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TRANSIENT PHENOMENA IN THE SOLAR ATMOSPHERE AND SOLAR WIND

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Observations of transient disturbances in the solar atmosphere are reviewed with emphasis on coronal mass ejection events. Although mass ejection events are surprisingly common (at least 66 were observed during the 227 day operation of the coronagraph on Skylab) and escape from the vicinity of the sun at speeds ranging from less than 100 to greater than 1200 km s^{-1} , present evidence strongly suggests that only the very fastest events produce shock wave disturbances in the solar wind at 1 AU. These fast events are almost always associated with large solar flares and metric wavelength Type II and/or IV radio bursts. However, the majority of coronal mass ejection events are associated with eruptive prominences (or disappearing filaments) and escape from the vicinity of the sun at speeds less than 500 km s^{-1} . Although these latter events eject of the order of a few times 10^{15} grams of coronal material and 10^{31} ergs into interplanetary space, they do not appear to affect significantly the velocity structure of the solar wind at 1 AU. However, they may be the source of anomalous, non-compressive density enhancements in the solar wind frequently observed at low and declining bulk flow speeds.

Statistical studies indicate that most shock wave disturbances in the solar wind at 1 AU are caused by very fast mass ejections associated with large solar flares. On the other hand, at large heliocentric distances (say beyond 3 AU) most interplanetary shocks arise from the steepening of the commonly observed high speed solar wind streams and thus, in general, have little to do with solar activity.

Introduction

Controversies form an important part of our scientific heritage. Two distinguished scientists - T. Gold and E. N. Parker - were the major protagonists in a controversy in the late 1950's and early 1960's concerning the origin of disturbances in the solar wind and the magnetic field geometry associated with these disturbances. Respective positions of the protagonists were staked out in scientific articles (e.g. Gold, 1959; Parker, 1961) and debates on the subject added spice to at least a few scientific gatherings (e.g. Davis, 1966; Parker, 1959). The crux of the argument between Gold and

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Parker boiled down to the question: At what height and where in the solar atmosphere do major solar wind disturbances originate? It was Parker's opinion that major solar wind disturbances probably resulted from a sudden increase in the rate of expansion of a part of the solar corona already previously expanding, i.e. a region already magnetically open to interplanetary space. According to this viewpoint, no additional magnetic flux is carried outward by disturbances, and all field lines in the solar wind remain open to the boundary of the heliosphere. Gold, on the other hand, was of the opinion that solar wind disturbances began with the ejection of material from regions low in the solar atmosphere where closed magnetic fields ordinarily restrained the gas from expanding. Both scientists agreed that if Gold's suggestion was correct closed magnetic loops or tongues would propagate out through the solar wind.

The Gold-Parker debate is of more than mere historical interest, for the problem of the field line geometry of solar wind disturbances remains unsolved (e.g. Gosling and Roelof, 1974; Gosling, 1975). Further, although we now know that Gold was essentially correct in suggesting that most major solar wind disturbances begin with the ejection of material from regions not previously participating directly in the coronal expansion, we have an excess of such ejections to explain. That is, there seem to be many more mass ejections from low in the solar atmosphere than major solar wind disturbances in the solar wind near 1 AU. Our discussion here will concentrate on reviewing those properties of solar mass ejection events that appear to be most germane to understanding their subsequent propagation through interplanetary space. At the end of this discussion we will suggest an identification of mass ejection events in the solar wind at 1 AU.

Eruptive phenomena on the surface of the sun and in the lower solar atmosphere (e.g. eruptive prominences, disappearing filaments, flare sprays) have been familiar to astronomers since the advent of H α observations of the sun. (See e.g. reviews in Öhman, 1968, and Tandberg-Hanssen, 1967.) However, with only H α observations available it is not possible to determine the coronal response to or participation in these eruptions. Further, one can usually not determine if the eruptive material actually escapes from the gravitational pull of the sun. Radio burst studies (see e.g. reviews by Wild and Smerd, 1972; Smerd and Dulk, 1971; Stone, 1974) and green line and white light studies of the corona with ground-based coronagraphs (e.g. DeMastus et al., 1973; Hansen et al., 1974) confirm that the corona often actively participates in eruptive behavior. Nevertheless, it was only with the successful orbiting of satellite coronagraphs (e.g. Koomen et al., 1974; MacQueen et al., 1974) that the dynamical nature of eruptive events in the corona could be properly appreciated and quantitatively documented.

The Appearance of Coronal Mass Ejection Events

An example of a mass ejection event in the corona, photographed in white light by the coronagraph experiment on Skylab, is shown in Figure 1. At least 66 qualitatively similar events were observed by the coronagraph experiment during its 227 days of operation (May 1973 - January 1974). In particular, the loop-like appearance, so reminiscent of Gold's magnetic bottles, is a common characteristic of most of these events (Gosling et al., 1974; Hildner et al., 1975a; 1975b). The "clouds" of gas described by the

Figure 1. A coronal mass ejection event photographed at 1448 UT on 10 August 1973 by the High Altitude Observatory's white light coronagraph experiment on Skylab. The field of view is 6 solar diameters. The sun is obscured by the occulting disk at the center whose effective diameter is 1.5 solar diameters. The very strong radial gradient of coronal radiance has been attenuated by vignetting within the instrument and by dodging the print. From Gosling et al. (1974).

OSO 7 coronagraph experimenters (e.g. Brueckner, 1972; Koomen et al., 1974) are almost certainly just the brighter portions of these loop-like structures, a result of the OSO 7 coronagraph's low sensitivity and resolution. Time lapse photographs reveal that the loops of material move outward while apparently retaining their connection to the sun along the footpoints of the loops. All loop-like structures observed within the Skylab coronagraph field of view (approximately 2-6 solar radii ($R_{\odot}$) from sun center in the plane of the sky) escaped outward, most of them moving at constant or ever increasing speed. MHD bow waves form around the material ejecta which compress the ambient corona ahead of the ejecta and deflect the ambient corona from its outward path; the bent appearance of the coronal ray just to the south of the outermost loop in Figure 1 is caused by the ray's interaction with such a bow wave.

Associations of Mass Ejection Events With Other Forms of Solar Activity

Approximately half of the mass ejection events observed with the Skylab coronagraph can be directly associated with other forms of solar activity (Gosling et al., 1974; Munro et al., 1976). For example, the 10 August 1973 event shown in Figure 1 was accompanied by an eruptive prominence on the west limb of the sun. This association is a common one; of the events with known associations with surface activity, approximately 2/3 accompanied eruptive prominences. The other 1/3 were associated with large solar flares (1 B or greater); these flares all produced sprays observable in H α . It is probable that most of the events with no known associations with surface activity were associated with solar activity on the back side of the sun. Further evidence of the strong correlation between surface solar activity and coronal disturbances as observed with the Skylab coronagraph can be found in

Figure 2. Total number of coronal transients observed during seven solar rotations and average sunspot number vs longitude. From Hildner et al. (1976).

Figure 2 where the total number of observed coronal events during seven solar rotations and the average sunspot number are plotted vs solar longitude (Hildner et al., 1976). Note how both the coronal disturbance and sunspot numbers peak near heliographic longitude 200 degrees.

Despite the close association of coronal mass ejections with flare sprays and eruptive prominences, it is not true that the coronal events are comprised primarily of chromospheric material thrown up into the corona. On the contrary, simultaneous observations of prominence material in $H\alpha$ and $HeII$ 304Å and of coronal disturbances with the Skylab coronagraph reveal (Hildner et al., 1975b; Poland and Munro, 1976): 1) most of the material in the coronal event originates in the lower corona; the chromospheric material comprises only a small fraction of the total; and 2) the entire event is far larger, more energetic, and longer lasting than would be inferred from the $H\alpha$ observations alone. This is illustrated for the event of 26, 27 August 1973 by the drawing to scale in Figure 3. Note how the leading edge of the coronal event extends out to almost $3 R_{\odot}$ while the prominence loops are constrained to a height less than $1.8 R_{\odot}$.

Metric wavelength type II and IV radio bursts often accompany coronal mass ejection events (Cosling et al., 1974; Stewart et al., 1974a,b). Ground detected bursts of this sort which originate within about ± 45 degrees of the solar limb almost invariably are associated with coronagraph-detected mass ejections. On the other hand, many mass ejection events do not produce observable metric wavelength type II and IV bursts. We shall see in the following section that the speed with which the material moves outward appears to determine whether or not a given disturbance will generate a metric wavelength burst.

Figure 3. A drawing of the appearance of the solar atmosphere above the northeast limb of the sun at 0000 UT on 27 August 1973. The inner loop is a large, slowly rising prominence observed in both H α and He II 204 Å. The much larger outer loop is a coronal mass ejection event observed with the Skylab coronagraph experiment. The large spatial separation between the prominence and the coronal event shows that the coronal mass ejecta does not originate in the prominence and that the coronal event is far larger than would be inferred from prominence observations alone. From Hildner et al. (1975b).

The Speeds of Coronal Mass Ejection Events

The outward speeds of mass ejection events observed by the OSO 7 and Skylab coronagraph experiments varied over a range extending from less than 100 to greater than 1200 km s⁻¹. A histogram of the speeds of the leading edges of the events observed by the Skylab coronagraph is displayed in the upper panel of Figure 4 (Gosling et al., 1976a). For all events the average speed within the field of view of the experiment (approximately 2 to 6 R_⊙) was 470 km s⁻¹, and approximately equal numbers of events were found above and below this average. It is interesting that this average speed is close to the average solar wind speed at 1 AU (approximately 450 km s⁻¹), although the range of observed solar wind speeds (e.g. Gosling et al., 1976b) is considerably less than that of coronal mass ejection events.

The number distribution of speeds for coronal events associated with eruptive prominences and with flares are displayed in the second and third panels of Figure 4. The distributions are distinctly different. The typical flare associated event had a speed more than twice as great as the typical prominence associated event, the average speed for each type of event being 775 and 330 km s⁻¹ respectively. Note that the average speed for the flare associated events is considerably greater than the average flow speed of the solar wind at 1 AU, while that of the prominence associated events is slightly less than this average.

Figure 4. The number distribution of measured speeds of the leading edges of mass ejection events (upper panel) and the number distributions of speeds for mass ejection events associated with eruptive prominences, flares, and type II and IV radio bursts (lower panels). The cross hatched pattern is used when the speed is only a lower limit estimate. The arrows indicate average values; the vertical dashed line indicates the gravitational escape speed for material 6 solar radii from sun center. From Cosling et al. (1976a).

From examination of the lower panel in Figure 4 it is apparent that metric wavelength type II and IV radio bursts are associated only with events moving faster than about 400 km s^{-1} ; all but two events moving faster than 500 km s^{-1} produced either a type II or IV radio burst or both. Because of their high speed, most of the flare associated events produced bursts of this sort; several of the faster prominence events did so as well. According to Wild and Smerd (1972) and others, metric wavelength type II bursts are generated by shocks traveling outward through the corona; similarly Dulk et al. (1976) suggest that some type IV bursts are also produced by shocks in the corona. This suggests that the bow waves running in front of coronal mass ejection events become shocks when their speed exceeds 400 or 500 km s^{-1} . If so, then the characteristic speed with which MHD signals propagate in the lower (1.1 to $3 R_{\odot}$) corona, where metric wavelength bursts are generated, must be about 400 to 500 km s^{-1} .

The Mass and Energy Content of Mass Ejection Events

Satellite coronagraphs observing in white light (such as the OSO 7 and Skylab instruments) can not measure disturbances with a mass content below a few times 10^{14} grams. This threshold sensitivity depends somewhat upon the geometry of an event and arises because of the surface brightness of the background dust and electron coronas. In addition, thus far no comprehensive analysis of the mass and energy content of coronal disturbances detected by the OSO 7 and Skylab coronagraphs has been performed. However, estimates

Table 1

Event Date 1973	Mass (grams)	Energy (ergs)	Associated Surface Event	Reference
11 Jan. a	17×10^{15}	10×10^{30}	Flare	Stewart et al. (1974a)
11 Jan. b	8	?	Flare	Stewart et al. (1974b)
10 June	5.4	8.7	EPL	Hildner et al. (1975a)
10 Aug.	4	8.4	EPL	Gosling et al. (1974)
21 Aug.	8	10	EPL	Poland and Munro (1976)
26,27 Aug.	1	2	EPL	Hildner et al. (1975b)
7 Sept.	24	110	Flare	Gosling et al. (1975)
14,15 Sept.	2.7	5.4	?	Dulk et al. (1976)

Mass and energy estimates of some large mass ejection events.

for some of the brighter (i.e. more massive) events are available in the literature and are summarized in Table 1. For these large events the mass estimates range from 10^{15} - 2.4×10^{16} grams, and the energy estimates range from 2×10^{30} - 1.1×10^{32} ergs. Although sizable, these estimates in general fall considerably below estimates of the mass and energy content of shock wave disturbances in the solar wind at 1 AU.

Frequency of Occurrence of Mass Ejection Events

We have previously alluded to the fact that at least 66 mass ejection events were detected by the Skylab coronagraph during its 227 days of operation. Because the coronagraph observes events projected against the plane of the sky (i.e. perpendicular to the sun-earth line), it is most sensitive to events which occur near the solar limbs. If we assume that events observed by the coronagraph originated within ± 45 degrees of the solar limb and that no particular direction in space was preferred during the Skylab interval, then approximately 33 ejections should have occurred within ± 45 degrees of the solar central meridian. Considering the spatial extent of mass ejection events (see Figure 1) it appears reasonable to assume that the large majority of these 33 events would have reached the vicinity of the earth.

A Direct Correlation of a Mass Ejection Event with a Shock Wave Disturbance in the Solar Wind at 1 AU

Direct correlations between coronagraph observed mass ejections and disturbances in the solar wind near 1 AU are difficult because the coronagraph observations are strongly biased toward the solar limbs while most solar wind observations are made near the earth. Thus far it has only been possible to associate directly a solar wind disturbance at 1 AU with an observed coronal mass ejection event on one occasion (Gosling et al., 1975). Following a 2B flare at W46S18 on 7 September 1973 a massive ($\sim 2.4 \times 10^{16}$ gm) and rapidly moving (~ 960 km s⁻¹) ejection was observed with the Skylab

coronagraph. Metric wavelength type II and IV radio bursts accompanied the outburst of material. Approximately two days later a very large shock wave disturbance (Figure 5) was observed at Pioneer 9. As can be seen in the figure, during the 7-9 September period Pioneer 9 was located at a solar longitude of 41 degrees west, almost directly above the flare site. Estimates of the mass and energy content of the solar wind disturbance are in reasonably good agreement with the coronal estimates, and the shock speed at 1 AU and transit time from the sun to 1 AU fit nicely the estimates of a numerical model of disturbance propagation in the solar wind (Hundhausen and Centry, 1969). Thus, we can be confident in this case that the coronal mass ejection event was the source of the shock wave disturbance observed at 1 AU.

Figure 5. A large solar wind shock wave disturbance observed by Pioneer 9 on 9 September 1973. A very large solar flare, type II and IV radio bursts, and coronal mass ejection event occurred approximately 2 days earlier at W46 S18, almost directly at the subsolar point for Pioneer 9. From Gosling et al. (1975).

A Search for a General Association Between Coronal Mass Ejection Events and Solar Wind Disturbances

Let us now briefly summarize several characteristics of mass ejection events discussed to this point.

1) Mass ejection events are generally associated with surface manifestations of solar activity, but more often with eruptive prominences than with solar flares (approximately in the ratio 2:1).

2) Mass ejection events exhibit a wide range of outward speeds. On the average, flare associated events travel outward considerably faster than do prominence associated events (775 vs 330 km s^{-1}).

3) Most events moving outward at speeds greater than about 500 km s^{-1} produce ground-detected metric wavelength type II or IV bursts, or both. Events with speeds less than about 400 km s^{-1} apparently never produce radio bursts of this sort.

4) A typical mass ejection event contains of the order of a few times 10^{15} grams and has an energy associated with it of approximately 10^{31} ergs.

5) During the 8-month Skylab interval approximately 30 mass ejecta should have been directed earthward.

6) One example has been documented wherein a large and rapidly moving mass ejection in association with a 2B flare produced metric wavelength type II and IV radio bursts and a major shock wave disturbance in the solar wind at 1 AU.

The question we would now like to address is the following: What is the overall effect of these mass ejections upon the solar wind as observed near 1 AU? The example of 7-9 September 1973 and previous statistical studies (e.g. Hundhausen, 1972a; Chao and Lepping, 1974) indicate that the faster moving ejections, which are usually associated with large solar flares and which usually produce metric wavelength type II and/or IV radio bursts, also usually produce shock wave disturbances in the solar wind at 1 AU. The reason they do produce such disturbances is that their outward speeds usually greatly exceed the speed of the solar wind gas into which they propagate. The flare associated events must also be the most massive and energetic of the coronal events, for measurements near the earth indicate that the average shock wave disturbance in the solar wind contains 3.5×10^{16} grams and 1.4×10^{32} ergs (Hundhausen, 1972b). (Of course the 1 AU estimates could be in error for they depend upon an assumption of the cross-sectional area of solar wind disturbances. The area used in deriving the solar wind estimates corresponds to 1/4 of the 1 AU sphere centered on the sun; it is quite possible that most shock wave disturbances are not this broad.) These average solar wind values are near the upper limit of presently measured coronal values.

On the other hand, it appears unlikely that the slower moving mass ejection events, which are usually associated with eruptive prominences, produce shock wave disturbances in the solar wind at 1 AU. For one thing, their speeds close to the sun do not appear to be high enough to perturb strongly the flow of the wind at larger distances. Also, they contain less mass and energy than normally associated with shock wave disturbances at 1 AU. And, finally, they occur much more frequently than do shock wave disturbances. During the Skylab interval not a single shock wave disturbance was detected by the earth-orbiting Imp 7 and 8 satellites. There are, of course, gaps in the Imp 7 and 8 solar wind data caused by the passage of the

satellites behind the earth's bow shock; a total of 5 geomagnetic sudden commencements (SC's) occurred in these data gaps. If we assume that all of these SC's were produced by shocks, then 5 seems to be the upper limit for the number of shocks that impacted upon the earth's magnetosphere during this interval (May 1973 - January 1974). Yet, we estimated earlier that approximately 30 mass ejections were directed earthward.

It is also unlikely that the slow moving, eruptive prominence associated events produce high speed solar wind streams; virtually all of the high speed streams which occurred during the Skylab interval are thought to have originated in coronal holes (Sheeley et al., 1976; Hundhausen et al., 1976). What, then, happens to these relatively common, but slow-moving, coronal mass ejecta? In the next section we suggest that these slow moving coronal events may be the source of anomalous density enhancements in the solar wind frequently observed at low and declining bulk flow speeds.

Non-Compressive Density Enhancements in the Solar Wind

High speed solar wind streams steepen as they progress outward from the sun. Material is rearranged within the streams as a result of this steepening. High densities are found on the leading edges of streams where material is compressed, and low densities are found in the centers and on the trailing edges of streams where rarefactions occur (e.g. Neugebauer and Snyder, 1966; Carovillano and Siscoe, 1969; Gosling et al., 1972; Hundhausen, 1973). This rearrangement of material within streams as they move outward from the sun is a major source of density variability in the solar wind at 1 AU. Nevertheless, large density signals often occur at low and declining solar wind speeds which apparently do not reflect directly this rearrangement process (e.g. Belcher and Davis, 1971; Gosling et al., 1972; Pizzo et al., 1973).

Examples of non-compressive density enhancements (i.e. density enhancements not associated with positive speed gradients) can be seen in Figure 6 where 3-hour averages of the solar wind speed, density, and proton temperature have been plotted for 1 solar rotation in late 1973. Intervals when non-compressive density enhancements are present are shaded in the figure. The anomalous enhancements may be identified not only by the lack of an associated positive speed gradient but also by the fact that the proton temperature is normally 180 degrees out of phase with the density (in an adiabatic compression the density and proton temperature vary in phase with one another). At times these non-compressive density enhancements, which generally occur at speeds below 400 km s^{-1} , can be quite common; at least 4 examples are evident in Figure 6.

A more detailed look at a non-compressive density enhancement is provided in Figure 7. Note the out of phase nature of the density and temperature variations, the change in the temperature anisotropy across the boundaries of the enhancement, and the fact that the enhancement is moving at a lower speed than the gas on either side of it. A sizable mass and energy signal is associated with the enhancement. If we assume the enhancement fills $1/16$ of 4π steradians centered on the sun, then the integrated mass and energy signal for this particular event is approximately 5×10^{16} gms and 1.4×10^{32} ergs. These values are somewhat higher than is typical for such events.

Non-compressive density enhancements appear to be excellent candidates as the solar wind signals of coronal mass ejection events associated with

Figure 6. Three-hour averages of the solar wind speed, density, and proton temperature for 1 complete solar rotation in late 1973. The shaded areas emphasize large non-compressive density enhancements where the density and temperature are 180 degrees out of phase, and the speed is constant or falling. Such enhancements may be caused by slow-moving coronal mass ejection events. LASL Imp 7, 8 data.

typical eruptive prominences. They are reasonably common, occur at low solar wind speeds, and contain sizable amounts of mass and energy.

A Model Calculation of the Radial Evolution of a Coronal Mass Ejection Event

Consider the ejection of a dense blob of hot coronal material (such as would be the case for a coronal mass ejection event) into an ambient solar wind moving at approximately the same radial speed as the blob. Because the blob is dense, it is at a higher pressure than its surroundings. This pressure imbalance causes the blob to expand more rapidly than the surrounding gas as both travel outward from the sun. If the expansion is adiabatic, the final state obtained far from the sun when the blob is in pressure equilibrium with its surroundings will be one where the blob is both denser and cooler than the surrounding gas. This is precisely the signal common to non-compressive density enhancements in the solar wind at 1 AU.

We can make the comparison more explicit by attempting a numerical calculation of the radial evolution of a density pulse introduced into the solar wind using the 1-dimensional, adiabatic solar wind stream code developed by Hundhausen (1973). A triangular shaped density pulse 2.5 hours wide and of amplitude 10 times the ambient density was inserted into the model code at a heliocentric distance of 0.1 AU. Figure 8 shows the subsequent evolution of the density and temperature signals associated with the pulse 5, 35, 86, and 167 hours later. As expected, at large heliocentric distances the pulse (indicated by the cross-hatched areas) is both denser and

Figure 7. The non-compressive density enhancement of 10-12 December 1973. The tops and bottoms of the vertical bars in the temperature plots indicate the maximum and minimum proton temperatures associated with the velocity distribution function. The density and temperature are out of phase for most of the event. LASL Imp 7, 8 data.

cooler than its surroundings. In addition, the model calculation suggests that a density and temperature signal (i.e. a pressure signal) propagates backward and forward from the original density pulse. This additional signal has not yet been identified in the solar wind data; it may be an artifact of a 1-dimensional calculation.

The purpose of the above calculation is to illustrate how slow moving coronal mass ejection might evolve with increasing distance from the sun. In practice, the evolution is undoubtedly more complex than this. We expect 2 and 3-dimensional effects to be important in damping out the pressure signal propagating outward from the density pulse, and the magnetic field should affect the evolution close to the sun as well. Further, because these events are slow moving, many will be swept up by high speed streams which follow. Such sweeping up effects are almost certainly the cause of abnormally large density compressions associated with some small amplitude high speed streams.

Concluding Comments

As we have discussed, there appear to be two different classes of coronal mass ejection events - 1) the more common eruptive prominence associated events, and 2) the large flare associated events. A distinguishing trait between these two classes of events is their outward speed; on the average the flare associated events travel more than twice as fast as the prominence associated events. The average mass and energy content of the

Figure 8. The radial evolution of temperature and density for a short duration density pulse introduced into the solar wind $t = 0$ hours. The shaded regions indicate the material originally within the density pulse; this material cools relative to the surrounding gas as the pulse expands.

two classes of events may be different as well, the flare associated events being more massive and energetic. These differences are reflected in the way the two classes of events affect the solar wind at 1 AU. The more rapidly moving flare events generally produce shock wave disturbances at 1 AU, while the slower moving prominence events generally do not. We have suggested that the latter events may be the sources of the relatively common (at times) non-compressive density enhancements observed at low solar wind speeds away from rising speed gradients.

Statistical studies of shock wave disturbances observed near 1 AU strongly indicate that most shocks at 1 AU are caused by flare associated mass ejections, and that few are caused by the steepening of high speed solar wind streams. At larger heliocentric distances, say beyond about 3 AU from the sun, the situation is reversed. At these distances virtually every large amplitude high speed stream has steepened into a sawtooth-like form with one or more shocks at its leading edge (Hundhausen and Gosling, 1976; Smith and Wolfe, 1976; Gosling et al., 1976c). These shocks are far more common than flare associated shocks. At least 8 such shocks can be seen in the two successive 25-day sequences of Pioneer 10 solar wind speed data taken between 4.03 and 4.23 AU and displayed in Figure 9. Because high speed streams during this interval generally originate in regions where the sun is inactive (i.e. coronal holes) and because stream steepening is strictly an interplanetary phenomenon, most shocks in the solar wind at large heliocentric distances have little to do with solar activity.

Figure 9. 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 the numerous shocks associated with high speed streams at these large distances from the sun. From Hundhausen and Gosling (1976).

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