NUMERICAL SIMULATIONS OF SOLAR DISTURBANCES AND THEIR INTERPLANETARY CONSEQUENCES

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ABSTRACT. Responses of the solar atmosphere and interplanetary medium to simulated solar disturbances were studied by time-dependent, MHD numerical simulations. This deterministic initial-boundary value problem was attacked in the classical way: a representative steady state is first established, then input parameters at the lower near-Sun boundary are perturbed. We discuss a number of 2- and 3-dimensional examples of coronal mass ejection (CME) simulations and some current controversies concerning the basic process of CME initiation. Footpoint shearing motion is tested to see whether it can provide a reasonable mechanism for CME development from arch filament configurations.

We also demonstrate possible interplanetary consequences to CME-like disturbances by using 3-D simulations to determine the dynamic response of the solar wind to a plasmoid injection from an eruptive filament or prominence. We also discuss the separate possibility whereby a plasmoid may be generated in the interplanetary medium by a solar-generated shock that propagates through a heliospheric current sheet. Application of the 3-D model for the interpretation of interplanetary scintillation observations is also discussed.

1. INTRODUCTION

1.1 Near-Sun Activity

The origin of coronal mass ejections (CMEs) is one of the major topics currently under active debate. Observations by white-light coronagraphs led to the first ideas and models for CMEs. Coronagraph images are produced by Thomson scattering of photospheric photons by coronal electrons. In addition to the problem of CME origin, the problems of CME propagation and evolution in interplanetary space are also important topics which provide the backdrop for this paper.

A variety of phenomenological descriptions have been applied to the transient white-light images detected by coronagraphs. First OSO-7 and then Skylab, P78-1, and SMM have contributed to the observations. As observed in the solar-occulted plane of sky (Howard et al., 1985), these traveling images have been called curved fronts, spikes, bubbles, loops, blobs, etc. Some workers considered them to be more-or-less planar struc-

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tures or helical, magnetically bound loops that escaped the Sun's gravitational attraction; other workers considered them to be compressions (followed by rarefactions) in the corona, produced by near-surface energy conversion that expanded quasi-spherically. Their rate of occurrence and solar-cycle dependence are in statistical dispute, with differences (one per day vis-a-vis two per day) most likely caused by variations in coronagraph design, resolution, and duty cycle. About half of the CMEs are associated with filament eruptions (easily detected at the solar limbs); some are associated with solar flares (not easily detected near the limbs because of the awkward remote-sensing line of sight from Earth); some are associated with both of the above; and sometimes there are no optical, radio, or x-ray observations temporally and spatially associated with CMEs (Munro and Sime, 1985; Webb and Hundhausen, 1987).

Three theoretical descriptions (reviewed by Dryer, 1982) have been offered: (a) White-light "loops" are magnetically driven by stresses in the curved, moving plasma column; (b) White-light "loops," followed by depleted brightness, are quasi-spherical shells of compressed coronal plasma followed by rarefactions; these "loops" are produced by a localized, near-surface change of properties in or near active regions; (c) Very-large-scale coronal magnetic topologies become unstable and trigger CMEs in some way.

Klimchuk (1989) has discussed theoretical ideas for physical mechanisms of CME initiation. He first identifies three basic questions:

"1) What causes the disruption of the large-scale magnetic field/plasma configuration?
2) How does the system evolve once the disruption begins?
3) How does the disruption trigger solar flares?"

Klimchuk addresses the first question within the framework of quasi-static evolutionary models. The second, he suggests, "will require a fully time-dependent MHD treatment." As noted by Dryer and Wu (1985),this point has been studied extensively. The third question is "likely [he noted further] to involve non-MHD plasma processes." Neither Klimchuk nor we discuss this third question.In SECTION 2 below, we discuss a numerically demonstrated MHD treatment that, in our opinion, is relevant to both the first and second questions.

1.2 Interplanetary Activity

Several radio astronomers (Hewish and Duffett-Smith, 1987; and Hewish and Bravo, 1986) have interpreted their observations of interplanetary scintillation (IPS) to be associated with geomagnetic activity. Scintillations of distant radio galaxies' radiation are caused by density fluctuations in the intervening solar wind. These fluctuations can be used to generate maps of enhanced and depleted solar wind density. These workers (see, also, Tappin et al., 1988) introduced an ability to generate "interplanetary images" of compressed and rarified solar wind plasmas once each day.

A controversy stems from the radio interpretation of these maps when the density-enhanced regions are back-projected to the Sun. The point of ejection is (according to Hewish, 1988) within (or within a 45° circle surrounding) a coronal hole. Hewish (1988) therefore inferred that an erupting stream within a coronal hole emits very-high-momentum flux that expands into a large (~ 90°) heliolongitudinal expanse and persists for several days. This high efflux of energy, he claims, is the source of geomagnetic storms. He asserts that solar flares are peripheral events.

The alternative view, as expressed by most of the solar physics community, is that the energy influx to the interplanetary medium is due to magnetic eruptions which produce a complicated interaction of shocks, compressions, and rarefactions. The net result [suggested by the 2-D and 3-D numerical MHD simulations by Dryer, Smith, and Wu (1988)] is the high dynamic pressure and IMF amplitude, negative B_z that are required for geomagnetic activity.

A number of transient interplanetary events (often preceded by shocks) have been described by spacecraft investigators as "magnetic clouds," or "plasmoids" (see the review by Burlaga, 1989). These magnetic clouds are characterized by: (1) a rotation of the IMF polarity through a large angle during a temporal interval of about a day, (2) an IMF magnitude which is higher than average, and (3) a solar wind temperature which is lower than average. It is not known if the global topology is disconnected from the Sun (i.e., a plasmoid); if the IMF is still connected to the Sun at both ends (i.e., extension of a solar loop arcade as suggested by Gold, 1959); or if the propagating shocks introduce large-amplitude MHD waves in their wake that cause the IMF to twist, then unwind, with one end rooted in the Sun and the other in interstellar space (Dryer, Wu, and Gislason, 1983). The plasmoid and extended loop are currently attracting much attention together with the notion of twisted, nearly-force-free, IMF "flux ropes."

Another interesting observational inference (based on in situ observations) is concerned with the IMF external to the magnetic cloud. Gosling (1989) has reviewed work that suggests that IMF draping around the object occurs in the sheath region between a bow shock and the presumed boundary of the "CME." Although there is no objective criterion for identifying the boundary of a "magnetic cloud" (Burlaga, 1989), this inference is reasonable, particularly if the object (CME, magnetic cloud, etc.) moves relative to the background solar wind with a velocity greater than the local magnetosonic speed.

2. RESULTS

2.1 Shear-Induced Instability

Figure 1 shows the schematic representation of a dipole magnetic field in an initial state of equilibrium in a stratified atmosphere. A 2 ½-D (i.e., non-planar) MHD model is used to simulate the response of the exponentially stratified atmosphere to a photospheric shearing motion as indicated by the sinusoidal velocity profile in Figure 1. It was found that upward plasma flow velocities are generated in the vertical direction. The velocities grow exponentially at first, with a growth rate equal to $\sqrt{8}\,(\overline{V}_A\, a)$, where $\overline{V}_A$ is the average Alfvén speed and a^{-1} is the characteristic length scale. The growth rate is saturated by the Lorentz force, but growth continues until it reaches the same order of magnitude as the Alfvén speed. MHD instability, which we suggest may be called "shearing-induced instability" (SII), occurs shortly thereafter. Physically, the simulation suggests that the central magnetic field lines are pinched, and the outer loops stretch upward with a tendency to open. This process may be considered as one of the fundamental mechanisms for CME initiation (Wu, Song, Martens, and Dryer, 1990).

The SII was studied for three values of plasma beta, β = 15.4, 1.54, and 0.06. The characteristic Alfvén velocities for these three cases are, respectively: 4.67, 46.7, and 232 km s^{-1}. Figure 2 shows the maximum upward velocity within the computational domain as a function of time. The peak shearing velocity (Figure 1) was 5 km s^{-1} for the two high values of β and 15 km s^{-1} for the (more realistic) lowest value. The growth rate for

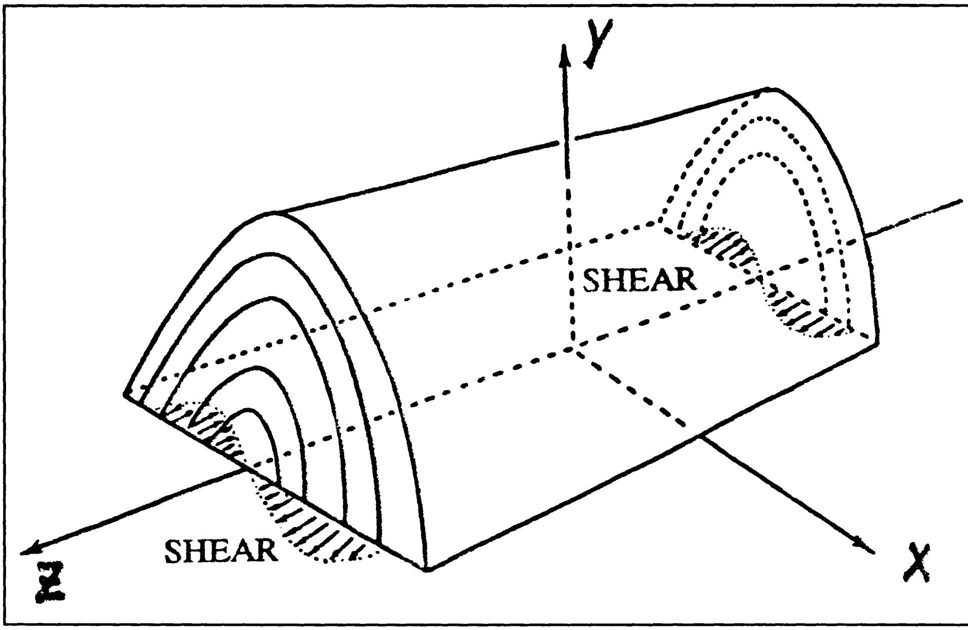


Figure 1. Schematic representation of an initial magnetic field (dipole) arcade which is subsequently sheared at the photosphere by the indicated velocity profile. The computational domain is: $x = \pm 8.4 \times 10^3$ km, and $y = 8 \times 10^3$ km. (Wu, Song, Martens, and Dryer, 1990.)

these upward velocities became unstable when the maximum deviation of the field at the coronal base reached shear angles of 63°, 48°, and 21° for $\beta = 15.4$, 1.54, and 0.06, respectively. Thus, instability is indicated for moderate shearing angles when the plasma betas are low, as expected in the lower corona.

It is important to note that the forcing function is a finite-amplitude perturbation upon a stable configuration that eventually becomes unstable. Reduction of the peak shearing velocity of 15 km s^{-1} to a more gentle value, say 0.15 km s^{-1}, could be accomplished via the principle of dynamic similitude (c.f., Wu et al., 1988). The computational run time must then be longer. In the present case of $\beta = 0.06$ (the "prototype"), the same realistic beta could be maintained for the "model," together with the same Struhal, Euler, and Froude numbers as well as the same ratio of magnetic to kinetic energy for a dissipationless fluid.

As suggested above, however, there is a problem in this particular case. The prototype ran for 7 Alfvén periods, where the Alfvén time was 35 seconds. Because of the desired hundred-fold decrease of shearing velocity, the model's rather excessive temporal requirement, τ_M, would be:

$$\tau_M = 7 \times 35 \times 10^2 = 24{,}500 \text{ s}.$$

2.2 Solar-Injected Plasmoid into the Solar Wind

Using the 3-D code of Han, Wu, and Dryer (1988), Detman et al. (1990) have simulated the injection of an initially spherical plasmoid into the solar

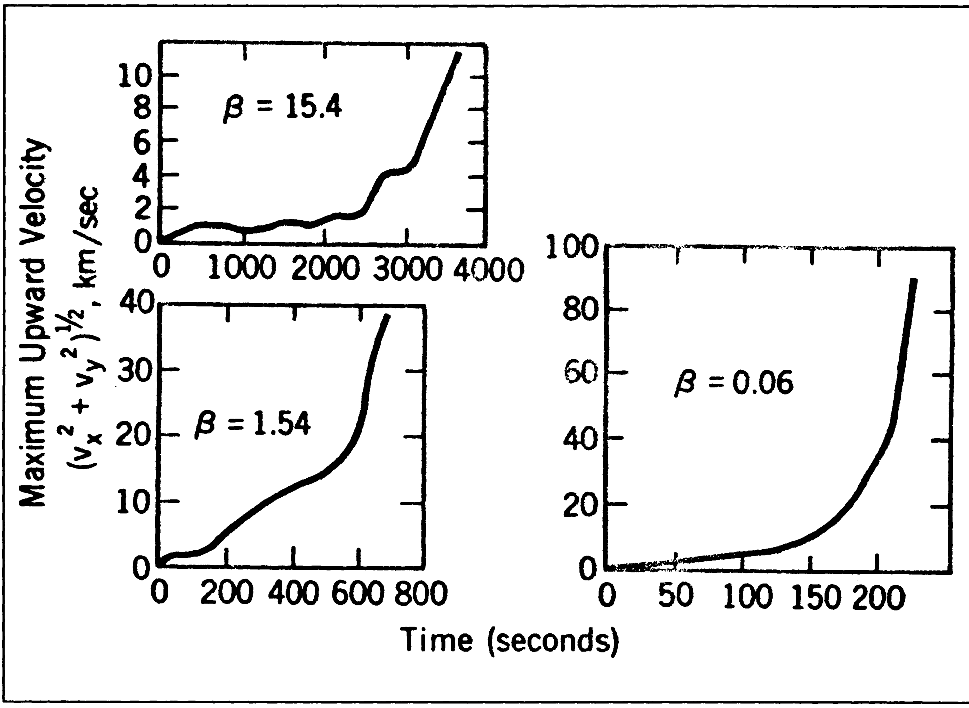


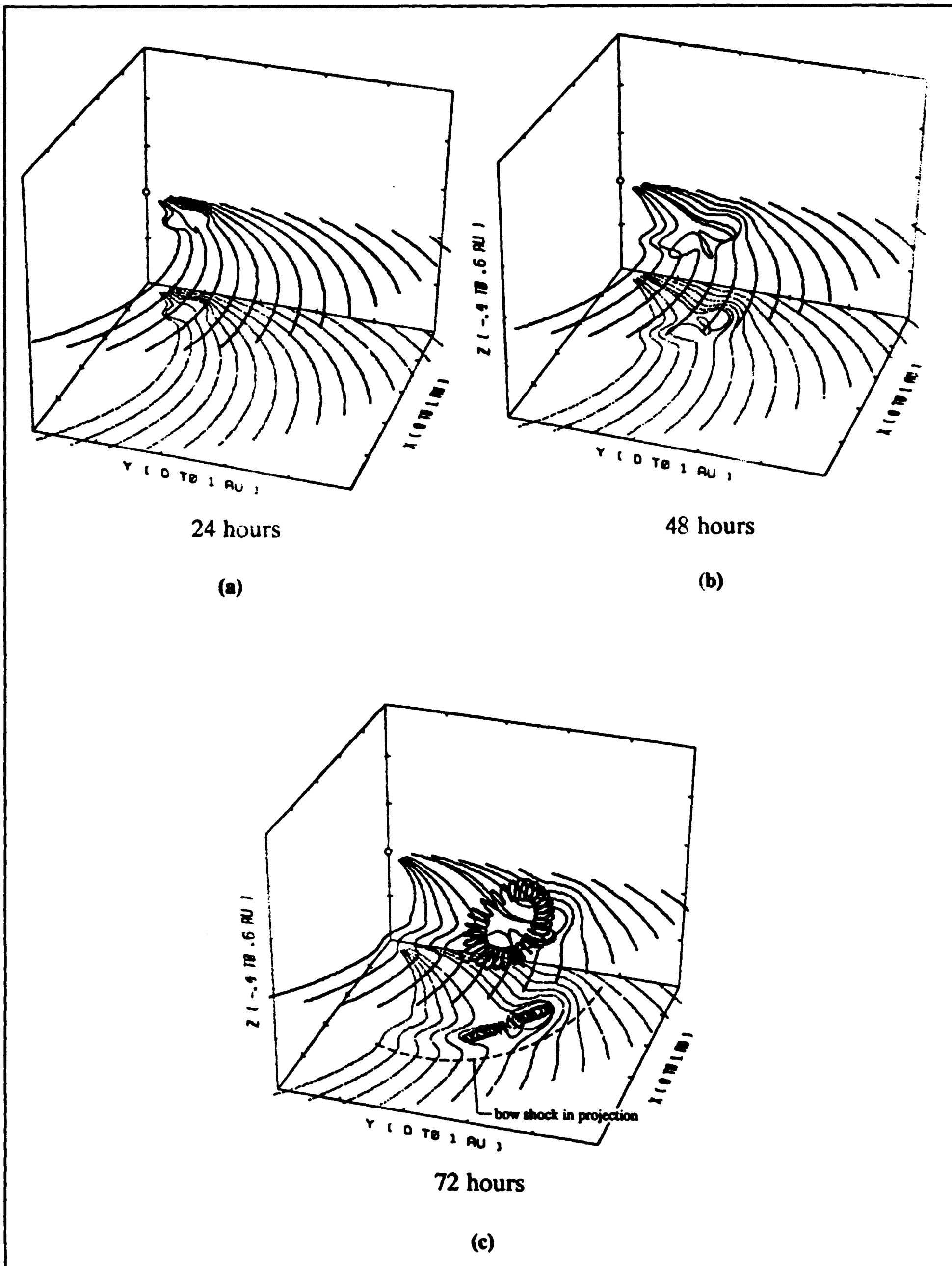
Figure 2. Maximum upward velocity in the computational domain (Figure 1) when photospheric shearing of a dipole magnetic field takes place. Note that "shearing-induced instability" takes place at t ≈ 200 s, for β = 0.06, after approximately seven Alfvén times. (From Wu, Song, Martens, and Dryer, 1990.)

wind. The plasmoid possessed both toroidal and poloidal magnetic field components, like a set of concentric "slinky toys" placed end to end. The plasmoid survived the injection and continued to propagate through the solar wind, even producing a substantial shock wave when injected at a speed greater (relative to the background solar wind velocity) than the magnetosonic speed. The approximate positions of the plasmoid and its shock wave, and the draping of the IMF around the plasmoid, were determined. Figure 3 shows a 3-D view of some representative IMF lines and their draping around the plasmoid. A representative magnetic field line within the plasmoid is also shown.

It is interesting to note that some reconnection (due to numerical diffusion) takes place between some of the plasmoid field lines and IMF lines that come into close proximity to the neutral points on the front and rear positions of the plasmoid.

2.3 Plasmoid Created at Heliospheric Current Sheet

In a separate numerical experiment, Dryer et al. (1989) showed how a cigar-shaped plasmoid might be generated by a shock wave that propagates through a flat heliospheric current sheet. The high total pressure, formed by the 3-D shock wave just within its outermost envelope, decreases to low values within the central portion, i.e., near the IMF reversal zone. The high pressure gradient, generated by the outward-moving, large-scale



24 hours

(a)

48 hours

(b)

72 hours

(c)

Figure 3. A 3-D view of the IMF as it is deflected by the bow shock, its draping around the solar-generated plasmoid, and a single helical magnetic field line within the plasmoid. Initially equatorial IMF lines are shown at t = 24, 48, and 72 hours in panels (a), (b), and (c), respectively. The viewing perspective is from 8 AU, θ = 60°, ϕ = 20°, where θ is the heliocolatitude and ϕ is the heliolongitudinal angle measured from the lower left of the 1 AU-sized box. (Detman et al., 1990.)

heliospheric shock wave, forces the opposite-directed IMF field lines together and causes them to reconnect.

Figure 4 shows the initial stage of reconnection at what will be the leading edge of the cigar-shaped plasmoid. Reconnection also takes place at the rear, pinching off the opposite-directed IMF as the entire structure propagates through the solar wind. The "cigar" would be oriented in a direction transverse to the outward motion of the large-scale global disturbance.

4. CONCLUDING REMARKS

We have briefly summarized some of our ongoing work in the field of non-planar and 3-D numerical simulations of solar disturbances and their possible interplanetary consequences. The classical initial boundary-value approach is scrupulously followed to ensure a deterministic response whenever a stable initial state is perturbed by a set of observationally in-

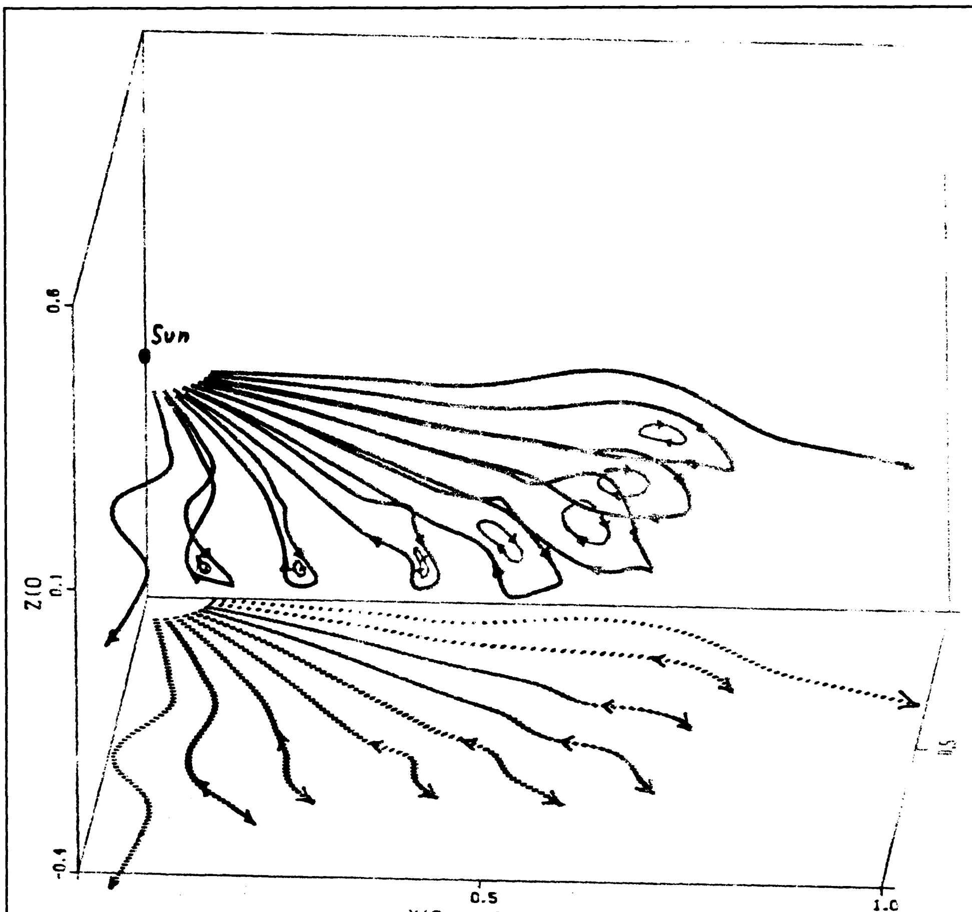


Figure 4. Initial stage of a cigar-shaped plasmoid that is formed in the interplanetary medium by the propagation of a shock wave through a flat heliospheric current sheet. (Dryer et al., 1989; S.M. Han, private comm., 1989.)

ferred parameter changes. Numerical experiments of this kind are a necessary step beyond the "cartoon" stage, and must be undertaken with the solution of the mathematical expressions for well-known physical laws together with reasonably chosen assumptions. The insight derived from simulations such as the three described here are essential for understanding large-scale global processes. Only investigation by multiple, in situ, spacecraft missions can confirm or refute the global predictions of such 3-D numerical experiments. Such missions have yet to be undertaken.

5. ACKNOWLEDGMENT

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DISCUSSION

FORBES: Was the initial state in your sheared arcade example potential or force-free? If so, it seems to me that your result completely contradicts the work of J. J. Aly which shows that such a disruption, which opens the field, by shearing should be impossible.

DRYER: The initial state is, indeed, a potential force-free magnetic arcade. When the footpoints are moved, they are moved rather rapidly. For example, the lowest beta case ($\beta = 0.06$) had a peak shearing velocity of 15 km/sec. Consequently, the system quickly evolves into a non-force-free system with pressure gradients. Thus, the force-free results of Aly do not apply. Also, the instability only results in a rapid expansion of loops and locally fast mass flows after the mean Alfvén speed is exceeded. This instability, moreover, does not necessarily open the magnetic field. You will recall that there is no resistivity in this model, nor are there any anti-directed fields where numerical reconnection could, in principle, take place. Thus, this model does not address the question of field-line-opening.

KUNDU: I am a little confused by your referring to flares as the cause of IPS-producing shocks rather than high-speed streams from coronal holes, which Tony Hewish believes. Since you showed Hewish's data, when you talked about IP shocks, I would like to know what the present status is with regard to flares versus coronal holes as the cause of IP shocks.

DRYER: Our use of Hewish's IPS data is decoupled from his interpretation that high speed streams from coronal holes are responsible for geomagnetic storms. If a transiently-developing coronal hole suddenly (say, on a few-hour time scale) develops, a shock could certainly develop. I have a constructive and friendly disagreement with Tony who believes that flares are peripheral events *vis-à-vis* geomagnetic storms. I believe otherwise. You will recall that IPS data contains no information about the IMF (which, if southerly-directed, is important for storm triggering); hence my comment above about decoupling. Of course, even a steady-state hole could develop a shock that develops in the corotating frame. My point is that *any* temporal and/or spatial solar inhomogeneity (*c.f.*, flare, eruptive prominence, or hole) could produce a shock. Hewish's point, however, about a transient event, followed by a *long-lasting* energy output (be it a flare or whatever) is an important point that is worth investigation. To this purpose, Zdenka Smith and I have recently completed a 2D MHD parametric study that is relevant to this point. A final point is worth making: there are no observables of erupting streams from coronal holes. Transient coronal hole area changes are not sufficient, in my opinion, to claim that a shock will propagate from such an event. The case for flares is well-established.

SWARUP: How does the intensity of shocks vary with solar distance in your models?

DRYER: When the temporal duration of an input pulse is short, say less than a few hours, the strongest part of the shock will decay similarly to a classical blast wave with shock speed $\sim R^{-1/2}$ where R is the heliocentric radius. If the energy input is long-lasting, say some 5-15 hours (as suggested by long duration X-ray flares) the shock could move out at a constant velocity (*i.e.*, as a piston-driven shock) for some tenths of an AU before decelerating as noted above in the frame of the background, moving solar wind.

PRIEST: (i) Is the plasma beta much smaller than unity in magnetic clouds and in your magnetic bubble?

(ii) If so, why should the plasma density changes be directly proportional to the initial density?

DRYER: (i) Your first question relates to our "magnetic bubble" numerical experiment. We were interested in examining the dynamics of a particular configuration and the response (*c.f.*, field draping) of the ambient solar wind and its interplanetary magnetic field to its projectile-like motion. Although we were not interested at this exploratory stage to make any comparisons with spacecraft-observed "magnetic clouds" the particular choice of the parameters (n,T,B,) within our input bubble produced plasma betas greater than unity. We would expect that other, judiciously-chosen, parameter combinations could produce betas less than one - as found in the observations. It is not clear, incidentally that the latter are bubbles - or whether they are gigantic loops with both ends rooted in the Sun.
(ii) The density fluctuations that give rise to IPS are experimentally correlated with *in situ* density measurements by Tappin (1986) and more rigorously, recently, by Zwickl *et al* (AGU abstract,1988).

UBEROI: In your analogy of magnetic bubble to Hill's vortex did you take care of the fact that some conservation theorems valid for vortices do not hold good for MHD theory?

DRYER: Thank you for bringing this possibility to my attention. No, we did not take this point into consideration.