TRANSIENT PHENOMENA ORIGINATING AT THE SUN - AN INTERPLANETARY VIEW

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ABSTRACT

An overview is given of various phenomena observed by numerous spacecraft in the interplanetary medium. These phenomena are related to transient solar events such as flares and coronal holes. The effects of such transient solar events are extensive. At times, a solar event can affect the interplanetary medium out to distances as far as 17.2 AU and over a wide range of azimuthal angles. Also some phenomena, such as high frequency fluctuations (precursors of shocks) in the interplanetary medium, appear beyond 1 AU. Thus, transient phenomena are significantly modified by their passage through this medium. The conclusion is reached that transient events originating on the sun and passing through the interplanetary medium represent complex and significant physical problems.

I. INTRODUCTION

An understanding of transient events originating at the sun is important because it provides insight into solar and interplanetary particle and field phenomena. Analyses of these events associated with solar phenomena can provide information on various processes and energy release mechanisms on the sun or in the solar corona. Comparisons of associated observations made at different points in the solar system provide information on the dynamics and evolution of plasma phenomena as they propagate through the interplanetary medium.

Initially highly localized phenomena can propagate identifiably near the ecliptic plane to large heliocentric distances and expand over a wide range of azimuthal (longitudinal) angles. Simultaneous particle and field measurements by the same spacecraft frequently show significant changes associated with the passage of transient phenomena in the interplanetary medium. At present a number of active spacecraft located near the ecliptic plane are providing in situ observations that can be used to study the spatial extent and the development of

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transient phenomena originating at the sun. An overall evaluation of
the latitude or three-dimensional solar system effects of these transi-
ent phenomena must await in situ observations out of the ecliptic, such
as those planned on the International Solar Polar Mission.

In this paper analyses of several transient phenomena are presen-
ted. Several of the interplanetary phenomena studied are apparently
associated with solar flares, others appear to be associated with
coronal holes. All of the events studied are recent, occurring in 1978
or 1979. Analyses of both the radial and azimuthal propagation of sev-
eral events based on in situ observations indicate that they can dras-
tically affect the structure of solar system particle and field regimes
at least to heliocentric distances of 17.2 AU and over a wide range of
($\geq 90^O$) of azimuthal angles.

II. OBSERVATIONS

Daily values of the solar wind proton number density and speed at
Venus during six solar rotations are shown in Figure 1. These parameters
were obtained at Venus by the NASA Ames Research Center plasma analyzer
(Intriligator et al., 1979a,b; Wolfe et al., 1979) on the Pioneer Venus
Orbiter spacecraft, after orbit insertion on December 4, 1978. The
variations of the parameters are indicative of the gusty nature of the
solar wind, particularly during the rising portion of the solar cycle.

The current solar cycle in terms of sunspot numbers is shown in
Figure 2. This figure is adapted from the Solar Geophysical Data and
indicates that to date this solar cycle has been exceptionally active
as compared with the average for the last thirteen cycles.

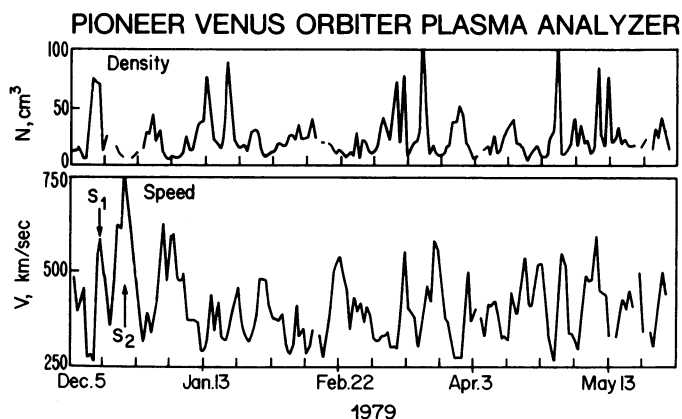The arrows in Figure 1 indicate two of the peaks in solar wind

Figure 1. Daily solar wind speeds and densities measured at
Venus. Values were obtained near noon UT for each orbit, upstream from
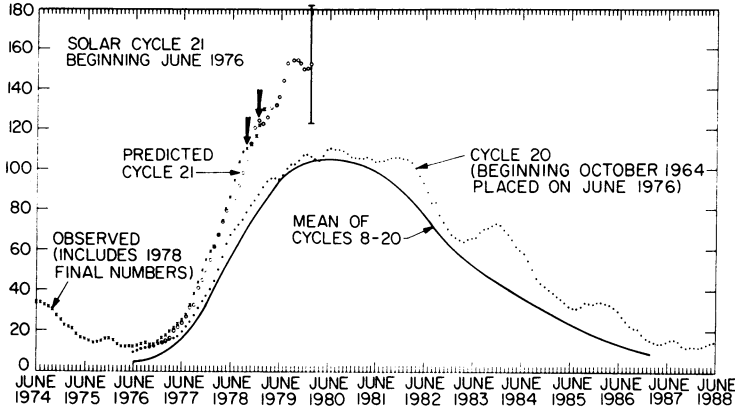the bow shock.

Figure 2. Observed and predicted sunspot numbers adapted from *Solar Geophysical Data*. The two arrows above the September 1978 and December 1978 values refer to the times of the two flares giving rise to transient phenomena discussed in this paper. Transient phenomena associated with a coronal hole in December 1978 are also presented.

speed that will be studied in greater detail below. The first event (S_1) we have tentatively associated with a 2N flare at S13 E29 on December 10th at 2332 UT. The event marked S_2 in Figure 1 appears to be a stream from a coronal hole, and forms an interesting contrast to the flare stream S_1. S_2 appears to represent a reemergence of stream activity near the region where a large coronal hole was located in previous solar rotations. In Figure 3 we have adapted the Carrington
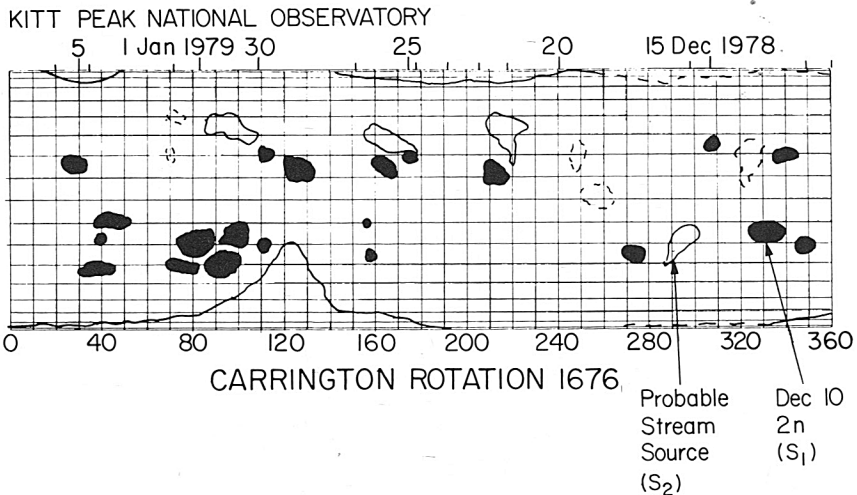

Figure 3. Carrington Rotation adapted from *Solar Geophysical Data*.

Rotation from the Solar Geophysical Data, and have indicated the location of the flare and the coronal hole.

Table I summarizes the sequence of events at the sun, Venus, and Earth associated with the December 10th flare. Also shown are the Pioneer Venus Orbiter (PVO) plasma data on an expanded time scale for December 13th indicating the forward shock. The ISEE magnetometer data indicating the subsequent forward shock near the Earth are shown, unfortunately ISEE plasma data are not available at this time. The ISEE data shown were kindly provided by Edward J. Smith. During this time Venus was located approximately 50° W of the flare site and Earth, approximately 30° W of it. The data in Table I, however, indicate that a forward shock was seen at both sites in association with this event.
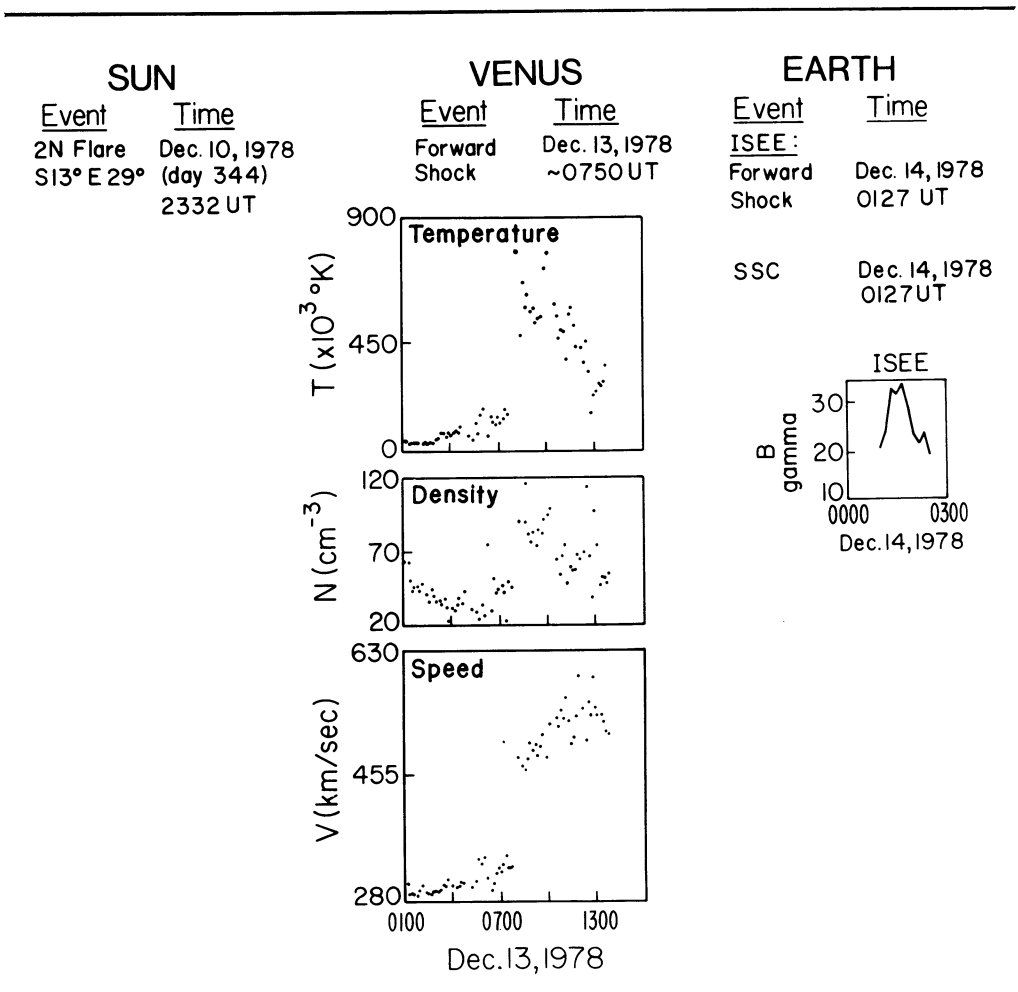
TABLE I

SUN		VENUS		EARTH	
Event	Time	Event	Time	Event	Time
2N Flare	Dec. 10, 1978	Forward	Dec. 13, 1978	ISEE:	
S13° E 29°	(day 344)	Shock	~0750 UT	Forward	Dec. 14, 1978
	2332 UT			Shock	0127 UT
				SSC	Dec. 14, 1978
					0127 UT

Dec. 13, 1978

Table II indicates the calculated local shock speed obtained at Venus using the flux conservation equation (Intriligator 1976):

$$V_{shock} \langle V,N \rangle = \frac{V_2 N_{p2} - V_1 N_{p1}}{N_{p2} - N_{p1}} \qquad (1)$$

for this event in December. This calculated local shock speed is compared with the average speeds of transit in Table III, where $V_{s \text{ to } V}$ refers to the average transit speed from the sun to Venus and $V_{s \text{ to } E}$ refers to the average transit speed from the sun to Earth.

The sequence of events summarized in Table I indicates that the flare associated plasma arrived at PVO at Venus on December 13, 1978 at 0750 UT and at Earth on December 14, 1979 at 0127 UT. Since, as noted above, at this time Venus (at 0.7 AU) was located approximately 50° W of the flare site and the Earth was located approximately 30° W of the flare site, it is particularly interesting to note the earlier time of arrival of the shock front at Venus. The comparison of the calculated shock speeds (Table III) indicates that the average transit speeds from the sun to Venus and from the sun to Earth were similar even though Venus was located approximately 20° further west of the flare site than the Earth. It is tempting to conclude that these analyses imply a spherically symmetric shock front over large ($\gtrsim 50^O$) azimuthal ranges. Alternatively, perhaps the shock front was not spherically symmetric and it propagated radially outward more rapidly within a few degrees ($\lesssim 20^O$) of the flare site and propagated radially outward more slowly at other azimuthal locations ($> 30^O$) from the flare

TABLE II

LOCAL SHOCK SPEED USING EQUATION (1)

EVENT	DAY	TIME, UT	V_1 km/sec	N_{p1} protons/cm^3	V_2 km/sec	N_{p2} protons/cm^3	$V_{SHOCK}\langle V,N \rangle$ km/sec
$S_1(V)$	D 347 1978	0750	330	46	465	137	533

TABLE III

COMPARISON OF CALCULATED SHOCK SPEEDS

EVENT	DAY	TIME, UT	$V_{s \text{ to } V}$ km/sec	$V_{SHOCK}\langle V,N \rangle$ km/sec	$V_{s \text{ to } E}$ km/sec
$S_1(V)$	D 347 1978	0750	533	533	563

site. In the case of the December 10th flare it is not possible to
unambiguously select one of these alternatives since at this time no
spacecraft was located within a few degrees of the flare site.

     In comparing Table II and Table III, it is interesting that the
local shock speed at Venus in the solar wind and the average transit
speed from the sun to Venus are the same for this event. Previous
observations, most notably of the August 1972 events (Intriligator 1976,
1977a; Smith 1976), have indicated essentially constant average speed of
propagation beyond 1 AU, but higher speeds near the sun.

     It is interesting to speculate that if, as is the case beyond 1 AU,
there is an essentially constant average speed of propagation near the
sun, it would imply for many previous flare studies (Intriligator 1976,
1977a; Smith 1976) that before the onset of the H-alpha flare there was
a local increase in the solar wind flux, and the solar wind speed. In
the case of the first large flare of the August 1972 events this would
imply that the enhanced solar wind flux began at approximately 2000 UT
July 29, 1972 or more than 100 hours earlier than the onset of the
H-alpha flare.

     There is a wide range of fluctutions in the solar wind associated
with these events. Figure 4 shows the low frequency power in the PVO
solar wind speed fluctuations associated with the December 10th event.
The variances (σ_v^2) shown are indicative of the levels of power in the
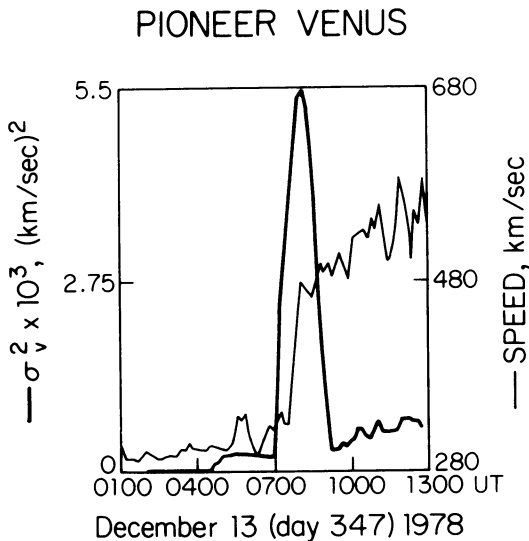10^{-3} to 10^{-4} Hz frequency range. These variances indicate that upon

PIONEER VENUS

Figure 4. Solar wind streaming speed and the variances (σ_v^2)
in the frequency range of ~10^{-3} to ~10^{-4} Hz associated with the fluctu-
ations of the hourly values of the speed at PVO.

the arrival of this event at PVO there are enhanced levels of low fre-
quency power associated with the fluctuations of the hourly values of
the solar wind speed. Figure 5 is from ISEE 3 and shows the higher
frequency power also observed at times. As indicated in the figure,
this higher frequency power occurs at frequencies six orders of magni-
tude higher than the fluctuations shown in the previous figure. These
data were kindly provided by F. L. Scarf, who has identified these
fluctuations as interplanetary ion sound waves.

        While many fluctuations are associated with high speed streams in
the solar wind (Intriligator, 1979), there are also other phenomena
associated with the propagation of high speed streams in the solar wind.
Figure 6 shows a high speed stream observed at 1 AU (IMP) and the same
stream as seen at Pioneer 11. As indicated in the figure, there is a
similarity in the overall speeds and duration of the stream at both
spacecraft but there are some differences particularly associated with
the peak of the stream. In this interval Pioneer 11 was at 1.6 AU
and was radially aligned with IMP. The histogram of each of these
streams is shown in Figure 7. Figure 7 shows that, as reported in
Intriligator (1977b), there is a narrowing of the solar wind speed his-
tograms with increasing radial distance. In addition, there is an
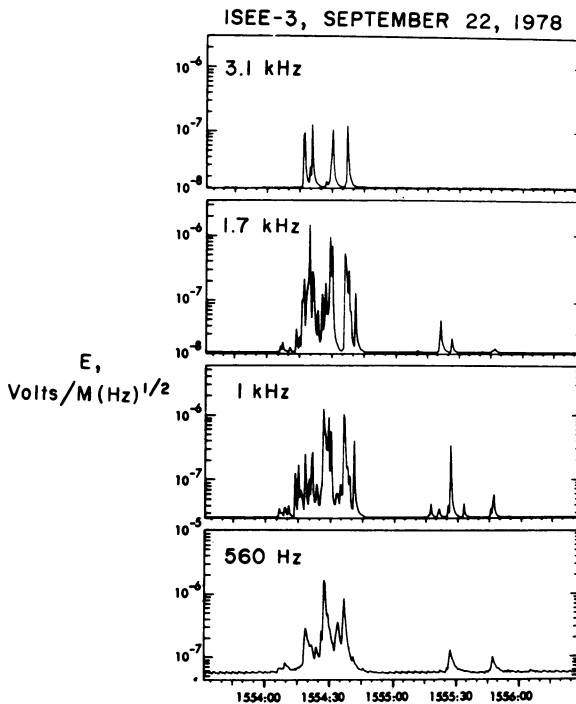erosion of the highest speeds as the stream propagates radially outward.

Figure 5. ISEE 3 plasma wave observations of the interplane-
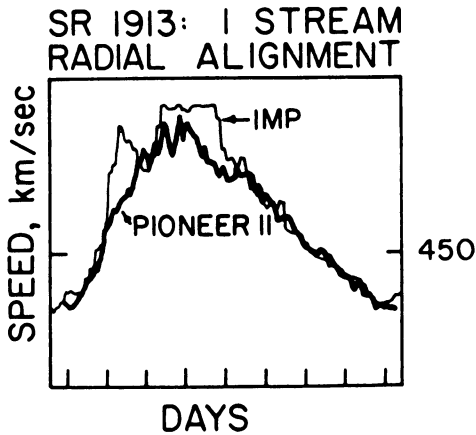tary ion sound waves at frequencies of ~10^{+3} Hz.

SR 1913: I STREAM
RADIAL ALIGNMENT

Figure 6. Superposition of solar wind speeds associated with a high speed stream at Pioneer 11 and at IMP.
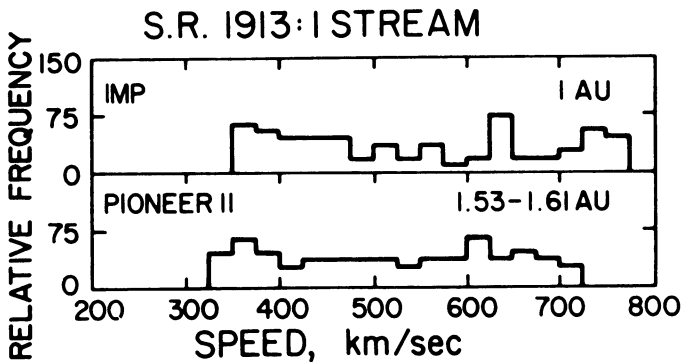
S.R. 1913:I STREAM

Figure 7. Solar wind speed histograms for the high speed stream shown in Figure 6.

    There has been successful modeling of the radial propagation of events in the solar wind. Dryer et al. (1979) used a one-dimensional magnetohydrodynamic model, input Pioneer 11 solar wind and magnetic field data at 2.8 AU, and predicted the parameters that would be observed at Pioneer 10 at 4.9 AU. Figure 8 is adapted from Dryer et al. and indicates the predicted Pioneer 10 parameters (dashed lines) and the observed parameters (solid lines). The curves in Figure 8 indicate that generally there is good agreement between the predictions of the model and the observed parameters. The temperature is the parameter that is not predicted well by this model and this could be the result of employing a single fluid model that does not allow for the thermal exchange between protons and electrons.
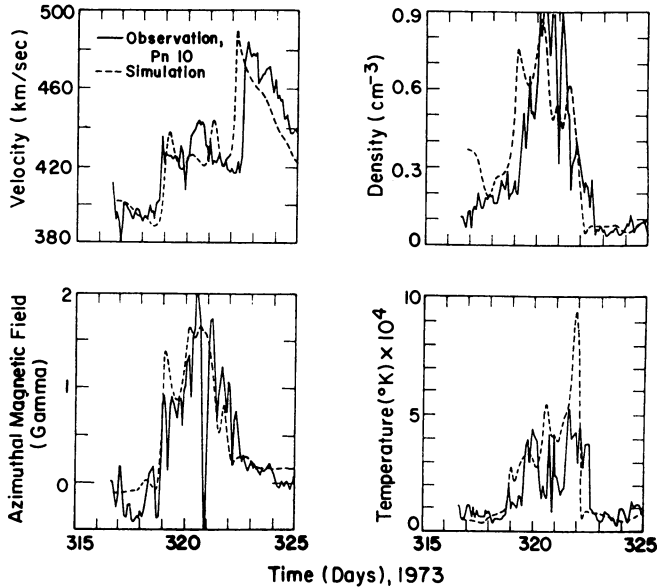
Figure 8. Comparison between 1-D MHD simulation and Pioneer 10 observations at 4.9 AU. The numerical simulation inputs Pioneer 11 observations at 2.8 AU, (Dryer et al., 1979).

At extended heliocentric distances, corotating interaction regions (CIR's) are formed in the solar wind (Smith and Wolfe, 1976). Figure 9 is from Smith and Wolfe and shows some of the characteristics in the plasma and field data that are indicative of the CIR's. At the leading edge of the CIR there is a forward shock that is characterized by a sharp increase in the solar wind speed, V, and the magnetic field magnitude, B. At the trailing edge of a CIR there is usually a reverse shock that is characterized by another sharp increase in the solar wind speed, V, and a distinct decrease in the magnitude of the magnetic field strength, B. In Figure 10, from Barnes and Simpson (1976), the Jovian electron (3-6 MeV) and the low energy proton data are shown. As indicated in the figure, the CIR's, which are denoted by the cross-hatched boxes above the abscissa, typically exclude the Jovian electrons and meanwhile there is an apparent increase in intensity of the 0.5-1.8 MeV protons. It is tempting to associate these proton observations and those of Marshall and Stone (1977, 1978); Pesses et al. (1978); McDonald et al. (1976), and Van Hollebeke et al. (1979) with some local interplanetary acceleration process which may, in fact, be accelerating the protons in the vicinity of CIR's.

Figure 11, which was kindly provided by F. L. Scarf, shows the high frequency (e.g., 1.78 kHz) precursors associated with an interplanetary shock observed at 2.25 AU in February 1978 by Voyager 2. These high frequency fluctuations were apparently not observed at 1 AU in association with this same shock (Scarf, private communication). Therefore,
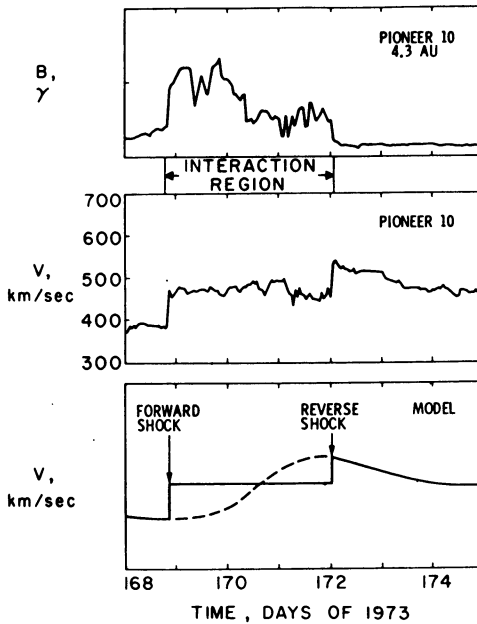
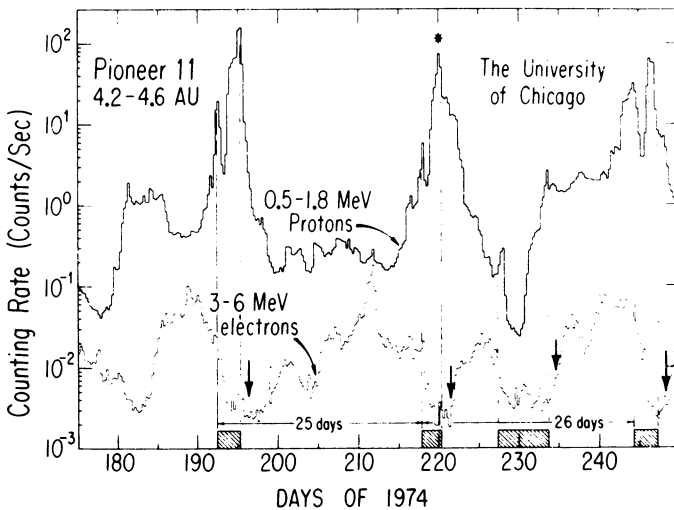Figure 9.   Corotating Interaction Region (CIR),   (Smith and Wolfe, 1976).

Figure 10.   The count rates for ~1 MeV protons and 3-6 MeV electrons are shown for ≈3 solar rotations. Well-identified CIR's occurring during this interval are indicated by cross-hatched bars along the abscissa. CIR's appear to exclude Jovian electrons and to produce MeV protons at forward-reverse shock pairs, (Barnes and Simpson, 1976).
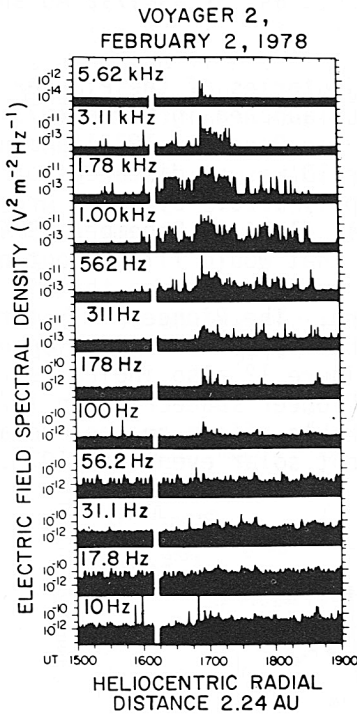
Figure 11. Precursors (e.g., 1.78 kHz) associated with an interplanetary shock at 2.24 AU as observed by the plasma wave experiment on Voyager 2. The shock occurred at approximately 1700 UT on February 2, 1978. High frequency precursor activity in several (e.g., 1.78 kHz, 1.00 kHz) channels began to be observed almost one hour before the shock. These data were kindly provided by F. L. Scarf.

at least in the case of this event, there are high frequency fluctuations that appear to be generated in the interplanetary medium as the shock propagates beyond 1 AU.

It is tempting to associate these high frequency fluctuations with the interplanetary acceleration processes that may give rise (e.g., through wave-particle interactions) to the observed increases in 1 MeV proton intensities in the vicinity of the CIR's. The identification of these interplanetary acceleration mechanisms is, in my opinion, one of the most important areas of interest in interplanetary physics today.

At times a transient phenomenon originating at the sun can drastically affect the overall structure of the particles and field environment in the solar system, over a wide range of heliocentric distances and azimuthal angles. In 1978, for example, a series of transient solar events occurred which significantly affected the solar system

environment out to heliocentric distances as far as 17.2 AU and over a
wide (>90°) range of azimuthal angles.

Figure 12 shows the outbound trajectories of the Pioneer 10 and
Pioneer 11 spacecraft. Pioneer 10 was launched in March 1972 and was
the first spacecraft to flyby Jupiter (in December 1973), and now is on
an escape trajectory. In 1978 Pioneer 10 was at distances of ~15 to
~17 AU. Pioneer 11 was launched in April 1973. By using gravity
assist at Jupiter during the Pioneer 11 flyby in December 1974, the
spacecraft was placed in a trajectory that would lift it out of the
ecliptic and carry it back across the solar system so that it would
be the first spacecraft to flyby Saturn. The Pioneer 11 Saturn flyby
successfully occurred in early September 1979. In 1978 Pioneer 11
was at distances of ~6.5 to ~8 AU. Figure 12 also indicates the wide
azimuthal separation between the two Pioneer spacecraft in 1978. The
next two figures illustrate the remarkable affect on the overall struc-
ture of the heliosphere of the transient solar events in 1978.
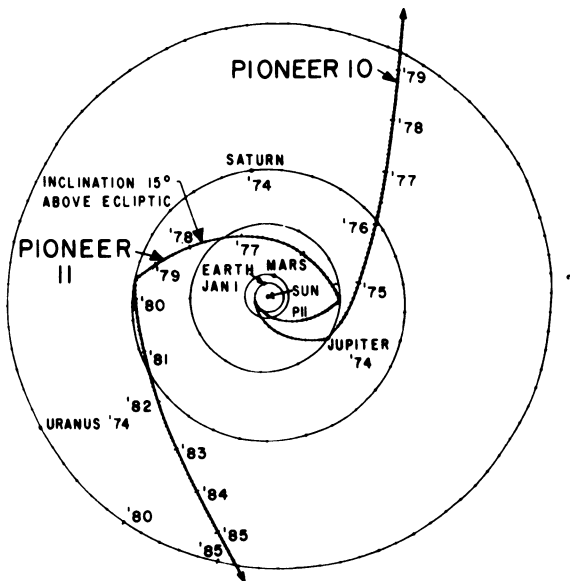

Figure 12. The Pioneer 10 and Pioneer 11 trajectories. The
location of Pioneer 10 in September 1978 is indicated by the arrow to
the right of the "Pioneer 10" label in the figure. Similarly, the
location of Pioneer 11 in September 1978 is denoted by the arrow to
the right of the "Pioneer 11" label in the figure. This figure indi-
cates the large heliocentric and azimuthal separation of the two space-
craft at this time.

Figure 13 is from Pyle et al. (1979) and shows that transients originating at the sun can affect the galactic cosmic ray intensities at distances of 15 to 17 AU. The curves in the top panel of Figure 13 indicate the galactic (energetic protons) cosmic ray intensities from late 1977 through 1978 observed on Pioneer 10. The anomalous helium intensities observed at Pioneer 10 are shown in the second panel in Figure 13. The solar wind velocities measured by the NASA Ames Research Center plasma analyzer on Pioneer 10 are shown in the third panel. The bottom panel in Figure 13 shows the Climax Neutron Monitor data for this time interval.

The Pioneer 10 observations indicate that for many months there were depressed levels of galactic cosmic ray intensities over a wide
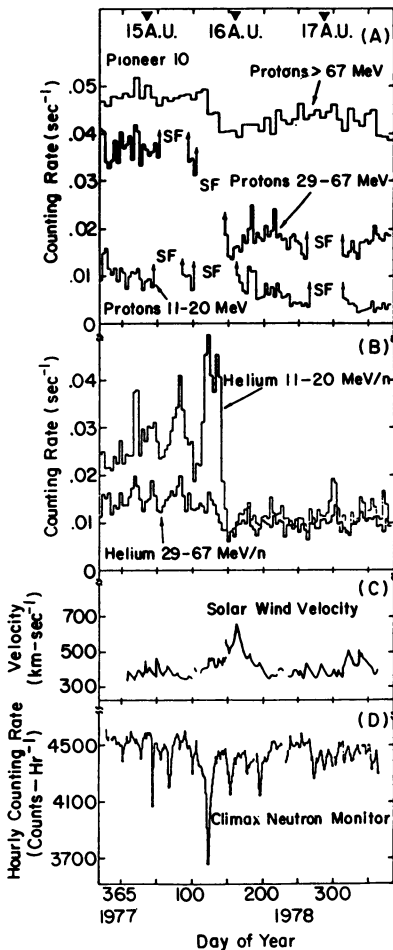

Figure 13. Pioneer 10 observations from ~15 AU to ~17 AU from Pyle et al. (1979). See text for a description of the observations.

range of heliocentric distances and angles. The onset of these de-
pressed levels was associated with a high speed stream in the solar
wind as indicated by the increase in the solar wind velocity data shown
in the figure. It is interesting to note that the high speed stream
persisted at these distances for several solar rotations.

Figure 14 is from Pyle et al. (1979) and depicts the 11-20 MeV and
low energy (0.5-1.8 MeV) protons, and the solar wind velocity at Pioneer
10 and 11, and IMP 8 during part of 1978. Pyle et al. state that the
higher energy protons observed at the spacecraft appear to be gener-
ated at the flare. They also interpret the times of arrival and patterns
of intensity buildup and decay in terms of expected effects on the par-
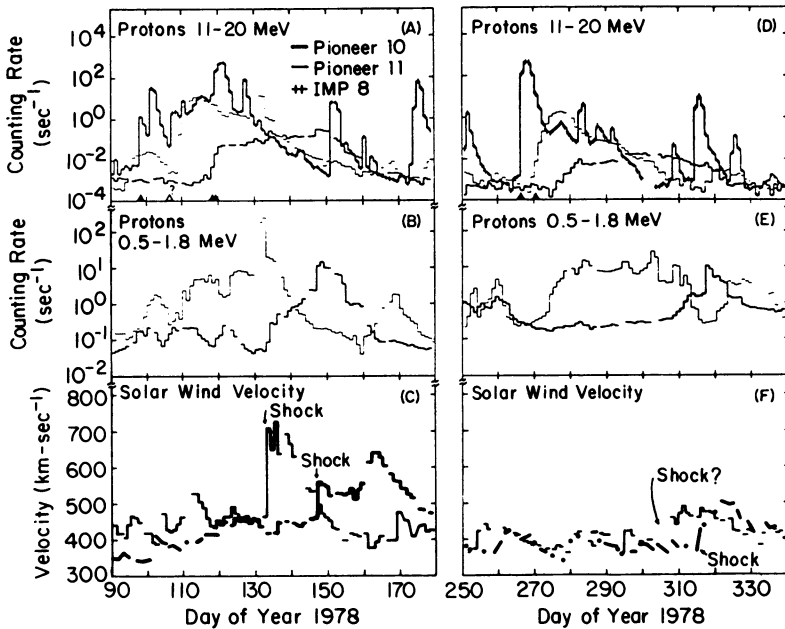ticles as they propagate away from the sun.

Figure 14. Pioneer 10, Pioneer 11, and IMP 8 observations in
1978 from Pyle et al. (1979). The top panels ((A) and (D)) show the
11-20 MeV proton observations, the middle panels ((B) and (E)) show the
0.5-1.8 MeV proton observations, and the bottom panels ((C) and (F)),
the solar wind speed.

III. DISCUSSION

The observations presented here give some indication of the wide range of complex and significant physical problems that are associated with an interplanetary view of transient phenomena originating at the sun. The observations show that phenomena originating at the sun affect the structure of the particles and fields regimes throughout the explored solar system, extending out to at least 17-20 AU in the vicinity of the ecliptic plane.

It is evident that further observational and theoretical studies along the lines of those presented here are necessary for future progress in this field. In particular, an understanding of the radial evolution of the interplanetary events and their associated phenomena (e.g., fluctuations) would require more multipoint spacecraft studies, including those among radially aligned spacecraft as emphasized in Intriligator (1979).

Additional studies between azimuthally separated spacecraft, however, can also significantly contribute to our understanding of solar and interplanetary physics. The discussion of the December 10th flare-associated phenomena presented above, serves as an appropriate illustration of this point.

Finally, in the next few years there is the prospect of making a great deal of progress in our understanding of the fundamental physical processes that govern these phenomena. We will have a number of well-instrumented spacecraft strategically located throughout the solar system obtaining important data. To make appropriate use of these observations we will need complementary theoretical studies including those in plasma physics and we will need to take an interdisciplinary approach interrelating the various aspects of the solar phenomena, interplanetary phenomena, and the basic physics and plasma physics phenomena. Our understanding of the solar and the interplanetary plasma processes associated with these phenomena is, in my opinion, one of the most significant scientific challenges today.

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DISCUSSION

Sheeley: Can you confirm Murray's (Dryer) suggestion (for the
Pioneer Venus quick look data) that there was a shock apparently
associated with the May 8, 1979 coronal transient?
    Intriligator: Available quicklook data suggest rapid changes in a
few hours, but do not clearly indicate a shock. We will have more
complete information on this event when data tapes are available.

Bhatnagar: Have you tried to look into the correspondence with
coronal transients and shocks observed at Saturn (etc.) distances?
    Intriligator: We have just started to look into the correspondence
of interplanetary phenomena and coronal transients. For example, the
coronal transients in May of this year were brought to our attention
by Dr. Dryer, and we have started analyses of our Pioneer Venus Orbiter
plasma analyzer data in the vicinity of Venus to ascertain the
correspondence between coronal transients and our observations. To date
we have not performed any studies of coronal transients and plasma

observations at extended heliocentric distances such as in the vicinity of Saturn. In the case of interplanetary shocks, Dryer et al., (*JGR*, *83*, 1165, 1978) have associated several flare generated shocks observed in conjunction with Type II radio bursts on 1976 March 20 (during STIP Interval II) with Pioneer 10 observations of a possible shock at 9.7 AU on 1976 April 9.

Dryer (Commet to Bhatnagar): I would like to comment on Dr. Bhatnagar's question concerning the interplanetary identification of coronal transients. There are two published cases in the literature. Wu et al. (*Solar Phys.*, *49*, 187, 1976) discuss the OSO-7 white light transient on 15–16 June 1972; the Adelaide IPS signature of an inter- planetary shock; a terrestrial sudden commencement; and the Pioneer 10 plasma observations of a possible shock followed by its disturbed flow. They used a 1-D hydrodynamic code to simulate the velocity and density profiles as observed at 1.6 AU by Pioneer 10. The observed (simulated) mass and energy in the interplanetary transient (assumed to subtend π steradians) were 7.7×10^{15}g (5.0×10^{15}g) and 1.4×10^{31} erg (4.5×10^{31} erg). The second published case is described by Gosling et al. (*Solar Phys.*, *40*, 439, 1975) who discuss the Skylab white light transient on 7 September 1973 and the Pioneer 9 plasma observations at 0.98 AU of a possible shock that was followed by its disturbed flow. The observed mass and energy in the interplanetary transient (again assuming π steradians) were 2.4×10^{16}g and 1.1×10^{32} erg.

The mass and energy for the two cases noted above are in reasonable agreement with the estimates given for coronal transients observed by Skylab (Rust et al., *Solar Flare Workshop;* P. Sturrock, Ed., pp. 314– 315, Colo. Univ. Press, 1979). Phenomenologically, then, we seem to have several good cases for identifying interplanetary "signatures" with the solar-observed coronal transient.

A third case is currently suspected. Michels et al. (this Proceedings) observed a coronal transient on 8 May 1979 with the P78-1 coronograph (Solwind). I have suggested, on the basis of daily samples of Pioneer- Venus-Orbiter plasma data, that this latter spacecraft at 0.78 AU may have detected the interplanetary "signature".

Sheeley: Did you say there was a solar event on the east limb 3–4 days ago?

Intriligator: McMath Region 16239 flared on the east limb on August 18th and 20th, and near the central meridian on August 26th. Region 16252 had a 98 minute 1B flare at 2137 UT on August 27th near the east limb, and minor flares on August 26th and early on the 27th that produced SID's.

Benz: The observed presence of ion acoustic waves in shocks could easily be explained by an unstable current. It represents enhanced resistivity and, by Ohm's law, an increase in the electric field. This can accelerate charged particles above a critical velocity (runaway process). Thus the observed presence of energized protons in shocks is probably not a coincidence. What is the ratio of electron to proton temperature?

Intriligator: As indicated in my presentation, I agree with you
that it is tempting to associate the enhanced intensities of 0.5 to
1.8 MeV protons at CIR's with wave-particle processes or other
acceleration processes. As to the ratio of electron to proton tempera-
tures, on Pioneer 10 and 11 generally the intensity of electrons was
not high enough beyond ~2 AU for us to measure them except during
special events such as the August 1972 events. Since, on Pioneer 10
and 11, CIR's were generally observed beyond ~3 AU we do not have
simultaneous plasma electron temperatures to compare with our plasma
proton temperatures.

Kahler: What is the interplanetary signature of a low-speed mass
ejection?
Intriligator: This is one of the areas we are studying at the
present time and hopefully in the near future we will have some specific
information on this.