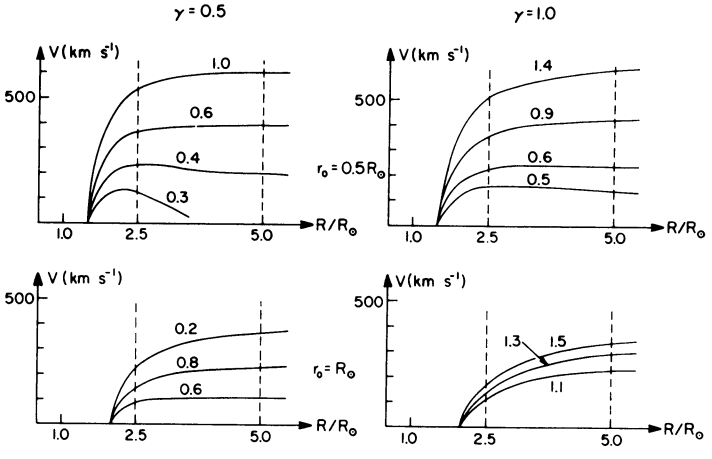


FIG 5.—The measured width (h) of the top portion of the 1973 August 10 loop transient as a function of distance (R) from the Sun's center. The linear least-squares fit (*dashed line*) has a slope of 0.8. The theoretical curve (*solid line*) has a slope of 1.

Anzer (1978) has addressed the question as to whether magnetic fields of the magnitude observed in the corona can accelerate and propel loop transients into interplanetary space with the observed velocities.

He used a very simple model where the transient is a current ring. Then the magnetic force is just the one which this ring current excerts on itself. Because the corona is a very good conductor the magnetic flux through the ring will be conserved. This then allows one to calculate the driving force acting on the loop and the resulting acceleration. Velocity curves for this model are shown in fig. 6. The different curves are for different initial radii and modifications of the circular geometry. The intention of this model was to demonstrate that coronal loop transients can be driven magnetically and should not be taken as an exact representation of the field configuration around loop transients. The main question which is still unanswered is whether initial field configurations of the type used here can be generated in the solar atmosphere. One possibility which one could imagine is that inside a loop with a longitudinal magnetic field currents are induced by rapid rotation of the foot points. This would lead to a situation similar to the one discussed above.



(a) (b)

Fig. 6. Calculated speed versus height curves. (a) gives the results for $\gamma = 0.5$ and two different values of r_0. Each curve is labelled with its value of the parameter a. (b) same as (a) except $\gamma = 1.0$.

Van Tend (1979) extended this model to describe the onset of transients. He considers the equilibrium case where the force on the ring current balances the gravity of the loop. Calculating the equilibria for different distances, R, of the loop from the sun's center he finds a range $R_1 < R < R_2$ for which the equilibrium is unstable. This instability then is assumed to initiate the transient. The results should not be taken too literally because the original model for the driving of transients is very crude, as mentioned earlier. Therefore, it is not clear how realistic a stability analysis of such configurations is (e.g. this sort of equilibrium will only hold near the top of the loop; the geometry of the loop could change as it evolves slowly, etc.).

Pneuman (1978, 1979) has developed a different model for transients. His idea is that transients originate from the closed upper parts of a helmet streamer and that they are propelled outward by forces associated with erupting prominences. The model is shown in fig. 7. Pneuman considers both loop configurations and arcades. He derived equations of motions for the radial distance of the transient, S, and for its thickness, D. His calculations are limited to the motion of the top of the transient. He assumes that D is small compared to S and that the gas pressure can be neglected everywhere. The magnetic field above the transient is set to zero. Taking flux conservation

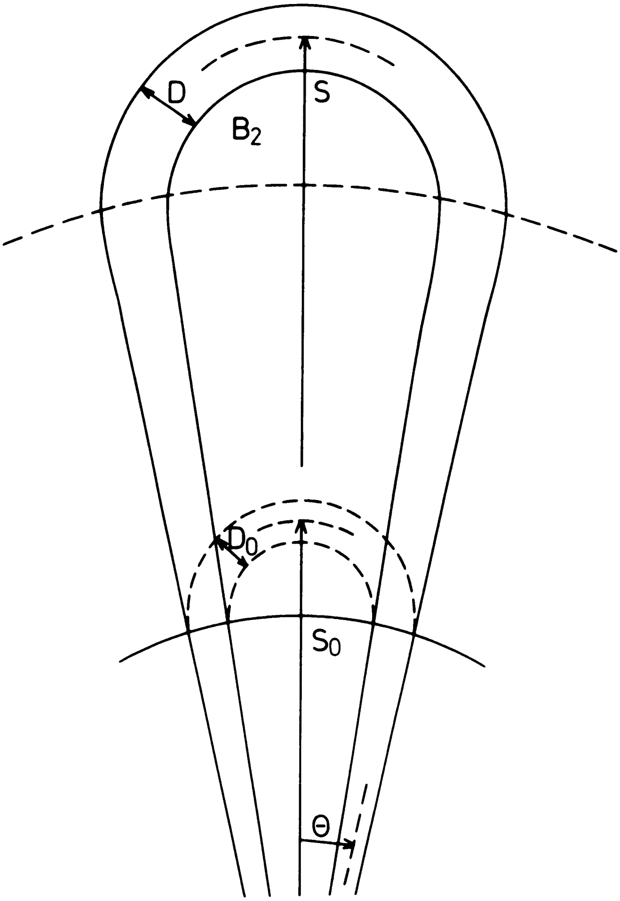


Fig. 7. Schematic of the idealized transient geometry. The dashed curves denote the boundary of the fluxtube in its equilibrium position with width D_0 and with its top at a distance S_0 from the solar center. The solid curves show the tube at some later time with width D and displacement S. B_2 is the driving field behind the transient and θ is the half-angle between the legs.

inside the transient and underneath it into account, one arrives at the following equations of motion:

$$\frac{d^2S}{dt^2} = \frac{B_{2o}^2}{8\pi\rho_o D_o}\left(\frac{S_o}{S}\right)^2 - \frac{D_o B_o^2(1+\tan\theta)}{4\pi\rho_o DS\tan\theta} - \frac{GM_\odot}{S^2} \qquad (1)$$

(arcade)

$$\frac{d^2D}{dt^2} = -\frac{B_{2o}^2}{4\pi\rho_o D_o}\left(\frac{S_o}{S}\right)^2 + \frac{D_o B_o^2}{2\pi\rho_o D^2} \qquad (2)$$

$$\frac{d^2S}{dt^2} = \frac{B_{2o}^2 D}{8\pi\rho_o D_o^2}\left(\frac{S_o}{S}\right)^3 - \frac{D_o^2 B_o^2(1+\tan\theta)}{4\pi\rho_o S_o D^2\tan\theta} - \frac{GM_\odot}{S^2} \qquad (3)$$

(loop)

$$\frac{d^2D}{dt^2} = -\frac{B_{2o}^2 D}{4\pi\rho_o D_o^2}\left(\frac{S_o}{S}\right)^3 + \frac{D_o^2 B_o^2 S}{2\pi\rho_o S_o D^3} \qquad (4)$$

Equilibrium solutions then can be found by setting the left hand sides of these equations equal to zero. Pneuman started from the following equilibrium values: B_o= 5G, B_{2o}= 7G, n_o= 10^9 cm^{-3}, S_o= 1.2 $R_\odot$ and D_o= 0.24 $R_\odot$. The assumed initial density seems rather high. At 2 $R_\odot$ this expanding loop would have a density of ~ $2x10^8$ cm^{-3}, whereas estimates of white light loops at 2 $R_\odot$ give ~ $2x10^7$ cm^{-3}. But if one lowers the initial density one can still obtain similar models by simply scaling the magnetic field correspondingly.

The eruption of a prominence then was simulated by a rapid increase of the supporting field (e.g. from 7 to 8 G in the model presented). The numerical calculations show a rapid acceleration of the transient and an almost constant velocity at large distances; between 2 and 6 $R_\odot$ the velocity increases from 500 to 750 km/s for a loop and from 300 to 400 km/s for an arcade. The thickness D shows some oscillations in the beginning but then approaches a linear increase with S. If one switches on the driving field more gradually then these oscillations are reduced.

The model is intended to describe a transient as being the response of the corona to an erupting prominence, but the assumption that initially the field underlying the loop is increased everywhere by a constant amount and that the resulting flux through this area is then conserved would better describe a situation where transients are driven by emerging photospheric flux.

An extension of this model by Pneuman and Anzer in which both dynamics of the prominence and driving by magnetic flux added through reconnection are considered is in progress. G. Pneuman will report on some aspects of this model during this conference.

2.2 Continuum models

Dryer, Han, Nakagawa, Steinolfson, Tandberg-Hanssen, Wilson and Wu have published a series of papers (e.g. Nakagawa et al. 1975, Steinolfson and Nakagawa 1976, Wu et al. 1978, Steinolfson et al. 1978, Dryer et al. 1979) in which they try to explain coronal transients as the response of the corona to a rapid pressure pulse at its base. Since their earlier models were purely gas dynamical and since there is strong observational evidence that transients are magnetically controlled, we can leave these models out of our discussion and concentrate here on their magnetohydrodynamical models.

The papers by Wu et al. (1978) and Steinolfson et al. (1978) should be considered as preliminary studies. In both of them the numerical computations are carried only to $R < 2\ R_\odot$ whereas reliable data for white light transients were obtained for $R \gtrsim 2\ R_\odot$. Since these two papers are very similar we shall discuss them together. Wu et al. study the evolution of structures which lie in the solar equatorial plane (an assumption which does not apply to most white light transients). They start from initial configurations where the corona is in isothermal hydrostatic equilibrium with $T_o = 1.5 \times 10^6$K and $n_o = 2.7 \times 10^8$ cm^{-3} at the base. They take two types of potential magnetic field configurations: a) open fields and b) closed fields. The notion "open" here only means that no field line closes within the region where the numerical computations were performed, but the field lines do not go to infinity. It should be also mentioned that in this case no line of polarity reversal ("neutral line") occurs. Steinolfson et al. investigate structures which lie in meridional planes. Their initial corona is described by a polytrope with $\gamma = 1.2$; the values at the base are $T_o = 1.5 \times 10^6$K and $n_o = 3 \times 10^8$ cm^{-3}. Again both open and closed potential magnetic field structures are considered (fig. 8). The values of the magnetic field

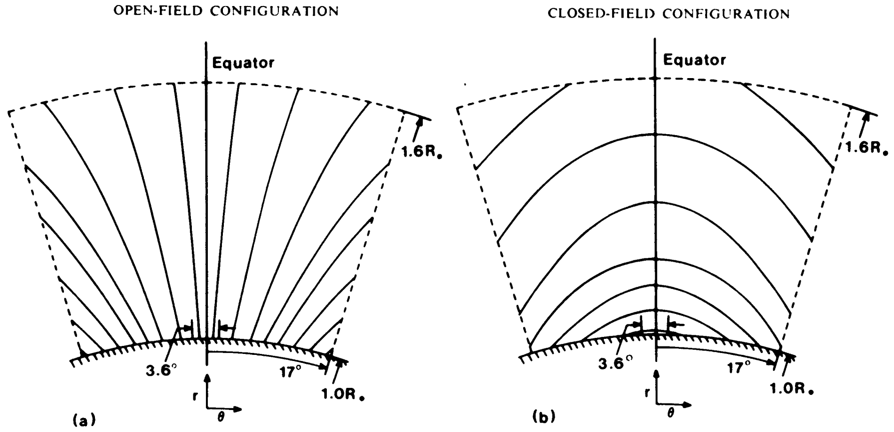


FIG. 8.—Schematic diagrams of open and closed magnetic field configurations in the meridional plane. The solar event is assumed to occur near the equator.

are chosen such that, at some reference point at the base either $\beta = 1$ or $\beta = 0.1$ holds ($\beta = p_{gas}/p_{magn}$). All these models are very special. The Lorentz force ($j \times B$) is set equal to zero and therefore the corona must be in hydrostatic equilibrium. However, if one allows for variations of the pressure (or density) at the base then one should find deformations of the magnetic field such that they can balance the pressure gradients.

In the models by Wu et al. the transient is initiated by a sudden temperature increase from T_o to 1.5×10^7K which lasts for 5s occuring at the base of the corona in a region of 40 000 km x 170 000 km. This produces a strong pressure pulse. Steinolfson et al. generate a similar pressure pulse by increasing both temperature and density ($T = 4.2 \times T_o$ and $n = 1.2 \times n_o$), but they assume that the pulse lasts much longer (5 min), and their area is only 40 000 km x 40 000 km. The perturbations of the solar atmosphere resulting from these pulses then are calculated numerically. An adiabatic index of $\gamma = 1.2$ is used for all models. In the case of open magnetic fields Wu et al. find that the contact surface between hot plasma and normal coronal plasma moves with velocities ~ 150 km/s whereas the MHD shock ahead of this piston has a velocity of 400 km/s. In the models by Steinolfson et al. the velocities of the leading edge (contact surface) are 290 km/s ($\beta = 1$) and 470 km/s ($\beta = 0.1$) for open configurations. No values for the shock velocity are given.

The authors also find that, for closed configurations the hot driving material cannot leave the solar atmosphere (a maximum height of 36 000 km is reached for $\beta = 1$), the closed magnetic field preventing the plasma from moving out into interplanetary space. Therefore these models with closed fields cannot produce transients. Wu et al. state that their numerical calculations show the occurrance of shocks, but the curves presented show no indication of discontinuities in density or velocity. Gradients of the same magnitude as at the "shocks" occur elsewhere in these curves as well. From their figures it is not clear how well-defined the "shocks" actually are. It is stated that the smearing out is due to the coarse grid (mesh size $\approx 2 \times 10^4$km). Steinolfson et al. have used a finer grid (7×10^3km). Unfortunately, they have not plotted any density curves which would allow one to test the interpretation given above.

Another point which is open to discussion is the use of an adiabatic index of $\gamma = 1.2$. Although a polytrope with $\gamma = 1.2$ might be perfectly adequate to describe the initial equilibrium, one should not automatically use the same γ for the adiabatic index of the perturbations. Since it was found that radiative losses can be neglected one would expect $\gamma = 5/3$, if thermal conduction is unimportant. The authors argue that including the effects of thermal conduction would reduce the value of γ. That this is not true in general can be seen from a consideration of the hot material which is ejected. Thermal conduction would tend to cool this material. Since this gas expands, it will also experience adiabatic cooling which is larger for $\gamma = 5/3$ than for $\gamma = 1.2$.

Therefore, in this case taking $\gamma < 5/3$ is a step in the wrong direction, at least for the simulations of the hot ejected gas. Steinolfson et al. concluded from their test calculation ($\gamma = 5/3$) that changes in γ cause only small effects. This interpretation should be taken with some caution because the calculations only cover a period of 10 min, twice the duration of the heating pulse. These early phases of the coronal perturbations will be mainly determined by the driving pulse whereas, during later phases the effects due to adiabatic expansion will develop. How big these effects are should be determined by numerical calculations which cover a sufficiently long period.

In the paper by Dryer et al. (1979), an attempt was made to compare extended calculations (up to 10 $R_\odot$) with observations obtained for the transient of 21 Aug., 1973. This transient was associated with a flare for which temperature and density curves were obtained from X-ray observations (e.g. $T_{max} = 1.4 \times 10^7$K and $n_{max} = 10^9$ cm^{-3}). The equilibrium values for the model were chosen as $T_o = 2 \times 10^6$K and $n_o = 5 \times 10^7$ cm^{-3}, γ was set to 1.08. An open field configuration was taken, and the cases $\beta = 0.1$ and $\beta = 1$ were considered. The models were rotationally symmetric. Fig. 9 shows the position of the shock front and the location of the strongest density increases. Note that if one takes the size of the occulting disk (1.6 $R_\odot$) into account, then the similarity between this pricture and white light photographs becomes less pronounced.

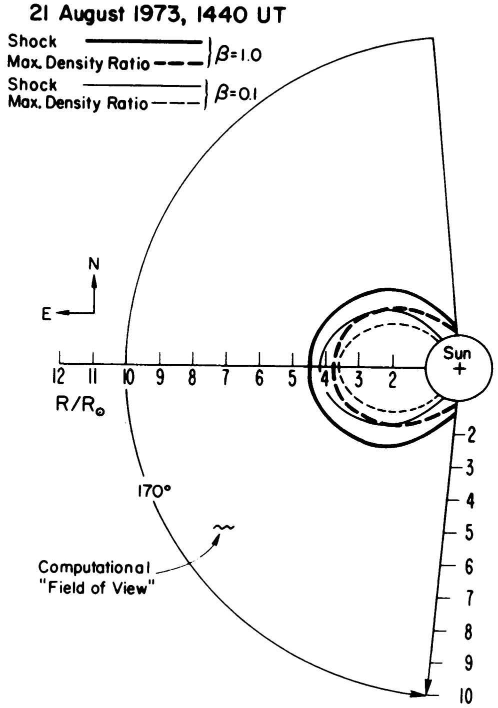


FIG. 9.—Simulated shock and maximum-density ratio positions at t = 1440 UT for β = 1.0 and β = 0.1.

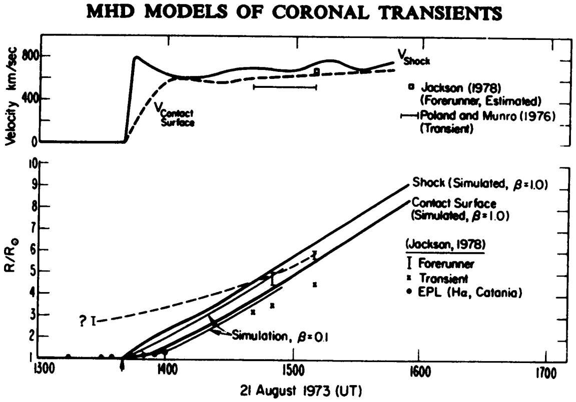


FIG. 10.—Comparison (along the axis of symmetry) of the simulated shock and contact surface trajectories and velocities with the observed Hα eruptive prominence and coronal white-light transient and forerunner. The arrow at 1340 UT marks the moment of the simulated flare initiation.

Fig. 10 shows the motion of the transient. The calculated contours of excess density have a loop-like structure, but for $\beta = 1$, most of the mass remains concentrated in the legs of the loop. Only for $\beta = 0.1$ is a sizeable fraction of the total mass in the top of the loop moving outward. It seems, therefore, that low β models would describe the evolution of transients better.

The total mass of the transient derived from this model amounts to 2.3×10^{16}g which is at least a factor 3 larger than the observed mass. This large excess mass could cause a problem. The initial configuration considered here had very low density (5×10^{7} cm^{-3} at the base). Taking more realistic densities would raise all mass estimates in the model and thus might lead to contradictions with the observations.

The main conclusion one must draw from these papers is that transients can only occur in regions of open fields. This assumption should be checked with the observations. If it is correct one should also include the motion of the solar wind which exists along open field lines and has a velocity which is comparable to that of transients. A point which speaks against these open field models is the lack of a "neutral line", because observations indicate that transients are associated with such lines of polarity reversal.

Another question is how good the assumption of azimuthal symmetry actually is. The authors assume that the line of sight depth of the transient is comparable to its width ($\sim 0.2\ R_\odot$ at $2\ R_\odot$). In this case the azimuthal extent is only 6°. Therefore the variations in the ϕ-direction will be as large as the ones in the other directions - in contradiction to the assumed symmetry. The effects of different values of γ should also be studied carefully. It is not sufficient to compare the very early phases ($t < 10$ min) of models with different γ and then extrapolate to $t \gtrsim$ several hours.

Finally, the interpretation of the observed fore-runners as being the calculated shocks seems to be a misinterpretation. These fore-runners rise very gradually out of the coronal background - it is even hard to define the outer edge of the fore-runners. On the other hand, shock fronts are associated with sharp density discontinuities which should also be observable.

3. CONCLUSION

Our understanding of coronal transients is still very fragmentary. The most serious limitation at present seems to me to be the fact that white light observations are confined to regions which are more than 1.6 $R_\odot$ from the sun's center. As a consequence of this, the cause of these transients is still an open question. The two candidates which have been discussed so far are flares and erupting prominences. One difficulty for the interpretation is that transients can be observed only if they lie close to the plane of the sky whereas many surface events are predominantly studied inside the solar disk. This could lead to a bias if one tried to find statistical correlations. It would favour the association of transients with limb phenomena. As far as the investigations of structures go one has to realize that the transients are optically thin and therefore that the observed intensities are always integrated over the whole line of sight. One can obtain only indirect estimates of the thickness of transients in the line of sight. Another important requirement is a knowledge of the coronal magnetic fields both prior to transients and during their occurance. Most theoretical models are based on magnetic fields, but little is known observationally.

The main difficulty which the theoretical models face is that the transients are 3-dimensional structures. 2-dimensional MHD-models may provide some insight into the basic mechanisms which drive transients, but it is not clear how close to reality these models actually are. On the other hand 3-dimensional MHD calculations are beyond the scope of any present investigation. For this reason modelling attempts based on discrete structures seem more promising. But since such models will be very idealized, it will be necessary to discuss thoroughly all omissions and their possible consequences.

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DISCUSSION

Petelski: Regarding the acceleration of particles by the magnetic field of a ring current, is that to be understood in analogy to the mirror effect in an inhomogeneous magnetic field whereby transverse kinetic energy is transformed into longitudinal energy?

Anzer: The model is purely MHD, with no calculation of individual particle motion.

Low: I concur with your criticism of models in which the flux tube has no external fields. The point is best illustrated by theoretical models of prominence where one finds that the Lorentz force acting on the prominence supporting its weight is due to the interaction between the internal field and the external (usually uniform) field. In the absence of external fields, there can be no net Lorentz force on the coronal transient flux tube.

Anzer: I agree.

Dryer: Your constructive comments regarding our model are appreciated. I would like to reply to several of them at this time: (i) Concerning the ejected mass estimate of Dryer et al. (for the 21 August 1973 event) of 2.3 x 10^{16} g... as compared to an observed mass ejecta which was less than a factor of 1/3 this number... please keep in mind that the simulated figure is based on a guess regarding the transient's thickness perpendicular to the planar plane of computation. Also, the observed esimate is made in a field of view above the $2R_{\odot}$ occulting disk. Hence variations by factors of 3 or so are not surprising. (ii) We have long recognized the eventual need for 3-D studies and are progressing toward that goal. (iii) Concerning our suggestion for identifying the leading edge of the white light forerunner with the shock, it is important to recall that the small density change indicated by the former is consistent with density jumps across weak shocks.

Anzer: (i) Your mass estimates were based on the assumption that the perpendicular thickness is the same as the width of the loop structure. I would be very surprised if these structures were much narrower in the perpendicular direction than in the radial direction. (iii) These shocks, then, must be very weak.

McLean: I would like to suggest that it is not possible on the basis of white-light observations to exclude the possibility that forerunners are shock fronts. If we envisage a spherical shock surface with a gradual density rise behind the discontinuity, then the two-dimensional density distribution, integrated along the line of sight, would be similar to that observed.

Anzer: If your interpretation is correct then forerunners are basically gradual density increases in front of a transient which may or may not have a shock in front of them.

Newkirk: It appears that neither of the theoretical interpretations of the mechanism driving coronal transients is satisfactory. With no recognizable distinction in morphology or other property, these events range in velocity over an order of magnitude and in kinetic energy over two orders of magnitude. This would suggest that a single mechanism provides the driving energy for all these events. Yet the impulsive mechanism proposed by Nakagawa *et al.*, has difficulty in accounting for the slow events, and the MHD models require that magnetic energy be continuously added as long as the transient continues to rise.

I have no specific model to propose; but it would appear that we are dealing with a response of the corona to a readjustment of the magnetic field in which photospheric motions have stored energy in the coronal field which then relaxes.

Anzer: The MHD models I discussed do not require a continuous energy input. They all are based on an initial increase in magnetic flux and evolutions which then conserve the flux. All these models also use some kind of instability for driving either flares or erupting prominences.