Fluid Aspects of Solar Wind Disturbances Driven by Coronal Mass Ejections

J. T. Gosling
Los Alamos National Laboratory
Los Alamos, New Mexico

Pete Riley
SAIC
San Diego, California

Abstract. Transient solar wind disturbances are largely associated with coronal mass ejections (CMEs). Such disturbances often produce large geomagnetic storms, gradual solar energetic particle events, and Forbush Decreases in the galactic cosmic ray intensity. This paper provides an overview of fluid aspects important in the evolution of these disturbances as they propagate out through the heliosphere. The intent is to illustrate the prime dynamic processes that govern disturbance evolution in the solar wind and to explore how different types of initial conditions, both within the CMEs themselves and within the ambient wind, affect disturbance evolution. The overview proceeds from simple one-dimensional simulations of the effects of simple speed perturbations propagating into a structureless solar wind to three-dimensional simulations that consider effects associated with compound speed and pressure perturbations propagating into a spatially structured solar wind.

Introduction

The most dramatic changes in the solar corona occur during coronal mass ejection (CME) events, during which somewhere between 10^{15} and 10^{16} g of solar material are injected into the solar wind [e.g., *Crooker, Joselyn, and Feynman*, 1997; *Gosling*, 1999; *Hundhausen*, 1997]. These events originate in closed magnetic field regions in the solar atmosphere not previously participating in the solar wind expansion. Most CMEs expand considerably as they propagate away from the Sun, quickly becoming considerably larger than the Sun that spawns them.

Ejection speeds within about 5 solar radii of the Sun's surface range from less than 50 km s^{-1} in some of the slower events to as high as 2000 km s^{-1} in some of the faster events [e.g., *Gosling et al.*, 1976; *Hundhausen et al.*, 1994; *Sheeley et al.*, 1999]. Many CMEs have outward speeds and internal plasma and magnetic field pressures that are quite different from that of the ambient wind into which they are injected. Such CMEs produce transient disturbances in the solar wind that propagate to the far reaches of the heliosphere.

Transient disturbances in the solar wind initiated by coronal eruptions have been modeled for many years, extending back at least to the self-similar analytical models of, among others, *Parker* [1961; 1963] and *Simon and Axford* [1966]. The first numerical computer code (one-dimensional, gas dynamic) to study disturbance propagation in the solar wind was developed in the late 1960s [*Hundhausen and Gentry*, 1969], and a variety of other codes ranging from simple one-dimensional gas dynamic codes through three-dimensional gas dynamic and magnetohydrodynamic codes have been developed in subsequent years. Until recently these codes usually have been applied to the problem of disturbances driven by fast CMEs propagating into a structureless solar wind. *Pizzo* [1985] provided an excellent summary of the level of understanding achieved from such simulation studies through about 1984, and other reviews have subsequently become available [e.g., *Dryer*, 1994; *Pizzo*, 1997; *Riley*, 1999]. Our own recent interest is in disturbances generated by slow CMEs [e.g., *Gosling and Riley*, 1996] and by CMEs having high internal pressures [e.g., *Gosling et al.*, 1994a; 1994b; 1998; *Riley and Gosling*, 1998] as well as disturbance propagation effects associated with a structured ambient solar wind [e.g., *Odstrcil et al.*, 1996; 1999a; 1999b; *Riley et al.*, 1997].

Our purpose here is to provide a brief tutorial on fluid aspects of solar wind disturbances derived from numerical gas dynamic simulations. For the most part we illustrate disturbance evolution by propagating idealized perturbations, mimicking different types of CMEs, into a structureless solar wind using a simple one-dimensional, adiabatic (except at shocks), gas dynamic code. The simulations begin outside the critical point where the solar wind goes supersonic and thus do not address questions of how the CMEs themselves are initiated. By limiting the simulations to one dimension (the radial direction), the code predicts too strong an interaction between newly ejected solar material and the ambient wind because it neglects azimuthal and meridional motions of the plasma that help relieve pressure stresses. Moreover, the code ignores magnetic forces and, by neglecting the magnetic field, underestimates the speed with which pressure disturbances propagate in the wind. Despite these limitations, calculations using this code provide an excellent starting point for illustrating and understanding how solar wind disturbances associated with CMEs evolve with increasing heliocentric distance. Our intent is to illustrate (1) the primary fluid processes that determine disturbance evolution and (2) the effect that initial conditions, both in the ambient wind and within the CMEs themselves, have on disturbance dynamics. This tutorial builds on and extends to different types of disturbances a tutorial by *Hundhausen* [1985], who used a similar one-dimensional fluid code to illustrate fluid aspects of solar wind disturbances initiated by fast CMEs. We refer the interested reader to that paper for an informative discussion of simulations of this nature. In the latter part of this paper we illustrate some of the additional effects that arise in solar wind disturbances due to structure in the ambient wind and transverse (to the radial) flows, as revealed by multidimensional simulations.

Formation and Propagation of Compressions and Rarefactions.

In all of the simulations discussed here the flow speed, plasma density, and pressure are first held constant at the inner boundary of the simulation at 0.14 AU (30 solar radii) for a sufficiently long time that a steady, highly supersonic solar wind expansion fills the computational mesh. Different types of simple perturbations are then introduced at the inner boundary. In the example shown in Figure 1 the steady state expansion produced an asymptotic solar wind speed of about 480 km s^{-1} at large heliocentric distances. The figure shows two snapshots of the radial evolution of a disturbance initiated by discontinuously increasing the flow speed from 400 to 700 km s^{-1} at the inner boundary while simultaneously holding the density and pressure constant. A compression region quickly forms as the faster plasma overtakes the slower wind ahead. This compression region expands both forward into the slow wind and backward into the fast wind because it is a region of high pressure. It is bounded by a strong forward-reverse shock pair in this case since the plasma flows supersonically into the compression region from both sides. The slower plasma is compressed and accelerated as it encounters the forward shock and the faster wind is compressed and decelerated as it encounters the reverse shock. The vertical lines in

Figure 1 bracket the last 30 hours of slow wind introduced at the inner boundary. This plasma parcel is compressed into an ever smaller volume as the forward shock passes through it. When the fast and slow plasmas have equal densities at the inner boundary, as in this example, momentum conservation dictates that a step function increase in speed produces nearly equal and opposite speed changes in the slow and fast wind. Essentially the same result is obtained if the speed increase at the inner boundary is more gradual than a step function, but the interaction develops more slowly and the shocks form farther from the Sun.

Figure 2 shows two snapshots illustrating the radial evolution of a disturbance initiated at the inner boundary in the opposite manner from that in Figure 1. In this case the steady state expansion produced an asymptotic flow speed at large distances of about 750 km s^{-1}. The disturbance was initiated by changing the speed at the inner boundary from 700 to 400 km s^{-1} in a step function decrease while holding the density and pressure constant there. A region of low pressure (a rarefaction) quickly forms at the interface between the two flows as the faster plasma runs away from the slower. The slower plasma behind the interface is accelerated as it encounters the enhanced outward pressure gradient associated with the rarefaction, while the faster plasma ahead of the interface is decelerated by the reverse pressure gradient associated with the leading portion of the rarefaction. It is of interest that the rarefaction in Figure 2 expands much faster than does the compression in Figure 1 because it is superimposed upon diverging flows. With increasing heliocentric distance, the overall speed profile flattens as the rarefaction spreads. Vertical lines in the figure bracket the first 30 hours of slow plasma introduced at the inner boundary. This parcel of plasma broadens as it moves out from the Sun and eventually all of the plasma within the parcel is accelerated to a higher speed as it encounters the rarefaction. The greatest acceleration is experienced by the plasma at the leading edge of the parcel; however, the change in speed at the leading edge of the parcel remains less than half the original difference in speeds between the fast and slow flows. This is a consequence of momentum conservation in a plasma whose overall density varies as R^{-2}, where R is heliocentric distance. The spherical nature of the overall solar wind expansion is also the reason why the pressure perturbation associated with the rarefaction is asymmetric about the interface, with the pressure minimum migrating into the plasma ahead of the parcel as the disturbance progresses out into the heliosphere.

Disturbances Produced by Fast CMEs

Figure 3 shows three snapshots of the radial evolution of a disturbance initiated by combining the above types of speed changes in a square wave increase in speed. In this case speed, density, and pressure were first held steady at the inner boundary at 0.14 AU until a stationary flow with an asymptotic speed of ~450 km s^{-1} filled the computational mesh. The disturbance was initiated at the inner boundary by raising the flow speed from 350 to 600 km s^{-1} and then dropping it back to 350 km s^{-1} 15 hours later. The initial disturbance mimics a moderately fast CME injected into a considerably slower wind and having an internal pressure equal to that of the ambient wind. As would be expected from Figure 1, a region of high pressure develops on the leading edge of the CME in the simulation as it runs into the slower ambient wind ahead. Because of the large amplitude of the initial speed perturbation, this region of high pressure is bounded by a forward-reverse shock pair. The propagation of these shocks produces an acceleration of the ambient wind ahead and a deceleration of the leading portion of the CME.

Simultaneously, a rarefaction develops on the trailing edge of the disturbance as the CME pulls away from slower trailing solar wind. Pressure gradients associated with this rarefaction produce a deceleration of the trailing portion of the CME and an acceleration of the trailing wind. After 69 hours the reverse shock and the leading edge of the rarefaction have propagated through one another in opposite directions, with the leading edge of the rarefaction being close to the front edge of the CME. The back edge of the rarefaction is now well into the trailing wind behind the CME. After 125 hours the reverse shock has propagated almost to the back edge of the CME, while the leading edge of the rarefaction has propagated almost up to the forward shock ahead of the CME. The disturbance thus evolves from an initial, limited square wave perturbation in speed into a more complex disturbance with an overall speed profile that resembles a double sawtooth. As a result of sharing its momentum with both the leading and the trailing ambient wind via the compression and rarefaction waves, the CME slows considerably as it propagates out into the heliosphere. The simulation thus explains why CMEs with speeds considerably higher than that of the normal wind are only occasionally observed far from the Sun. Only those

CMEs with exceptionally large momentum contents will not be slowed substantially as they interact with a slower ambient solar wind. Finally, although the simulated CME was not expanding at the inner boundary and has a radial width near 1.7 AU that is comparable to its width (0.22 AU) at the inner boundary, it does expand once the reverse wave has passed through its back edge. When the perturbation at the inner boundary is of shorter duration than in the present example, the reverse wave passes more quickly through the CME and expansion begins sooner. The simple simulation shown in Figure 3 is qualitatively consistent with near-ecliptic observations of many CME-driven solar wind disturbances, although reverse shocks are only rarely detected in these disturbances except possibly near their center lines [e.g., *Gosling et al.*, 1988].

Disturbances Produced by Slow CMEs

It is instructive to consider the inverse problem of a slow CME injected into a much faster surrounding solar wind such as might happen at high latitudes. Figure 4 shows two snapshots of calculated radial speed and pressure profiles of a solar wind disturbance produced in our one-dimensional simulation by introducing a very slow pulse into a faster ambient wind. Starting with the same steady state solution as in Figure 3, the disturbance is initiated at the inner boundary by dropping the flow speed from 350 to 200 km s^{-1} and then raising it back up to 350 km s^{-1} in a square wave pulse 15-hours long. A rarefaction quickly forms on the leading edge of the simulated CME that rapidly spreads forward into the ambient wind and back through the CME. Simultaneously a compression region, which is bounded by a forward-reverse shock pair, forms on the trailing edge of the CME. After 41 hours the forward shock and the trailing edge of the rarefaction have passed through one another in opposite directions such that the rarefaction extends nearly to the back edge of the compressed CME. After 111 hours the rarefaction extends well behind the CME but still leads the reverse shock, while the forward shock has propagated entirely through the CME and the leading edge of the rarefaction has run well ahead of both the CME and the forward shock. The combined effect of the shocks and the rarefaction wave produces a compressed CME that, at 1 AU, is traveling almost at the speed of the ambient wind as yet unaffected by the the disturbance. Indeed at this distance the entire CME is traveling faster than the decelerated ambient wind immediately ahead of the forward shock. An untrained observer might mistakenly believe that the forward-reverse shock pair was driven by a CME that initially had a higher speed than that of the ambient wind ahead.

The simulation shown in Figure 4 demonstrates that if a slow CME is inserted into a faster solar wind it rapidly is accelerated up to nearly the speed of the surrounding wind [*Gosling and Riley*, 1996]. The CME in this case represents a negative momentum pulse that rapidly is shared via the compression and rarefaction waves with an ever larger volume of the ambient wind. The forward shock and the leading rarefaction persist to large distances and thus provide telltale evidence of the acceleration process. Observations, particularly in the outer heliosphere and at high heliographic latitudes, provide a few relatively dramatic examples where CMEs have been accelerated to higher speed because of interactions of this sort, although those observations can not be explained in terms of simple square wave inputs such as specifically simulated here. Moreover, most slow CMEs observed in the ecliptic plane to not appear to have been accelerated substantially by this sort of interaction since they are typically not associated with large rarefactions or shocks [*Gosling*, 1994]. Both *in situ* and coronal [e.g., *Sheeley*, 1999] observations indicate that virtually all low-speed CMEs in the solar wind are accelerated outward by the same sort of pressure gradients that accelerate the normal slow solar wind out from the Sun.

Disturbances Produced by the Overexpansion of CMEs

Coronagraph observations reveal that most CMEs expand considerably as they propagate away from the Sun, quickly becoming much larger than the Sun that spawns them. For most CMEs this expansion continues far out into the heliosphere and is readily evident in the fact that the leading edges of most CMEs observed in the solar wind at any heliocentric distance have higher speeds than the trailing edges. Since the expansion occurs in all three dimensions, the density and temperature of the plasma within a CME typically decrease with increasing heliocentric distance more rapidly than does that of the normal solar wind. Thus, at 1 AU CMEs in the solar wind often are characterized by anomalously low kinetic temperatures [e.g., *Gosling et al.*, 1973; 1987; *Montgomery et al.*, 1974; *Richardson and Cane*, 1995], and, at distances beyond about 3

AU, by unusually low plasma densities as well [*Gosling et al.*, 1998].

Several processes can contribute to the expansion of a CME. A CME can expand simply because it is injected into the solar wind with a substantial front-to-rear speed gradient. Another possibility is that expansion is a CME's response to a rarefaction wave produced by relative motion between the CME and the surrounding solar wind, as discussed above. Finally, a CME may expand because it has a higher internal pressure than that of the surrounding solar wind. The higher pressure can be a result of a higher density, a higher temperature, a stronger magnetic field, or some combination thereof. We have used the term "overexpansion" to describe CME events where a higher internal pressure contributes substantially to the expansion. The relative importance of these various expansion processes differs from event to event, depending on the physical character of the CME and on initial conditions within the surrounding solar wind.

Figure 5 show snapshots of solar wind speed and pressure as a function of heliocentric distance obtained in a simulation of an overexpanding CME. In this case the initial steady state boundary conditions produced a highly supersonic flow with a speed of 750 km s^{-1} at 6.0 AU and a density of 2.5 cm^{-3} at 1 AU, matching average high-latitude flow conditions observed by Ulysses on the declining phase of the last solar cycle [e.g., *Phillips et al.*, 1995]. The disturbance was initiated at the inner boundary by increasing the density (and hence also the pressure) by a factor of four in a bell-shaped pulse 10-hours long while simultaneously holding the temperature and speed constant. This mimics the injection into the heliosphere of a dense CME whose internal pressure is higher than that of the surrounding wind and whose speed is the same. The temporal duration of the initial pulse corresponds to a CME radial width of 0.17 AU at the inner boundary.

Because of its initial high internal pressure, the CME expands as it travels out from the Sun so that at 3.2 AU it has a radial width of 0.40 AU. The overall disturbance width at this distance is 0.67 AU since the expansion drives a forward wave into the ambient wind ahead and a reverse wave into the trailing wind. These pressure waves steepen into relatively weak shocks by the time they reach 3.2 AU. The expansion also produces a declining front-to-rear speed gradient across the CME and causes the pressure within the CME far from the Sun to be lower than that in the ambient wind surrounding the disturbance. The disturbance thus evolves from one where high pressure is concentrated within the CME to one where high pressure is concentrated in the regions immediately downstream from the shocks and where the region interior to the CME has lower than average pressure. Since the background pressure continues to decrease with increasing heliocentric distance in the simulation, the CME continues to expand as it travels into the far reaches of the heliosphere [*Riley and Gosling*, 1998]. This conclusion would be modified if pickup ions contribute substantially to the background pressure at large distances. Insofar as we are aware, events such as this have not been observed at low heliographic latitudes at any heliocentric distance. On the other hand, events of this nature constituted a large fraction of the CME-related events observed at high heliographic latitudes by Ulysses during the decline and near the minimum of solar cycle 22. In particular, the disturbance produced by the simple simulation in Figure 5 closely resembles solar wind disturbances observed by Ulysses in February 1994 at 3.5 AU and S54° and in April 1994 at 3.2 AU and S61° [*Gosling et al.*, 1994b].

Disturbances Produced by Compound Perturbations

The simulation results shown in Figures 3-5 illustrate the basic types of fluid interactions that CMEs have with the surrounding solar wind as they evolve outward from the Sun. Additional complexities arise when a CME represents both a speed and a pressure perturbation to the ambient wind. Figure 6 illustrates some of this additional complexity by introducing different types of perturbations into the same steady state flow (~430 km s^{-1} at large heliocentric distances). The disturbance on the left was initiated in the same manner as the one in Figure 5, albeit into lower speed ambient wind, by increasing the density at the inner boundary by a factor of four in a bell-shaped pulse 10-hours long while holding the temperature and speed constant there. The overexpansion of this pressure pulse produces the speed and pressure profiles shown 59.1 hours after initiation at the inner boundary. In contrast, the disturbance shown in the middle of Figure 6 was initiated by increasing the flow speed by a factor of two in a bell-shaped pulse, also 10-hours long, while holding the density and pressure constant. This disturbance evolves much the same as the one shown in Figure 3, although differences arise because of the shorter and more gradual nature of the initial perturbation at the inner boundary when compared to the Figure 3 example.

Finally, the disturbance shown at the right in Figure 6 was initiated by combining these perturbations in a single pulse. That is, the disturbance was initiated at the inner boundary by simultaneously increasing both the speed (by a factor of two) and the density (by a factor of four) in a bell-shaped pulse 10-hours long while holding the temperature constant there. This input mimics injection of a moderately fast, high pressure CME into a slower ambient solar wind. Because of the greater initial momentum of the CME in this simulation, the forward shock near 1 AU is considerably stronger than in the example shown in the middle of the figure, and the CME slows less rapidly as it travels out from the Sun. After 59.1 hours the CME is also broader than the disturbances in the other panels because both the trailing rarefaction and the initial over pressure contribute to the expansion. We note that the resulting disturbance near 1 AU includes only a single, relatively weak, reverse shock. This shock is associated with expansion of the compression region on the leading edge of the CME. The shock is weakened and retarded considerably as it encounters the forward wave associated with CME overexpansion. The weaker forward expansion wave is essentially obliterated by that interaction. On the other hand, the reverse wave associated with overexpansion of the CME never really develops fully in this case because the CME runs away from the trailing plasma faster than the reverse wave can effectively expand back into it. Overall, the disturbance bears a greater resemblance to the example driven by a pure speed pulse (middle panel) than that driven by a pure pressure pulse (left panel). This simulation thus illustrates the dominant role that relative speed plays in the evolution of most CME-driven solar wind disturbances.

Figure 7 provides a somewhat similar comparison for the case of slow CMEs injected into a much faster ambient solar wind flow (asymptotic speed of 750 km s^{-1} in this case). The disturbance in the left panel was initiated by dropping the speed from 700 to 400 km s^{-1} at the inner boundary and then raising it back up to 700 km s^{-1} in a bell-shaped pulse 30-hours long. In this case the outer edges of the simulated CME have the same high speed as the ambient wind, while the central portion of the CME has a much lower speed. Because of the more gradual nature of the initial perturbation, its greater duration, and the fact that it is superposed upon a much faster ambient wind, this disturbance evolves more slowly with heliocentric distance than does the square-wave example shown in Figure 4 . Nevertheless, the development of the rarefaction on the leading edge of the disturbance and the compression on the trailing edge of the disturbance are clear. Moreover, the CME is accelerated in much the same manner as in the

Figure 4 example. By 4 AU, all portions of the simulated CME have speeds greater than 650 km s^{-1} as a result of momentum sharing with the surrounding wind, whereas the CME would have a minimum speed of ~480 km s^{-1} at large heliocentric distances in the absence of the dynamic interaction. Different choices for the edges of the CME within the original negative speed pulse would not alter this conclusion.

The disturbance in the right panel of Figure 7 was initiated at the inner boundary of the simulation by decreasing the speed in the same manner as in the left panel while simultaneously increasing the density by a factor of four in a bell-shaped pulse 30-hours long. When compared to the disturbance in the left panel, it is clear that the effect of adding the density/pressure perturbation is to broaden both the CME and the overall disturbance, to weaken the forward shock and retard its advance into the CME, to strengthen the reverse shock propagating back into the trailing ambient wind, and to lessen the overall acceleration of the CME. All of these effects are consequences of the added inertia of the initial perturbation and the additional expansion provided by the high initial internal pressure. Once again it is notable that expansion shocks, such as those produced when pure pressure signals of this same amplitude are introduced at the inner boundary (see Figure 5 and the left panel of Figure 6), do not form in this example. The reverse wave associated with expansion of the high-pressure CME is effectively obliterated as it interacts with and retards the forward shock associated with the compression on the trailing edge of the disturbance, while the forward expansion wave never really develops because the ambient wind ahead runs away from the CME faster than the CME can expand into it. The two examples shown in Figure 7 again illustrate the dominant role that relative speed plays in the evolution of most solar wind disturbances. The resulting disturbance in the right panel resembles a disturbance observed by Ulysses at 4.5 AU and S35˚ in July, 1993 [*Gosling and Riley*, 1996].

Disturbance Propagation Effects Associated With Latitudinal Structure in the Ambient Solar Wind

The examples shown in Figures 1-7 illustrate most of the basic fluid effects underlying CME-driven disturbance evolution in the solar wind. They also illustrate the sensitivity of that evolution to initial conditions and provide considerable guidance for interpreting observations.

Real solar wind disturbances are, of course, often quite a bit more complex than illustrated in these simple simulations. Because of spatial structure within the ambient solar wind and within the CMEs themselves, as well as the possibility of transverse flows, we can not hope to replicate all the details of these disturbances with one-dimensional simulations. Additional effects arise when one considers spatial inhomogenieties and allows for transverse flow in the simulations. Figure 8 provides an example of some of these effects [*Riley et al.*, 1997]. The figure shows the result of a two-dimensional fluid simulation of a CME propagating into a solar wind characterized by dense, slow radial flow from the equator to a latitude of 20˚ and by tenuous, fast radial flow above 20˚. At large heliocentric distances the steady state flow prior to initiation of the disturbance was ~450 km s^{-1} at low latitudes and ~750 km s^{-1} at high latitudes. This approximates the average latitudinal structure observed by Ulysses during its first polar orbit about the Sun on the declining phase of solar cycle 22 [e.g., *Phillips et al.*, 1995]. It represents the limiting case of a three-dimensional model in which the ambient flow close to the Sun is structured into a band of low-speed wind above the magnetic equator and a considerably higher-speed wind at higher magnetic latitudes. In this case the tilt of the solar magnetic dipole relative to the rotation axis of the Sun is exactly zero so that there is no stream structure at low or high heliographic latitudes and thus corotating interaction regions (CIRs) do not form.

The disturbance shown in Figure 8 was initiated at 0.14 AU by introducing into the simulation a fast, hot and dense bell-shaped pulse of 10-hour duration. The pulse extended from the equator up to 45˚ latitude, extending well across the boundary between the low and high-latitude flows. The speed of the plasma in the pulse at all latitudes was identical to that in the ambient wind at high latitudes and the maximum gas pressure within the pulse was 6 times greater than that which prevailed at both low and high latitudes in the ambient wind. The simulation thus mimics injection into the solar wind of a CME that initially has a speed equal to that of the ambient wind at high latitudes, a speed considerably faster than the ambient wind at low latitudes, and a higher internal pressure than the ambient wind at all latitudes. The upper portion of Figure 8 shows snapshots of the radial and meridional flows and the pressure 6.9 days after initiation of the disturbance at the inner boundary, while the bottom portion shows differences between the disturbance and steady state solutions of these parameters. The solid line in all panels outlines the material introduced within the pulse at the inner boundary and thus outlines the pseudo-CME in the simulation. The following items are of interest here:

1. The disturbance has evolved in a completely different fashion within the low and high-latitude regions. At low latitudes, disturbance evolution is dominated by the relative speed between the CME and the slower ambient wind ahead, as in the one-dimensional example shown in the right panel of Figure 6. As in that one-dimensional simulation, the disturbance at low latitudes is fronted by a strong forward shock, while the reverse wave associated with the interaction is almost invisible. At high latitudes, disturbance evolution is driven primarily by the overexpansion of the coasting CME, as in Figure 5, and a relatively weak forward-reverse shock pair bounds the disturbance.

2. The CME has essentially separated into two pieces. The radial separation is caused by the strong velocity shear between the slow and fast ambient solar wind. The latitudinal separation is a result of the rarefactions that develop in the two different pieces of the CME. Pressure gradients associated with those rarefactions drive meridional flows across the original interface between the low and high-speed flows; those flows produce the latitudinal separation. The rarefaction at low latitudes is a result of the CME running away from the slower ambient behind (as in Figure 3 and in the middle and right panels in Figure 6). At high latitudes the rarefaction is the result of the overexpansion of the CME (as in Figure 5 and the left panel in Figure 6).

3. After 6.9 days the CME, originally confined to latitudes below 45°, extends poleward to 63° and the associated forward and reverse shocks have reached the pole. Most of this latitudinal expansion occurs close to the Sun where, because of the diverging geometry, latitudinal distances are relatively small. This poleward expansion is not yet obvious in high-latitude observations obtained to date.

4. The high-pressure region at the front of the low-latitude portion of the disturbance extends poleward across the slow/fast interface by ~10°. This extension is a result of the transverse expansion of the compression region and is associated with the strongest meridional flow velocities (50 km s^{-1}) within the disturbance.

The disturbance profiles produced in this two-dimensional simulation at high and low latitudes are similar to disturbance profiles observed in the ecliptic plane at 1 AU by IMP 8 and at S54° and 3.5 AU by Ulysses during a CME event that occurred in February 1994 [*Gosling et al.*, 1995]. Although the two-dimensional simulation introduces additional complexities and provides a global perspective not possible in the one-dimensional simulations, the basic nature of the disturbances at high and low latitudes is correctly inferred from the simpler one-dimensional simulations.

Disturbance Propagation in a More Realistic Three-Dimensional Geometry

The geometry of the ambient solar wind flow close to the Sun is probably never as simple as assumed in Figure 8. Stream structure and CIRs always are present to some degree in the solar wind at low heliographic latitudes. A more realistic, but still highly idealized, initial geometry is that which has been used to simulate three-dimensional aspects of CIRs [*Pizzo*, 1991; 1994; *Pizzo and Gosling*, 1994]. In those simulations it is assumed that a uniform band of slow, dense wind encircles the Sun at low heliographic latitudes, while uniform regions of fast, tenuous wind emanate from higher latitudes. Fast and slow flow regimes are separated by a relatively sharp transition and the slow flow band, centered on the solar magnetic equator, is tilted relative to the heliographic equator. Typical tilts range from about 10° to 30°, reflecting observed tilts of the solar magnetic dipole relative to the rotation axis of the Sun. Gas dynamic and MHD simulations using this type of geometry provide a credible approximation to the gross latitudinal structure of the solar wind observed by Ulysses [e.g., *Phillips et al.*, 1995] and successfully reproduce and predict the basic three-dimensional structure of high-speed streams and CIRs and associated rarefactions over a wide range of latitudes out to distances of at least 5 AU.

In the three-dimensional simulation used to produce Figure 9 [*Odstrcil and Pizzo*, 1999a], the slow flow band was 30° wide, centered on the magnetic equator which, in turn, was tilted 20° relative to the heliographic equator. Initial conditions at the inner boundary at 0.14 AU were chosen to be 600 (300) km s^{-1}, 125 (500) cm^{-3} and 2 (0.5) x 10^6 K in the fast (slow) wind. These produced an ambient background state with speed 718 (359) km s^{-1}, density 2.08 (8.45) cm^{-3}, and temperature 1.30 (0.33) x 10^5 K in the fast (slow) wind at 1 AU, which are close to typical observed values. The resulting CIRs and rarefactions associated with this initial state are similar to those previously produced in this type of simulation [e.g., *Pizzo and Gosling*, 1994] and are nominally similar to observed CIRs over a wide range of latitudes and distances [*Gosling et al.*, 1993; 1997].

The CME was introduced at the inner boundary as a time-dependent pulse situated within the slow flow, centered at the point where the magnetic equator crosses the heliographic equator, with a cone half angle of 15˚ (see Figure 9). The pulse ramps were each 1 hour long and the pulse duration was 12 hours. Maximum values of radial velocity, density, and temperature within the pulse were 600 km s^{-1}, 1000 cm^{-3}, and 2 x 10^6 K, respectively. Thus, the radial velocity and temperature within the CME-like pulse were equal to the fast wind value and the pressure was thus 8 times greater than that in both the high and the low-speed ambient wind. Overall the initial pulse associated with the CME was shaped roughly like a prolate spheroid, with the long axis in the radial direction.

Figure 9 shows azimuthal slices of the resulting solar wind disturbance at four different polar angles 12 days after its launch from the inner boundary; Figure 10 shows a single meridional slice passing through the central longitude of the original perturbation obtained 10 days after launch. Originally confined to a 15˚ cone half angle, the CME has broadened by more than 30˚ in each transverse dimension. This spreading is a consequence of the high initial pressure within the CME as well as the additional pressure enhancement produced as the fast CME overtakes slower wind. The combined effects of radial flow collision, lateral material expansion, and interaction with a highly structured background solar wind velocity and density structure produce the bent and twisted pancake-like CME structure shown in Figures 9 and 10. The CME is retarded most near the equator where the CME plows directly into the slow, dense flow. In contrast, the high-latitude extensions of the CME are rapidly pulled outward by the fast flow there. Such effects are responsible for producing both the bowed-out appearance of the CME in Figure 10 as well as the systematic shift with latitude of the orientation of the CME in Figure 9. The CME is most compressed (thinnest) just north of the equator where it is swept into the CIR; the CME is most extended in the south where it is relatively free to expand in the high-speed flow there.

Beyond several AU, the steady state solution into which this CME was propagated contained corotating shocks aligned roughly along the nominal Archimedean spiral direction in the azimuthal direction but tilted in the meridional plane. At the central longitude of the CME, those shocks do not extend far below the equator (see, for example, Figures 1 and 2 in *Pizzo and Gosling* [1994]). The overall shock structure is significantly modified by the CME-driven disturbance. The shocks can be discerned in Figures 9 and 10 as regions where the density contours are most closely spaced. Shock strengths are greatest, and the entire structure narrowest, where the forward and reverse shocks, driven by the relative motion and expansion of the CME, merge with the CIR shocks into a single shock pair north of the equator. At those latitudes the CME becomes entrained within the CIR. At southern latitudes a relatively weak forward shock - the result of both relative motion between the CME and the ambient wind and the expansion of the CME - stands well off in front of the CME. At the highest southern latitudes of the CME the front does not appear to be a shock. A relatively weak reverse shock, the result of overexpansion of the CME, trails most of the southern portion of the CME.

This three-dimensional simulation, although highly idealized, graphically demonstrates the complexities that arise in a CME-driven disturbance propagating into a spatially structured solar wind (see also *Odstrcil and Pizzo* [1999b]). The CME becomes distorted in all dimensions and the shock strengths and stand-off distances (relative to the CME) are strong functions of position. Even when the CME itself is spatially uniform close to the Sun, the disturbance the CME produces in the solar wind is a strong function of latitude and longitude as well as heliocentric distance.

Concluding Comments

Our goal in this paper has been to provide a simple physical description of fluid aspects of the evolution of CME-driven disturbances in the solar wind. This evolution becomes ever more complex as one proceeds from considering the effects of idealized speed perturbations introduced into a structureless solar wind using a simple one-dimensional fluid code to considering compound pressure and speed perturbations introduced into a solar wind that is highly structured in all three dimensions using a three-dimensional fluid code. Although the two and three-dimensional simulations provide unique global perspectives of disturbance evolution and include effects that simply can not be explored with the one-dimensional simulations, most of the basic physical processes and effects in both types of simulations are most simply understood in the context of the one-dimensional simulations.

We note that even the three-dimensional simulations are highly idealized approximations to what nature actually provides. The ambient solar wind nearly always contains detailed structure beyond what is predicted by the tilted slow-wind band model. Not only is the flow usually spatially and temporally variable within both the slow-wind band and the high-speed wind, but also the slow-wind band may be warped rather than planar. The structure of the ambient solar wind can also be seriously modified by earlier CME-driven disturbances, an effect that is more common near solar activity maximum than near solar activity minimum. In addition, it is unlikely that real CMEs provide initial perturbations that are as simple and spatially uniform as has been assumed in the simulations to this point. Moreover, the inner boundary for all of the simulations discussed here lies well outside the critical point where the solar wind flow becomes supersonic. This choice simplifies the numerics at the price that we learn little about how CMEs are initiated or evolve during the first 1/7th of their journey out to 1 AU. It also ensures that pressure perturbations produced in the wind do not propagate back to the inner boundary, since all pressure perturbations are superimposed on a highly supersonic outflow. Thus, for example, the reverse compression waves associated with over-expanding CMEs are convected outward with the rest of the wind, which would not be the case were the simulations initiated inside the critical point. We have suggested previously [*Gosling et al.* 1994b] that the reverse waves associated with overexpansion may actually be present in the solar wind only in CMEs that have supersonic speeds close to the solar surface. Such a class of supersonic CME events is clearly present in coronagraph observations [e.g., *Sheeley*, 1999].

Finally, for simplicity we have explicitly ignored effects of the magnetic field in all of our discussion despite the fact that CMEs are inherently a magnetic phenomenon. It is expected, however, that the magnetic field plays a relatively minor role in solar wind dynamics because the momentum and energy associated with the magnetic field usually are far less than that associated with the bulk flow of the plasma. And, as we have noted with respect to Figures 6 and 7, in most CME-driven disturbances relative motion is the primary factor governing disturbance evolution in the solar wind. Nevertheless, (1) the magnetic field increases the characteristic speed with which small amplitude pressure signals propagate in the wind, and (2) the magnetic pressure typically is comparable to, and can be greater than, the thermal pressure of the plasma, depending on the plasma beta (the ratio of plasma to magnetic field pressure). This indicates, for example, that solar wind disturbances spread more rapidly than is suggested by the fluid simulations, and overexpanding CMEs may actually be a result more of an enhanced magnetic pressure than an enhanced thermal pressure. We would not expect that either of these effects would seriously modify the conclusions drawn from the fluid simulations, although they would affect detailed comparisons of simulation results with observations. Even though the magnetic field usually plays a secondary role in disturbance evolution, it is a vital part of any CME-driven disturbance and plays a crucial role in space weather effects. The magnetic field within a CME-driven disturbance evolves along with the plasma. The ambient magnetic field must drape about a fast CME as the CME pushes its way outward through the heliosphere; further, the magnetic field within both the ambient wind and the CME becomes stronger as the plasma is compressed. In addition, the mixture of doubly anchored, singly anchored (in the Sun), and disconnected field line topologies present within a CME provides important clues for understanding CME origins in processes close to the Sun.

Acknowledgment. This paper is based on a tutorial presented at the SHINE workshop held in Boulder, Colorado in June, 1999. JTG thanks N. Crooker for travel support to the workshop and D. Odstrcil and V. Pizzo for providing Figures 9 and 10. Work at Los Alamos was performed under the auspices of the U. S. Department of Energy with support from the National Aeronautics and Space Administration. Work at SAIC....

References

Crooker, N., J. A. Joselyn, and J. Feynman, editors, *Coronal Mass Ejections, Geophys. Monogr. Ser.*, vol. 99, pp 1-299, 1997.

Dryer, M. Interplanetary studies: Propagation of disturbances between the Sun and the magnetosphere, *Space Sci. Rev., 67*, 363, 1994.

Gosling, J. T., Coronal mass ejections in the solar wind at high solar latitudes: An overview, in *Proceedings of the Third SOHO Workshop: Solar Dynamic Phenomena and Solar Wind Consequences*, ESA SP-373, The Netherlands, pp 275-284, 1994.

Gosling, J. T., Coronal mass ejections, in *Summary-Rapporteur Volume of the International Cosmic Ray Conferenc*e, edited by B. Dingus, AIP Conf. Proc., in press, 1999.

Gosling, J. T., and P. Riley, The acceleration of slow coronal mass ejections in the high-speed solar wind, *Geophys. Res. Lett., 21*, 2867, 1996.

Gosling, J. T., V. Pizzo, and S. J. Bame, Anomalously low proton temperatures in the solar wind following interplanetary shock waves: Evidence for magnetic bottles?, *J. Geophys. Res., 78*, 2001, 1973.

Gosling, J. T., E. Hildner, R. M. MacQueen, R. H. Munro, A. I. Poland, and C. L. Ross, The speeds of coronal mass ejection events, *Solar Phys., 48*, 389, 1976.

Gosling, J. T., D. N. Baker, S. J. Bame, W. C. Feldman, R. D. Zwickl, and E. J. Smith, Bidirectional solar wind electron heat flux events, *J. Geophys. Res., 92,* 8519, 1987.

Gosling, J. T., S. J. Bame, E. J. Smith, and M. E. Burton, Forward-reverse shock pairs associated with transient disturbances in the solar wind at 1 AU, *J. Geophys. Res., 93*, 8741, 1988.

Gosling, J. T., S. J. Bame, D. J. McComas, J. L. Phillips, V. J. Pizzo, B. E. Goldstein, and M. Neugebauer, Latitudinal variation of solar wind corotating stream interaction regions: Ulysses, *Geophys. Res. Lett., 20,* 2789, 1993.

Gosling, J. T., S. J. Bame, D. J. McComas, J. L. Phillips, E. E. Scime, V. J. Pizzo, B. E. Goldstein, and A. Balogh, A forward-reverse shock pair in the solar wind driven by over expansion of a coronal mass ejection: Ulysses observations, *Geophys. Res. Lett., 21*, 237, 1994a.

Gosling, J. T., D. J. McComas, J. L. Phillips, L. A. Weiss, V. J. Pizzo, B. E. Goldstein, and R. J. Forsyth, A new class of forward-reverse shock pairs in the solar wind, *Geophys. Res. Lett., 21*, 2271, 1994b.

Gosling, J. T., D. J. McComas, J. L. Phillips, V. J. Pizzo, B. E. Goldstein, R. J. Forsyth, and R. P. Lepping, A CME-driven solar wind disturbance observed at both low and high heliographic latitudes, *Geophys. Res. Lett., 22*, 1753, 1995.

Gosling, J. T., S. J. Bame, W. C. Feldman, D. J. McComas, P. Riley, B. E. Goldstein, and M. Neugebauer, The northern edge of the band of solar wind variability: Ulysses at ~4.5 AU, *Geophys. Res. Lett., 24*, 309, 1997.

Gosling, J. T., P. Riley, D. J. McComas, and V. J. Pizzo, Overexpanding coronal mass ejections at high heliographic latitudes: Observations and simulations, *J. Geophys. Res., 103*, 1941, 1998.

Hundhausen, A. J., Some macroscopic properties of shock waves in the heliosphere, in *Collisionless Shocks in the Heliosphere: A Tutorial Review, Geophys. Monogr. Ser.*, vol. 34, edited by R. G. Stone and B. T. Tsurutani, pp 37-58, 1985.

Hundhausen, A. J., Coronal mass ejections, in *Cosmic Winds and the Heliosphere*, edited by J. R. Jokipii, C. P. Sonett, and M. S. Giampapa, University of Arizona Press, Tucson pp 259-296, 1997.

Hundhausen, A. J., and R. A. Gentry, Numerical simulation of flare-generated disturbances in the solar wind, *J. Geophys. Res., 74*, 2908, 1969.

Hundhausen, A. J., J. T. Burkepile, and O. C. St. Cyr, The speeds of coronal mass ejections: SMM observations from 1980 and 1984-1989, *J. Geophys. Res., 99*, 6543, 1994.

Montgomery, M. D., J. R. Asbridge, S. J. Bame, and W. C. Feldman, Solar wind electron temperature depressions following some interplanetary shock waves: Evidence for magnetic merging?, *J. Geophys. Res., 79*, 3103, 1974.

Odstrcil, D., M. Dryer, and Z. Smith, Propagation of an interplanetary shock along the heliospheric plasma sheet, *J. Geophys. Res., 101*, 19,973, 1996.

Odstrcil, D., and V. J. Pizzo, Three-dimensional propagation of coronal mass ejections (CMEs) in a structured solar wind flow 1. CME launched within the streamer belt, *J. Geophys. Res., 104*, 483, 1999a.

Odstrcil, D., and V. J. Pizzo, Three-dimensional propagation of coronal mass ejections (CMEs) in a structured solar wind flow 2. CME launched adjacent to the streamer belt, *J. Geophys. Res.,* *104*, 493, 1999b.

Parker, E. N., Sudden expansion of the corona following a large solar flare and the attendant magnetic field and cosmic ray effects, *Astrophys. J., 133*, 1014, 1961.

Parker, E. N., *Interplanetary Dynamical Processes*, Wiley Interscience, New York, 1963.

Pizzo, V. J., Interplanetary shocks on the large scale: A retrospective on the last decade's theoretical efforts, in *Collisionless Shocks in the Heliosphere: Reviews of Current Research, Geophys. Monogr. Ser.*, vol. 35, edited by B. T. Tsurutani and R. G. Stone, pp 51-68, 1985.

Pizzo, V. J., The evolution of corotating stream fronts near the ecliptic plane in the inner solar system, 2. Three-dimensional tilted-dipole fronts, *J. Geophys. Res., 96*, 5405, 1991.

Pizzo, V. J., Global, quasi-steady dynamics of the distant solar wind, 1, Origins of north-south flows in the outer heliosphere, *J. Geophys. Res., 99*, 4173, 1994.

Pizzo, V. J., Global modeling of CME propagation in the solar wind, in *Coronal Mass Ejections, Geophys. Monogr. Ser.*, vol. 99, edited by N. Crooker, J. A. Joselyn, and J. Feynman, pp 261-267, 1997.

Pizzo, V. J., and J. T. Gosling, 3-D simulation of high-latitude interaction regions: Comparison with Ulysses results, *Geophys. Res. Lett., 21*, 2063, 1994.

Phillips, J. L., S. J. Bame, W. C. Feldman, B. E. Goldstein, J. T. Gosling, C. M. Hammond, D. J. McComas, M. Neugebauer, E. E. Scime, and S. T. Suess, Ulysses solar wind plasma observations at high southerly latitudes, *Science, 268*, 1030, 1995.

Richardson, I. G., and H. V. Cane, Regions of abnormally low proton temperature in the solar wind (1965-1991) and their association with ejecta, *J. Geophys. Res., 100*, 23,397, 1995.

Riley, P., CME dynamics in a structured solar wind, in *Solar Wind Nine*, edited by S. R. Habbal, R. Esser, J. V. Hollweg, and P. A. Isenberg, AIP Conf. Proc., 471, Woodbury, NY, pp 131-136, 1999.

Riley, P., and J. T. Gosling, Do coronal mass ejections implode?, *Geophys. Res. Lett., 25*, 1529, 1998.

Riley, P., J. T. Gosling, and V. J. Pizzo, A two-dimensional simulation of the radial and latitudinal evolution of a solar wind disturbance driven by a fast, high-pressure coronal mass ejection, *J. Geophys. Res., 102*, 14,677, 1997.

Sheeley, N. R., Using LASCO observations to infer solar wind speed near the Sun, in *Solar Wind Nine*, edited by S. R. Habbal, R. Esser, J. V. Hollweg, and P. A. Isenberg, AIP Conf. Proc., 471, Woodbury, NY, pp 41-45, 1999.

Sheeley, N. R., J. H. Walters, Y.-M. Wang, and R. A. Howard, Continuous tracking of coronal outflows, *J. Geophys. Res.*, in press, 1999.

Simon, M., and W. I. Axford, Shock waves in the interplanetary medium, *Planet. Space Sci., 14*, 901, 1966.

Figure Captions

Figure 1. Simulated solar wind speed and pressure versus heliocentric distance 83 and 250 hours after introducing a 300 km s^{-1} step function increase in speed at 0.14 AU. Vertical lines bound the last 30 hours of slow wind introduced into the simulation prior to the speed increase. Adapted from *Gosling and Riley* [1996].

Figure 2. Simulated solar wind speed and pressure versus heliocentric distance 83 and 250 hours after introducing a 300 km s^{-1} step function decrease in speed at 0.14 AU. Vertical lines bound the first 30 hours of slow wind introduced at the inner boundary. Adapted from *Gosling and Riley* [1996].

Figure 3. Simulated solar wind speed and pressure versus heliocentric distance for a solar wind disturbance initiated by a 15-hour long, 250 km s^{-1}, square wave increase in speed at 0.14 AU. The snapshots shown were obtained 27, 69 and 125 hours after onset of the perturbation. Vertical lines bound the material introduced at higher speed at the inner boundary, and thus mark the CME in the simulation. Adapted from *Gosling* [1999].

Figure 4. Simulated solar wind speed and pressure versus heliocentric distance for a solar wind disturbance initiated by a 15-hour long, 150 km s^{-1}, square wave decrease in speed at 0.14 AU. The snapshots shown were obtained 41 and 111 hours after onset of the perturbation. Vertical lines bound the material introduced at lower speed at the inner boundary, and thus mark the CME in the simulation. Adapted from *Gosling* [1999].

Figure 5. Simulated solar wind speed and pressure versus heliocentric distance for a solar wind disturbance initiated by a 10-hour long, factor or four, bell-shaped increase in density at 0.14 AU. The snapshots shown were obtained 55 and 194 hours after onset of the perturbation. Vertical lines bound the material within the density pulse, and thus identify the CME in the simulation. Adapted from *Gosling et al.* [1998].

Figure 6. Solar wind speed and pressure versus heliocentric distance for three simulated disturbances, obtained 59.1 hours after initiation at 0.14 AU. In the left, center, and right panels respectively the disturbances were initiated by increasing the density by a factor of four, by increasing the speed by a factor of two, and by increasing both the density (by a factor of four) and the speed (by a factor of two) in bell-shaped pulses 10-hours long. Vertical lines bracket the plasma originally within the bell-shaped pulses at the inner boundary and thus identify the CMEs in the simulation. Adapted from *Gosling et al.* [1995].

Figure 7. Solar wind speed and pressure versus heliocentric distance for two simulated disturbances, obtained 83 and 250 hours after initiation at 0.14 AU. In the left and right panels respectively, the disturbances were initiated by decreasing the speed by 300 km s^{-1} and by simultaneously decreasing the speed by 300 km s^{-1} and increasing the density by a factor of four in bell-shaped pulses 30-hours long. Vertical lines bracket the plasma originally within the bell-shaped pulses at the inner boundary and thus identify the CMEs in the simulations. Adapted from *Gosling and Riley* [1996].

Figure 8. Upper panels: Color-coded, meridional plots of simulated radial velocity, meridional velocity, and pressure 6.9 days after the initiation of the disturbance at 0.14 AU. The disturbance was initiated in this two-dimensional simulation as a 10-hour long, bell-shaped pulse with a speed equal to that of the ambient, high-latitude wind and a maximum pressure 6 times greater than that in the ambient solar wind at both high and low latitudes. At the inner boundary the pulse extended from the equator up to a latitude of 45°. The solid line in each panel marks the boundary of the material originally within the bell-shaped pulse and thus identifies the CME in

the simulation. Lower panels: Same as in the upper panels except that the difference between the solution at 6.9 days and the steady state solution is shown. Adapted from *Riley et al*. [1997].

Figure 9. Left: Schematic illustrating the geometry of the three-dimensional simulation at 0.14 AU. A 30˚ band of slow, dense wind, tilted at 20˚ to the heliographic equator encircles the Sun. It is surrounded on either side by fast, tenuous wind extending up to the polar regions of the Sun. The initial perturbation filled a 15˚ cone centered in the low-speed wind at the heliographic equator. Plasma within the pulse, which lasted for 14 hours, had the same speed as the high-latitude wind and an internal pressure eight times greater than that within the ambient wind at both high and low latitudes. Right: Longitudinal slices of the disturbance at four different polar angles 12 days after its launch from 0.14 AU. The slices extend from 2.5 to 5 AU and cover azimuths from 50˚ to 130˚. The initial disturbance was centered at an azimuth of 90˚. The radial velocity is indicated by the gray scale and the density is indicated by contours. The injected material density, representing the CME, is normalized to 1 AU values and is color-coded. Adapted from *Odstrcil and Pizzo* [1999a].

Figure 10. Similar to Figure 9 except that this shows a meridional cut at the central longitude of the disturbance obtained 10 days after the initial perturbation at 0.14 AU. The cut extends from 1 to 5 AU and covers polar angles from 30˚ to 150˚. Adapted from *Odstrcil and Pizzo* [1999b].