Answers to the problem set for Chapter 8 "The Structure and Evolution of the Three-Dimensional Solar Wind" in the book "Evolving Solar Activity and the Climates of Space and Earth."

1. What ultimately counts is not the strength of the field in the polar regions, but rather the strength of the field where field lines cross the magnetic equator. Field lines from the polar regions cross the dipole equator at relatively large heliocentric distances. The strength of a dipole field varies as Mr^{-3} $(1 + 3 \cos^2\theta)^{0.5}$, where M is the dipole magnetic moment, θ is the co-latitude and r is heliocentric distance. The plasma pressure falls off with heliocentric distance much slower than does the magnetic tension and ultimately exceeds the magnetic tension at the dipole equator. Field lines that originate at the poles cross the dipole equator at the largest heliocentric distances and are thus the first and easiest field lines opened up by the pressure of the plasma.

2. Reconnection can affect the overall magnetic flux budget of the heliosphere only when it occurs between magnetic field lines of fundamentally opposite (outward and inward) magnetic polarity. Reconnection of a pair of field lines of opposite polarity always produces newly closed field lines tied to the Sun at both ends. Reconnected field lines jet away from a reconnection site at approximately the Alfvén speed of the local solar wind. If such reconnection occurs outside the Alfvén critical point the newly formed closed field lines cannot collapse back to the solar atmosphere because the solar wind flow in which the reconnected field lines are embedded is super-Alfvénic. In this case reconnection does not affect the overall magnetic flux budget of the heliosphere. On the other hand, if reconnection between fundamentally opposite polarity field lines occurs inside the Alfvén critical point the newly closed field lines collapse back to the solar atmosphere faster than the solar wind flow in which they are embedded can carry them away from the Sun. In that case reconnection would affect (reduce) the overall magnetic flux budget of the heliosphere.

As an aside, reconnection in the solar wind (and possibly in the corona as well) most commonly occurs between field lines having the same fundamental magnetic polarity. Such reconnection does not affect the overall magnetic flux budget of the heliosphere at whatever heliocentric distance it occurs, although it does change the overall magnetic topology of the heliosphere.

3. Stream steepening produces a region of high pressure on the leading edge of a stream that typically exceeds the pressure both in the slow wind ahead and in the trailing high-speed wind. Owing to its elevated pressure, the compression region expands both forward into the slow wind and backward into the fast wind, which is why both forward and reverse waves are commonly observed on the leading edges of high-speed streams. When the amplitude of the speed increase associated with a

stream exceeds about twice the characteristic speed with which small amplitude pressure waves propagate the waves eventually steepen into shocks.

4. Reverse shocks propagate sunward in the solar wind rest frame and accelerate sunward any plasma they encounter. The downstream plasma (i.e., any plasma the shock has encountered) thus travels away from the Sun at a slower radial speed than does the upstream plasma (i.e., plasma the shock has not yet encountered). A spacecraft samples the downstream region of a reverse shock prior to sampling the upstream region, which is why a spacecraft observes an increase in speed (but a decrease in density, temperature, and field strength) when it crosses a reverse shock.

5.

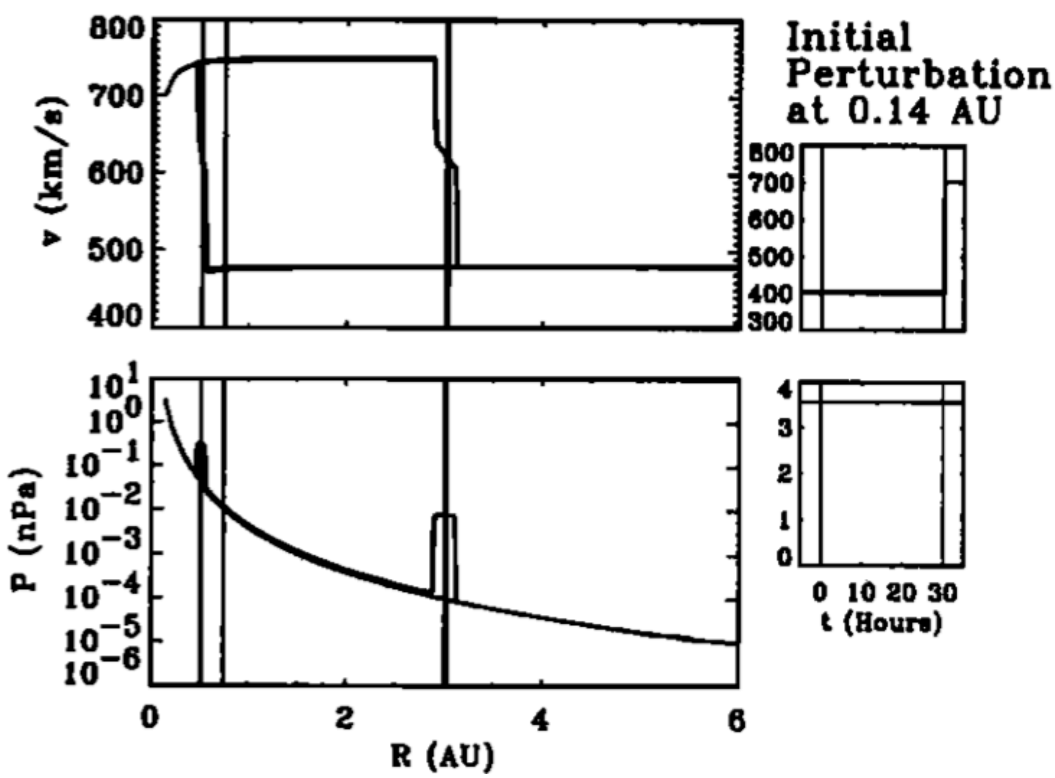

Figure 1. Left: Solar wind speed and pressure versus heliocentric distance 83 and 250 hours after introducing a step function increase in speed at 0.14 AU. Right: Temporal perturbation introduced at the inner boundary. Vertical lines bracket the last 30-hr of slow wind passing 0.14 AU. Adapted from a 1D gas dynamic simulation by Gosling and Riley (GRL, 23, 2867, 1996).

A region of high pressure quickly forms at the interface between the slower and faster plasmas as the faster wind overtakes the slower wind. This compression region is bounded by a strong forward-reverse shock pair. With increasing heliocentric distance the compression region broadens as the forward shock propagates into the slower wind ahead and the reverse shock propagates back into the trailing high-speed plasma. The slower plasma is compressed and accelerated as it is swept up by the forward shock and the faster wind is compressed and decelerated as it encounters the reverse shock. When the slow and fast wind densities are equal at the inner boundary, as in this example, a step function increase in speed results in approximately equal and opposite speed changes in the fast and slow wind. The last 30 hours of initially slow wind is increasingly compressed at larger heliocentric distances yet never experiences a change in speed greater than half the original difference in speed between the fast and slow flows. This result is a consequence of overall momentum conservation.

6.

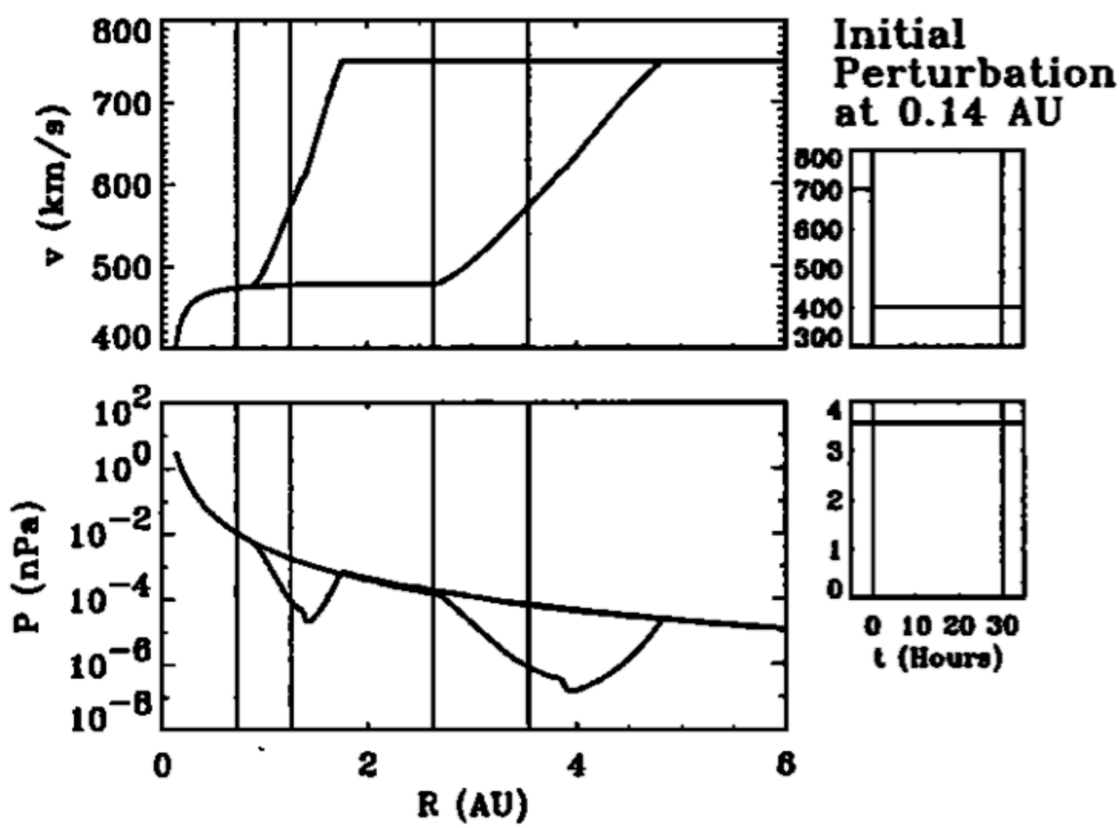

Figure 2. Left: Solar wind speed and pressure versus heliocentric distance 83 and 250 hours after introducing a step function decrease in speed at 0.14 AU. Right: Temporal perturbation introduced at the inner boundary. Vertical lines bracket the first 30-hr of slow wind passing 0.14 AU. Adapted from a 1D gas dynamic simulation by Gosling and Riley (GRL, 23, 2867, 1996).

A region of low pressure quickly forms at the interface between the two flows as the faster plasma runs away from the slower. The slower plasma just behind the interface is accelerated forward into the rarefaction by the enhanced outward pressure gradient, while the faster plasma just ahead is decelerated back into the rarefaction by the reverse pressure gradient. With increasing heliocentric distance the overall speed profile flattens as the rarefaction spreads both backward into the slower wind and forward into the faster wind. The first 30 hours of initially slow plasma gets ever broader as it moves out from the Sun and eventually all of that 30-hr parcel is accelerated to a higher speed; nevertheless, the change in its leading-edge speed remains less than half the original difference in speeds between the fast and slow flows. (The leading-edge speed increase is exactly half the difference if the perturbation in introduced at a distance where the ambient wind is no longer accelerating.) Again, this result is a consequence of overall momentum conservation.

7.

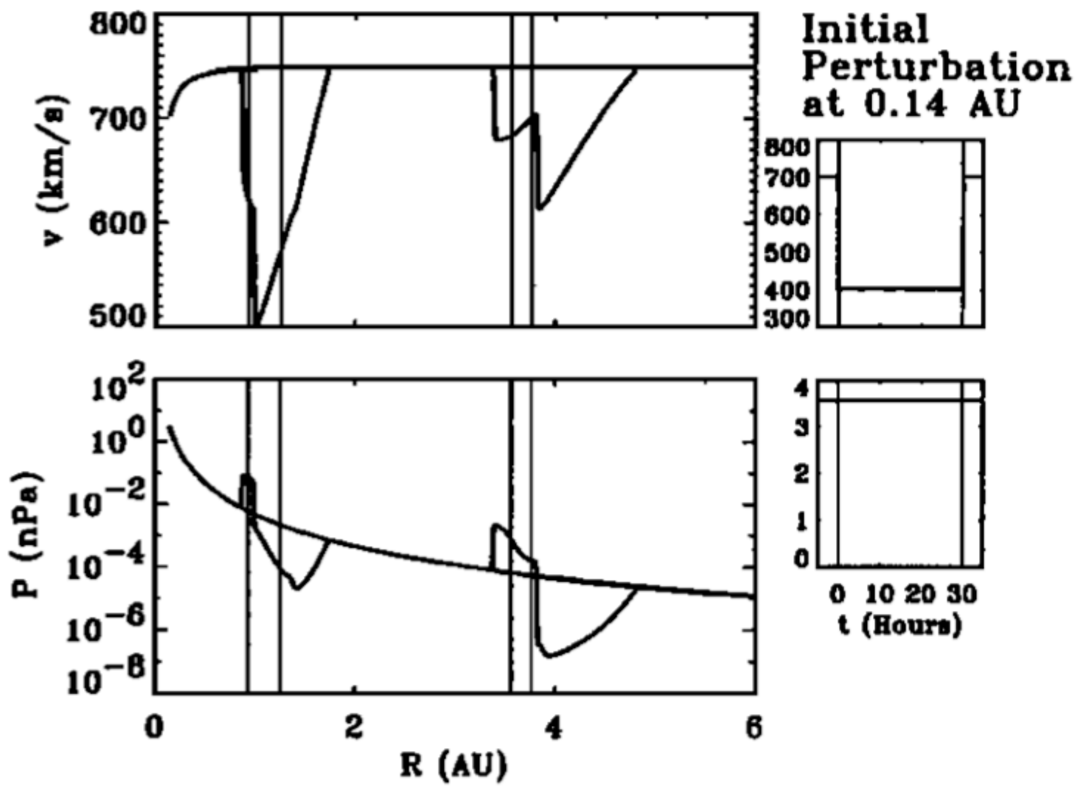

Figure 3. Left: Solar wind speed and pressure versus heliocentric distance 83 and 250 hours after introducing a square wave decrease in speed at 0.14 AU lasting 30 hours. Right: Temporal perturbation introduced at the inner boundary. Vertical lines bracket the 30-hr parcel of slow wind passing 0.14 AU. Adapted from a 1D gas dynamic simulation by Gosling and Riley (GRL, 23, 2867, 1996).

This example mimics in 1 dimension the ejection of a broad and relatively slow CME into a much faster surrounding ambient wind of the same density. A rarefaction forms on the leading edge of the 'CME' that spreads both forward into the ambient wind ahead and back through the CME. The forward propagation of this rarefaction produces a deceleration of the faster ambient wind ahead, while the backward propagation produces an acceleration of the CME and eventually also the trailing (modified) ambient wind. A region of strong compression, bounded by a forward-reverse shock pair, forms on the trailing edge of the CME. The reverse shock propagates back into the trailing high-speed wind, compressing and decelerating it, while the forward shock propagates into and, eventually, through the CME, compressing and accelerating it. By the time the CME reaches 3.6 AU it is traveling at a speed of ~680 km/s, only 70 km/s slower than that portion of the ambient wind as yet unaffected by the disturbance. Indeed, at 3.6 AU the CME is traveling faster than the (decelerated) ambient wind immediately ahead and behind.

The CME initially shrinks in size and begins to expand only after the forward shock passes its leading edge. With increasing heliocentric distance both shocks weaken, the disturbance amplitude decreases, and the CME speed increasingly approaches that of the undisturbed ambient wind. The CME represents a finite (negative) momentum pulse that increasingly is shared via the compression and rarefaction waves with an ever-larger volume of the ambient high-speed wind. The end result of this momentum sharing with what is effectively an infinite medium is that the CME eventually gets accelerated nearly up to the ambient wind speed.

8. In the kinematic model the region of radial field is not populated by plasma. However, as noted in the answers to problems 6 and 7, a sudden drop in flow speed produces a sudden drop in pressure and a rarefaction wave immediately propagates both forward into the high-speed flow and backward into the low-speed flow. The high-speed wind is decelerated by its interaction with the rarefaction wave and the low-speed wind is accelerated by that interaction. The net effect is to populate the region between the originally fast and originally slow wind (i.e., the region of radial field in Figure 8.13) with plasma, to enlarge the region where the field does not follow a Parker spiral, to bend the field therein more toward the spiral direction, and to smooth out the sharp kinks in the field evident in Figure 8.13.