MODELING OF TRANSIENT DISTURBANCES IN CORONAL-STREAMER CONFIGURATIONS

R. S. Steinolfson
Department of Physics
University of California
Irvine, California 92717

ABSTRACT

Numerical simulations of the formation and propagation of mass-ejection, loop transients in coronal streamers are discussed. The simulations of the streamer configuration and the subsequent transient are accomplished with numerical solutions of the single-fluid, ideal MHD equations of motion in the meridional plane. The streamer is produced by simulating the relaxation of an initially radial hydrodynamic flow coupled with a dipole magnetic field. The simulated transient then results from an energy release at the base of the streamer. The "legs" of the loop transient thus produced remain essentially stationary while the loop expands mainly in the radial direction with velocities of 400 - 750 km s^{-1} (determined by the magnitude of the energy release). Once the leading-edge of the transient has passed out of the lower corona, the initial streamer configuration is restored after 15 - 24 hours. A second energy release two hours later than, and with an energy release identical to, the first does not produce a significant coronal disturbance.

Introduction

The coronal response to a solar event is determined to a large extent by the magnetic-field configuration and magnitude, the thermodynamics, and the velocity of the pre-event corona. The role of the ambient magnetic field has been demonstrated (Steinolfson et al. 1978) by simulating the considerably different transients in open as opposed to closed magnetic-field configurations. However, that study, as well as the majority of other multi-dimensional numerical studies of transient formation and propagation in the lower corona, is for a hydrostatic atmosphere. A trivial extension to an ambient nonstationary corona was made by Wu et al.(1981), who considered radial flow in a radial magnetic field. In that particular study the role of the magnetic field was more passive than active.

A model for the propagation of transients through coronal-streamer configurations has been developed in a series of papers by Steinolfson et al. (1982) and Steinolfson (1982a), henceforth referred to as Papers I and II, respectively. Coronal streamers consist of open field lines, with field-aligned flow, overlying closed field lines near the solar surface in which the atmosphere is in hydrostatic equilibrium. The solar event responsible for the transient occurs at the base of the closed-field region. This model is attractive from an observational viewpoint since transients can often be associated with eruptive prominences (with or without flares, Munro et al. (1979)) which, in turn, are believed to lie over neutral lines - lines along which the vertical photospheric magnetic field reverses sign. The present paper contains a brief description of the model and the characteristic transients that it produces in streamers, as well as studies involving the coronal relaxation following the transient.

Simulation Procedure and Relevant Parameters

The ambient coronal streamer and the subsequent transient are simulated in the meridional plane with numerical solutions of the time-dependent, dissipationless (except at shock waves), magnetohydrodynamic equations of motion. The equations, the method of numerical solution, the appropriate boundary and symmetry conditions, and details of simulating the solar event are given in Papers I and II.

The entire simulation consists of two separate simulations; one for the streamer and an independent one, which uses the computed streamer as the initial state, for the transient. The streamer is obtained by allowing the corona to relax from a nonequilibrium state following the procedure in Paper I, which is reviewed in these proceedings by Suess (1983). The transient is then produced by simulating a solar event, located at the center of the base of the closed-field region, with an increase in the thermal pressure.

The most important parameters are the plasma beta β, which is referenced to the center of the base of the closed-field region in the pre-streamer corona, and the magnitude and duration of the pressure increase. For the results discussed here, the energy input was maintained for 1 hr. in all cases. The other parameters are discussed along with the separate simulations. Parametric studies involving several parameters are presented in Paper II.

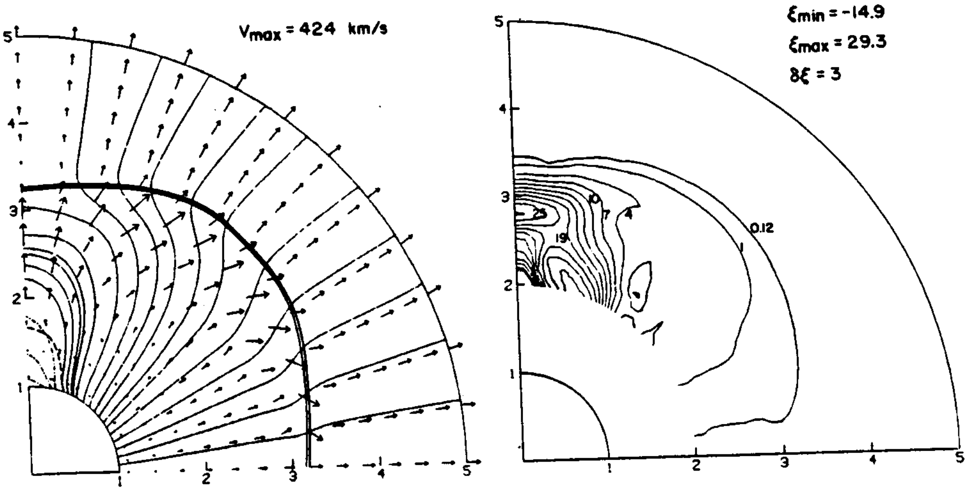
Numerical Results

As mentioned previously, all of the transient simulations presented here are initiated in an ambient coronal-streamer configuration. A typical streamer is shown later [Figure 3(b)] where it is compared to the corona after it has relaxed following the passage of a transient through it.

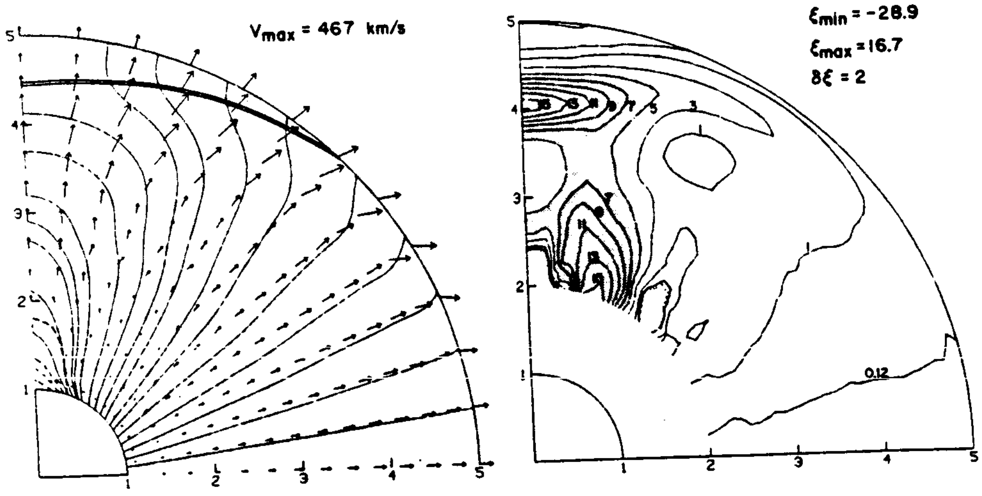
A representative coronal response to a solar event at the base of the streamer is shown at two times (referenced to the start of the solar event) in Figure 1. The vertical axis is the equator, the horizontal axis is the pole, and the axes are labelled in units of solar radii. The mass-excess (the contour plot) is proportional to the mass in the transient ρ_t less the mass in the initial streamer ρ_s with the same definition as in Paper II; i.e.,

$$\xi = \frac{\rho_t - \rho_s}{\rho_r} \frac{r}{R_\odot} \sin\theta ,$$

where ρ_r is reference density (2.5×10^{-18} gm cm^{-3}), $R_\odot$ is the solar radius, and r and θ are locations in the meridional plane. The contours are only shown beyond the approximate location of the occulting disk on the Skylab coronagraph. The mass in the transient is less than that in the streamer below the lowest contour near the equator. As can be seen, the transient, as determined in terms of the largest values of the mass excess, has the shape of a radially expanding loop. The legs of the expanding loop remain essentially stationary (centered, at 2 solar radii, at approximately 20° from vertical) and subtend less than 60° in latitude. The latitudinal motion of the legs is restrained by magnetic pressure



(a) t = 60 min



(b) t = 90 min

Figure 1. Coronal response for $\beta = 0.1$ and a solar event with a pressure increase of p/p_0 (where p_0 is the initial value) = 14.3 and a density increase of $\rho/\rho_0 = 1.3$. The left figure shows the magnetic field lines, velocity vectors, and shock trajectory (represented by the parallel lines), and the right figure shows the mass-excess contours where $\delta\xi$ is the contour increment.

forces due to the larger magnetic field in the coronal hole near the pole than near the equator in a coronal streamer. This is demonstrated in Figure 2 which shows the latitudinal variation, at 2 solar radii, of β and the magnetic-field magnitude for a streamer and for a hydrostatic atmosphere with a dipole magnetic field. The much larger magnetic-field gradient for the streamer acts to constrain the transient legs.

After the transient has passed through the lower corona and the energy input due to the solar event has ended, the corona should once again relax to an equilibrium. Approximately 15 - 24 hrs. are generally required for the streamer config-

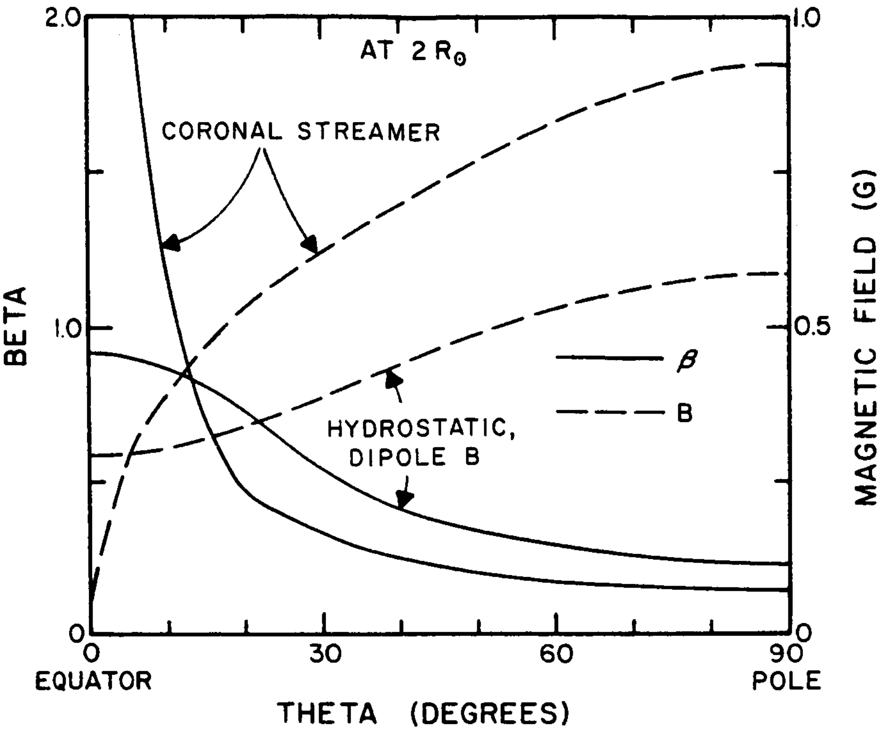


Figure 2. Latitudinal distribution of magnetic field magnitude and plasma beta at 2 solar radii for a reference value of $\beta = 0.1$, and for both a streamer configuration and a hydrostatic atmosphere.

uration to be reestablished -- depending on the parametric values and the magnitude and duration of the energy input. The corona, 16 hrs. after initiation of the energy input, is compared to the initial streamer in Figure. 3 Some slight differences still exist between the two coronae, but clearly the streamer configuration has been restored after the transient disrupted it.

Since such a relatively long period of time is required for the corona to recover following a transient, it follows that a second solar event at the same location as an earlier one may produce quite a different coronal response if sufficient time has not elapsed. Results for a simulation of such a scenario are shown in Figure 4. The simulated solar events are identical with the second initiated 2 hrs. after the start of the first. Both events last 1 hr. so the corona in Figure 4(a) is shown for the same time lapse following the first event as is the corona in Figure 4(b) following the second event. The first event produces a well-defined transient in the mass-excess contours while the second event does not produce a noticeable effect on the mass excess. In fact, the mass-excess contours in Figure 4(b) are almost identical to those that occur if the second event is not included (Steinolfson, 1982b). However, the second transient does produce a shock wave with a velocity almost identical to that produced by the first.

Comparison With Observations

One form of observational results which may be used to evaluate the physical relevance of the simulations of the previous section is the brightness images

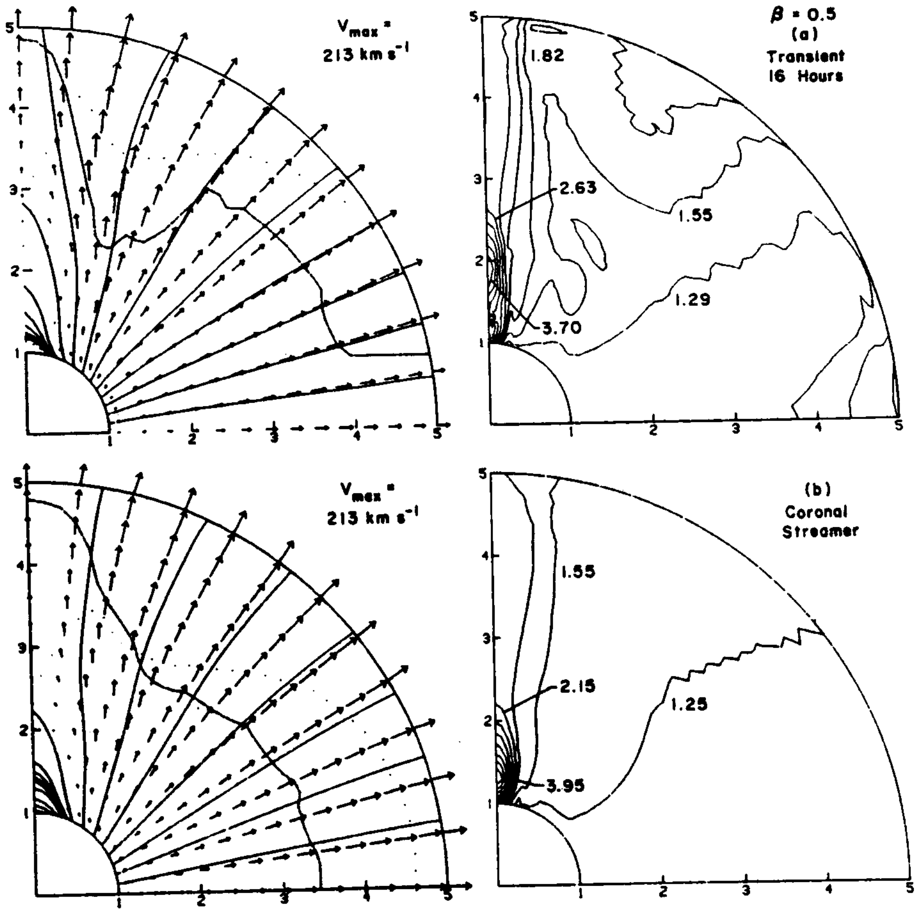


Figure 3. Coronal relaxation following a transient (a) compared with the initial streamer configuration (b). The transient was produced by a pressure increase of $p/p_0 = 10$. The right figures are pressure contours (p/p_0), and the left are magnetic field lines and velocity vectors. Note the high pressure (also high temperature and density) and low velocity in the closed-field region.

obtained with white-light coronographs. The technique for converting these observations into excess columnar density (a pre-event image subtracted from a transient image) has been described by Hildner et al. (1975). Aside from the absolute level (determined by unknown and, therefore, assumed geometric factors), these observations are directly comparable to the computed mass excess.

One characteristic feature of observed mass-ejection, loop transients is that the legs of the radially expanding loop remain stationary while the loop expands outward (Hildner, 1977). The success of this model in simulating this observation is shown in Figure 1.

Another observational result that the present model can simulate has been described by Wagner et al. (1981). They reported that a visible transient (by a white-light coronagraph) was not recorded for a flare at the same location as, but 2 hrs. later than, an earlier smaller flare which did produce an observed transient. Simulations, using the present model, of two successive flares and the resulting transients are consistent with this observation, as shown in

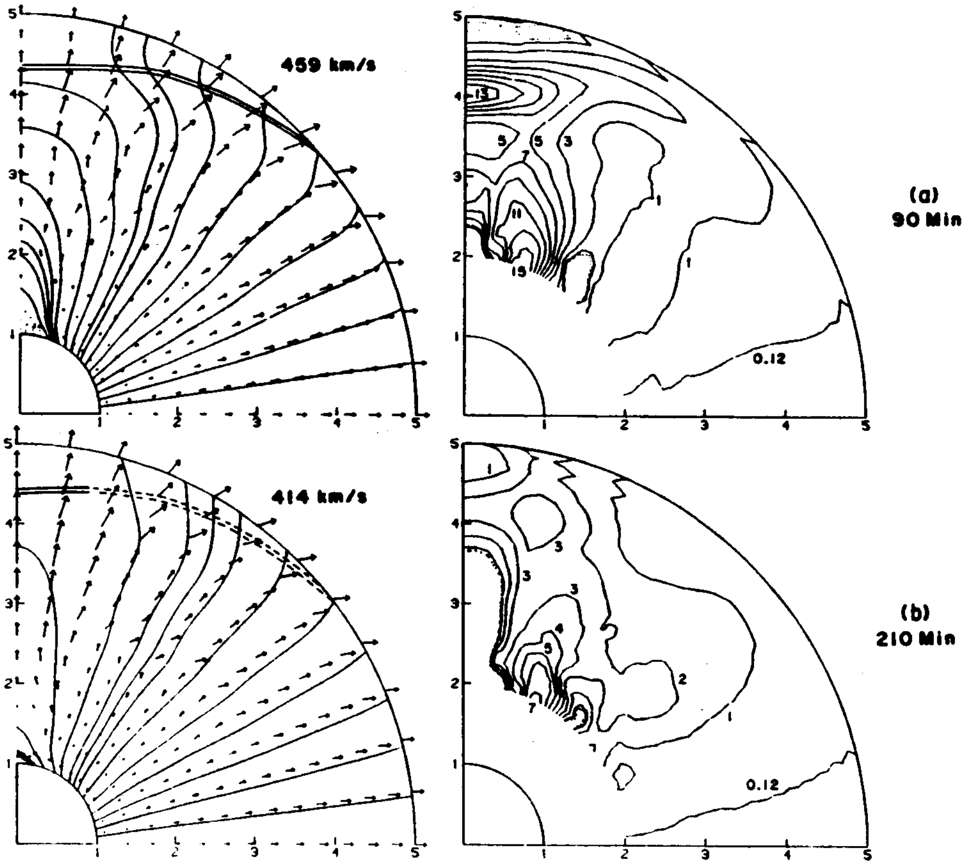


Figure 4. Coronal response to two successive solar events at the same location with the second 2 hrs. later than the first. The parameters are the same as those used for Figure 1. Mass excess contours are shown in the figures on the right.

Figure 4. The simulations also suggests that, although the second flare did not produce an effect observable in white-light coronagraphs, the fact that the second transient did contain a shock implies that it may produce observable type II or type IV radio bursts.

Conclusions

The numerical simulations discussed here demonstrate the, not unexpected, results that the state of the corona through which a transient propagates can have a large effect on the shape of the simulated transient (in terms of mass excess). The simulations also show that the larger magnetic field overlying open-field regions in streamers, as opposed to that over the closed-field region, may be responsible for constraining the latitudinal movement of the legs of the transient which gives some transients the characteristic shape of a radially-expanding loop. In addition, it is shown that approximately 15 - 24 hrs. are required for the streamer configuration to be restored after being disturbed by a transient. The above simulated results have been shown to be consistent with observations of coronal transients.

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