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Global Aspects of Stream Evolution in the Solar Wind

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Abstract

A spatially variable coronal expansion, when coupled with solar rotation, leads to the formation of high speed solar wind streams which evolve considerably with increasing heliocentric distance. Initially the streams steepen for simple kinematic reasons, but this steepening is resisted by pressure forces, leading eventually to the formation of forward-reverse shock pairs in the distant heliosphere. The basic physical processes responsible for stream steepening and evolution are explored and model calculations are compared with actual spacecraft observations of the process. The solar wind stream evolution problem is relatively well understood both observationally and theoretically. Tools developed in achieving this understanding should be applicable to other astrophysical systems where a spatially or temporally variable outflow is associated with a rotating object.

Introduction

The solar corona is highly non-uniform, being structured by the complex solar magnetic field into a series of arcades, rays, holes, and streamers. Thus it is not surprising that the solar wind at 1 AU is highly variable since solar rotation insures a progression of different coronal structures at the central meridian of the sun. Spacecraft observations reveal that the major excursions of solar wind speed, density, and pressure conform to a characteristic pattern of variability,¹ which has come to be known as solar wind stream structure.

Figure 1, which shows the result of superposing data from 25 streams², illustrates the typical appearance of a solar wind stream at Earth's orbit. At the leading edge there is a rapid rise in flow speed, which is followed by a much slower decline back to low values. As the speed rises, the density quickly attains a maximum several times greater than its average value. As the speed falls, the particle density falls to abnormally low values. The gas pressure also maximizes as the speed rises and is relatively constant throughout much of the trailing portion of the stream. On the leading edge of the stream, the flow is deflected first to the east (i.e. flow from the east of the sun) and then to the west.

The above pattern of variability is the inevitable consequence of the evolution of a stream as it progresses outward from the sun. Such evolution continues as a stream moves beyond Earth's orbit, producing dramatic changes in stream structure in the distant heliosphere. Gas dynamic^{3,4} and magnetohydrodynamic^{5,6} codes of varying degrees of sophistication have successfully modeled the stream evolution process. Indeed, the agreement between model predictions and spacecraft observations over a wide range of heliocentric distances is one of the major triumphs of solar wind physics. In this paper we shall be concerned with providing a simple physical description of the problem and in exploring consequences of stream evolution in the distant heliosphere. The paper is intended to be a mini-tutorial rather than a review, and no attempt has been made to provide comprehensive referencing. More detailed treatments of the subject can be found elsewhere.^{7,8}

Solar Origins of Stream Structure and Kinematic Stream Steepening

As previously mentioned, the solar wind expansion is spatially variable, with high speeds generally originating in magnetic unipolar regions of low coronal density known as coronal holes^{9,10} and low speeds originating in regions of high density near field polarity reversals such as found in coronal streamers.^{11,12,13} Alternately slow, then fast, then slow, etc. plasma is directed Earthward as the sun rotates. A snapshot of the speed of Earthward-bound plasma as a function of heliocentric distance inside of 1 AU at some initial time, t_0 , might appear as in the upper panel of Figure 2. The dots in the snapshot identify discrete parcels of plasma moving at different speeds; these parcels originated from different positions on the sun at different times. (A similar radial variation in speed would result if the coronal expansion were spatially uniform but temporally variable on a time scale of several days.) The faster-moving plasma at the crest of the stream overtakes and collides with the slower plasma ahead while simultaneously running away from slower-moving plasma behind it as the stream moves out from the sun. As a result, the stream evolves towards a sawtooth form with increasing heliocentric distance as illustrated in the middle and bottom panels of Figure 2. In addition, material within the stream is rearranged as the stream steepens; parcels of plasma near the leading edge are compressed and heated while parcels on the trailing edge are rarified and cooled. Some of the slow moving plasma ahead is swept up by the stream. The temporal variations of solar wind speed, density, and pressure shown in Figure 1 are readily identified with such evolved streams.

Dynamical Response of the Solar Wind to Kinematic Stream Steepening

To this point, the evolution of a solar wind stream has been discussed purely as the kinematical result of a nonconstant radial velocity profile, which in turn is a consequence of nonuniform coronal expansion and solar rotation. In actual fact, there is a dynamical response to the steepening process which both limits the steepening and leads to new features at very large distances from the sun. Consider, for example, a fluid parcel approximately halfway up the leading edge of the stream. If the stream amplitude is v_0 , as in Figure 3, then this parcel sees plasma streaming towards it from both the sunward and the anti-sunward directions at speeds ranging up to $v_0/2$. Because the plasma is constrained from interpenetrating by virtue of the weak magnetic field imbedded in it, the pressure builds up to resist this inflow of material from both sides. The onrushing plasma is decelerated, compressed, and heated as it encounters the pressure gradient. In the reference frame of the Earth these decelerations appear as an acceleration of the low speed plasma near the trough of the stream and a deceleration of plasma near the crest. The result is a transfer of momentum and energy from the fast-moving plasma to the slow-moving plasma.

Shock Formation

The pressure ridge induced by stream steepening initially propagates outward into the onrushing plasma at the fast mode speed, c_f , which at 1 AU is $\sim 70 \text{ km s}^{-1}$. So long as $c_f - v_0/2 > 0$, the stream will gradually damp out as described above. However, for large amplitude streams where $c_f - v_0/2 < 0$ the pressure ridge can not expand outward rapidly enough at the fast mode speed to

warn the onrushing plasma of the impending collision. When this occurs the pressure grows nonlinearly as the stream steepens and a pair of shocks form on either side of the high pressure region. One of these shocks propagates backward towards the crest of the stream, while the other propagates forward towards the trough. However, both shocks are convected away from the sun by the very high bulk flow of the wind. Observations indicate that few, if any, streams steepen sufficiently inside 1 AU to cause shock formation by the time streams cross the Earth's orbit.² Nevertheless, because c_f decreases with increasing heliocentric distance, virtually all large solar wind streams should eventually contain a double shock structure at very large distances from the sun.

A Simple Model Calculation of Stream Evolution Beyond 1 AU

Using "reasonable" boundary conditions near the sun, numerical models incorporating the physics discussed above can reproduce the coupled variations in speed, density, and pressure which are observed in the solar wind at 1 AU. Further, the codes can be used in conjunction with the 1 AU observations to predict stream evolution beyond Earth's orbit. Figure 4 shows the result of such a calculation of stream evolution¹⁴ using a simple 1-dimensional gas dynamics code.³ Three successive repetitions of the "average" stream structure shown in Figure 1 with peak velocities separated by eight days were used as the input signal at 1 AU to calculate the stream structure at larger distances. The figure displays solar wind speed and density as functions of heliocentric distance at a time when the three streams introduced at 1 AU are spread out between 1 and 6 AU. Clearly visible in this display are the formation of the forward-reverse shock pair bounding the compressed shell of plasma on the

rising portion of each stream. These shocks give the velocity profile the appearance of a double sawtooth. The stream amplitude decreases and the compression region expands with increasing heliocentric distance as the reverse shock propagates back into the crest of the stream and the forward shock propagates into the lower speed plasma ahead. Thus, damping of the stream occurs by removal of the fastest and slowest material. By 5 AU a large fraction of the mass in the solar wind flow should be found within compression regions at the leading edges of streams.

Observations of Solar Wind Streams in the Distant Heliosphere

Observations of solar wind streams in the distant heliosphere by instruments aboard Pioneers 10 and 11 and Voyagers 1 and 2 are in reasonably good agreement with the predictions of this simple 1-dimensional model. Figure 5 shows two successive 25-day sequences of hourly solar wind speed values obtained between 4.03 and 4.23 AU.¹⁴ It is quite clear that each stream during this interval was sawtooth-like in appearance, there being one or more abrupt rises in speed at the leading edge of each stream. More complete observations, including measurements of density, temperature, and field strength establish that the abrupt jumps in speed are, in fact, the shocks predicted by the model.^{15,16}

Experimental Test of a Stream Evolution Model

This comparison has been made more explicit by taking advantage of intervals when one of the distant Pioneers or Voyagers was nearly radially aligned with the sun and Earth. In such cases measurements made near Earth can

be used to predict stream structure further out, and this predicted structure can be compared in detail with the actual observations. Figure 6 illustrates the result of such a comparison.¹⁷ The upper panel contains the solar wind speed profile measured near Earth by IMP 7. (A gap in the data is caused by passage of IMP 7 into the Earth's magnetosphere where the solar wind can not be directly sampled.) The middle panel shows the speed profile of this same stream measured approximately 16 days later at 4.65 AU by Pioneer 10. In order to compare the two profiles, the Pioneer 10 data have been shifted forward in such a manner that the leading edge of the stream would be coincident at both spacecraft had the plasma on the leading edge of the stream propagated at constant speed from the Earth out to Pioneer 10. In fact, the stream arrived two days "early" at Pioneer 10, a consequence of the advance of the leading edge of the stream into the slower plasma ahead. In addition, the Pioneer 10 profile is more sawtooth-like and contains two shocks on the leading edge which were not present at 1 AU. Finally, the high frequency structure present at 1 AU between days 6-10 is considerably damped in the Pioneer 10 data.

The bottom panel of Figure 6 shows the predicted speed profile at Pioneer 10 using the IMP 7 measurements of speed, density, and pressure as inputs to the aforementioned 1-dimensional gas dynamics code. Agreement between the predicted and the observed speed profiles is quite good, although the model overestimates the amplitude of the shock transitions and underestimates the width of the shell of compressed gas between the shocks. (More sophisticated codes, for example, 2 or 3-dimensional MHD, improve the agreement between model predictions and observations.¹⁸) Note that the model predicts that the short wavelength structure present on the leading edge of the stream as it passed 1 AU should be damped out by the time the stream reaches 4.65 AU, as observed.

Local velocity fluctuations are quickly wiped out as each sub-stream exchanges momentum with its immediate surroundings and is swept up by the longer wavelength stream. Thus the stream evolution process makes the solar wind act like a "low-pass filter" in the sense that only the longest wavelength velocity structures survive at large heliocentric distances.

Stream Structure in Two Dimensions

Thus far we have concentrated on stream evolution at a fixed longitude in space. An appreciation of the global extent of this evolution can be gained from Figure 7, which shows a model calculation of the equatorial density structure of the stream in Figure 6 at a particular instant in time assuming that the coronal expansion is time stationary (but spatially variable) in a frame of reference corotating with the sun.¹⁷ Curved arrows in the figure are streamlines, which trace out the locus of all parcels of plasma originating at common positions on the sun, but at different times. The various shadings represent density levels differing by factors of four and normalized to that for a steady structureless flow (r^{-2} decline). Darker shadings correspond to the higher densities. This entire pattern corotates with the sun; however, it is worth emphasizing that only the pattern rotates--each parcel of solar wind plasma moves outward nearly radially.

Figure 7 helps emphasize that the region of high compression is nearly aligned with the streamlines. Plasma flows into the compressed shell from both sides. In this particular example, maximum compression is attained at about 3 AU. Beyond 3 AU the region of greatest compression expands slowly. The total region of compression expands more rapidly as the strong forward-reverse

shock pair propagates away from the center of compression. By 5 AU streamlines originally separated by 180° in solar longitude are contained within the compression region bounded by the shocks.

In the absence of any other streams in the equatorial plane of the sun, the forward shock eventually overtakes the reverse shock from the same stream on the previous rotation,²⁰ as illustrated in Figure 8. Thus when the coronal expansion is time-stationary, all streamlines eventually cross one or the other of the shocks. In the example shown in Figure 8, the last streamline has a shock crossing beyond 20 AU from the sun. When two or more streams are present in the equatorial plane, the forward and reverse shocks from the various streams intersect before the above closure can occur. For example, Figure 9 illustrates that for two streams identical to the one shown in Figure 8 all streamlines contain shocked plasma beyond about 10 AU from the sun.

The basic structure of the solar wind in the distant heliosphere thus differs considerably from that observed at 1 AU. Stream amplitudes are reduced and high frequency velocity structures are damped out. What is left is expanding regions of high gas and field pressure²¹ fronted by shocks which intersect and interact with one another.²²

Stream Evolution in Three Dimensions

For time-stationary solar wind streams, it is solar rotation that ultimately drives the evolution of stream structure with increasing heliocentric distance. Thus we might expect stream evolution to proceed at different rates at different solar latitudes; streams should evolve most

rapidly in the solar equatorial plane, and more slowly at higher solar latitudes.^{23,24} Figure 10 shows a model calculation of the possible 3-dimensional configuration of a shock surface resulting from stream evolution.²⁴ In this particular example a stream uniform in latitude but having a square-wave variation of speed with longitude was assumed near the sun. For such a stream the rate of streamline convergence induced by solar rotation is a maximum in the equatorial plane and is zero over the poles. As a result, the shocks associated with the evolution of the stream form closest to the sun in the equatorial plane, and the shock surface takes the form of a Chinese pennant. Other shock surface geometries are obtained for different initial stream configurations. Nevertheless, the result is general: Streams should evolve at a slower rate at high solar latitudes. As spacecraft observations to date have been limited to near the ecliptic plane, this prediction has not yet been verified observationally. However, tests should be possible with data obtained from the International Solar Polar Mission, now scheduled for launch in 1986.

Numerical Code Comparison: 1-D, 2-D, 3-D; MHD, HD

From the foregoing it is apparent that the stream evolution problem is inherently 3-dimensional in character. Further, a magnetic field is imbedded within the solar wind, suggesting that magnetic forces play a role in stream dynamics. Nevertheless, as we have seen, 1-dimensional (1-D) gas dynamics codes are useful for obtaining an understanding of much of the basic physics involved and provide predictions in reasonable agreement with observations. The 1-D codes do, however, always predict too strong an interaction at the leading edge of a stream. In multi-dimensional codes (and in interplanetary

space) the plasma can partially relieve the stresses induced by kinematical stream steepening by simply slipping aside. Such slippage is responsible, for example, for the east-west deflection in the flow on the leading edge of a stream¹⁹ (see Figure 1). Further, MHD codes enhance this slippage since the magnetic field provides an additional pressure force and also increases the characteristic speed (fast-mode) with which the pressure signal can expand into the surrounding volume. In this section we wish to examine briefly the relative advantages of multi-dimensional codes with and without inclusion of the magnetic field.

Before proceeding it is useful to remember that it is solar rotation which drives stream evolution. The interaction front at the leading edge of a time-stationary stream is aligned nearly along a spiral (see Figures 7, 8, 9) and the largest pressure gradients all are perpendicular to this front. Thus the pressure forces associated with stream steepening produce primarily azimuthal and radial deflections of the flow. (Azimuthal deflections are more important inside of 1 AU where the spiral is generally inclined less than 45° to the radial direction and radial deflections are more important outside of ~ 1 AU where the spiral becomes inclined more nearly perpendicular to the radial direction.) Meridional deflections, on the other hand, are a second order effect.

Figure 11 shows hypothetical variations in solar wind flow speed, density, and temperature at 0.3 AU.²⁵ The pattern is periodic in longitude and the magnetic field is of uniform strength (45 nT). Figure 12 shows the result of projecting this stream out to 1 AU in the ecliptic plane using 1-D, 2-D, and 3-D MHD models.²⁵ (The 1-D code relates the 0.3 AU longitudinal signal of

Fig. 11 with a temporal signal at that same distance by equating ϕ and Ωt , where ϕ is solar longitude, Ω is the angular rotation rate of the sun, and t is the time.) In going from 1-D to 2-D, relatively large changes in the predicted stream profile occur. The 1-D calculation (dashed line) overestimates the degree of compression and for this stream produces the familiar forward-reverse shock pair well inside of 1 AU. On the other hand, as expected from the above discussion, differences between the predictions of the 2-D and the 3-D calculations are minor. Both calculations indicate that azimuthal shears can delay substantially formation of the forward-reverse shock pair. However, since the spiral interaction front becomes more nearly perpendicular to the radial direction at larger heliocentric distances, both the 2-D and 3-D models eventually develop the shocks. The relatively minor differences between the 2-D and 3-D calculations clearly indicate that the computationally simpler 2-D codes are adequate for predictions in the solar equatorial plane where most measurements are made.

Figure 13 provides a similar comparison of the effect of including and neglecting the magnetic field.²⁵ In both examples illustrated, the stream of Fig. 11 was projected out to 1 AU in the equatorial plane using a 2-D model. In the HD (hydrodynamic, i.e. gas dynamic) calculation the forward-reverse shock pair again develops inside of 1 AU and the plasma is more highly compressed than in the MHD calculation. The plasma is better able to resist the kinematic steepening of the stream in the presence of a magnetic field because the magnetic field both provides an additional pressure force and increases the characteristic speed with which the pressure wave expands into the surrounding plasma. As the boundary conditions shown in Fig. 11 appear reasonable based upon direct solar wind measurements in the inner

heliosphere,²⁶ and because forward-reverse shock pairs associated with time-stationary streams are rare at 1 AU,² it is clearly important to include the magnetic field in model calculations of solar wind stream evolution.

Temporal Effects

Throughout this paper we have tacitly assumed that the coronal expansion, which produces the solar wind, is time-stationary. This assumption is most valid during the approach to and at the minimum of the solar 11-year activity cycle.²⁷ At other phases of the activity cycle the coronal expansion usually is variable on a time scale shorter than one solar rotation (~27 days as viewed from Earth), and transient solar wind disturbances are more common. Under these conditions the structure of interplanetary space is more complex than that illustrated in Figs. 7-10. Nevertheless, the basic physical processes outlined in this paper continue to operate at all phases of the solar cycle. We have emphasized that kinematical stream steepening is an inevitable consequence of variable flow speed along a radial line, and such steepening should occur regardless of what is responsible for establishing the radial velocity profile in the first place. For example, we mentioned near the beginning of the paper that the radial velocity profile of Fig. 2 could be the result of a temporally variable coronal expansion rather than a spatially variable one. In such a situation the compression region need not be aligned nearly along a spiral. In fact, for a spatially uniform but temporally variable coronal expansion the pressure ridge is an outward-moving spherical shell centered on the sun. More typically, high speed solar wind streams result from a combination of spatial and temporal variability, and the global structure of interplanetary space reflects such origins.

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Figure Captions

Figure 1. Characteristic variations in flow speed, density, pressure, and flow direction associated with a solar wind stream at Earth's orbit. These are average profiles of 25 streams which contained relatively large density compressions.²

Figure 2. A solar wind stream steepens kinematically. Plasma at the crest of the stream is moving faster than plasma in the trough and thus gradually catches up with it. As the stream steepens, parcels of plasma (indicated by dots) on the leading edge of the stream are compressed together, while those on the rear are spread out into a rarefaction.

Figure 3. Kinematic stream steepening leads to an enhancement in pressure on the leading edge of a stream. This pressure increase serves to limit the steepening of the stream by transferring momentum from the fast plasma at the crest to slow plasma in the trough. When the stream amplitude, v_0 , is large relative to the fast mode speed, a pair of shocks form on either side of the pressure enhancement. Typically this shock formation occurs well beyond the orbit of Earth.

Figure 4. Solar wind speed and density versus heliocentric distance predicted by a 1-dimensional gas dynamics model for three solar wind streams introduced at 1 AU. The light dashed lines indicate the variation with heliocentric distance expected for a steady, structureless flow.¹⁴

Figure 5. One-hour values of the solar wind speed observed by Pioneer 10 during a 50-day period when the spacecraft moved between 4.03 and

4.23 AU. The vertical lines emphasize abrupt speed jumps which are shocks.¹⁴

Figure 6. A comparison of the speed profiles of a solar wind stream observed first at 1 AU by IMP 7 and later at 4.65 AU by Pioneer 10 together with the stream profile at 4.65 AU predicted by a 1-D gas dynamical model. The 1 AU observations were used as the boundary conditions for the model calculations.¹⁷

Figure 7. Calculated equatorial density structure of the high speed solar wind stream of Fig. 6. The various shadings represent density levels differing by factors of four and normalized to the r^{-2} variation expected for structureless flow. The curved arrows are stream lines and the heavy, jagged lines are the shocks formed by stream steepening.¹⁷

Figure 8. Stream compression region in the solar equatorial plane for a stream similar to that of Figs. 6 and 7 assuming steady state for four solar rotations. The compression region beyond ~ 3 AU is bounded by a forward-reverse shock pair (solid lines), and hence broadens with increasing heliocentric distance. Beyond ~ 20 AU the forward and reverse shocks intersect one another in this example.

Figure 9. Stream compression regions in the solar equatorial plane for two identical, stationary streams. The compression regions for the two streams begin to overlap at ~ 10 AU in this example; beyond that point all of the plasma in the equatorial plane has been shocked at least once.

Figure 10. A model's prediction of a single corotating shock surface in three dimensions. The location of the equatorial plane is indicated by lines radiating from the sun.²⁴

Figure 11. Hypothetical stream structure at 0.3 AU as a function of heliographic longitude. These initial conditions constitute the input for the model calculations shown in Figs. 12 and 13.²⁵

Figure 12. The effect of geometry on stream evolution and shock formation. Three models differing only in their dimensionality are used to project the stream structure of Fig. 11 out to 1 AU in the solar equatorial plane. Speed is at top; number density is below.²⁵

Figure 13. The effect of magnetic field on stream evolution and shock formation. Here, two-2-D models, one with and one without the magnetic field, map the flow to 1 AU.²⁵