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Compression of the Venusian Ionosphere on May 10, 1979, by the Interplanetary Shock Generated by the Solar Eruption of May 8, 1979

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An interplanetary shock wave that was produced by a solar eruption and its associated coronal transient on May 8, 1979, has been 'tracked' through interplanetary space to a rendezvous 2 days later with Venus. The interaction of the shock wave with the ionospheric obstacle at Venus produced a significant compression of the dayside ionosphere. It is believed that the tracking, as it were, was accomplished for the first time via the diagnostic observations provided by Hα and white light imagery near the sun and the plasma and field measurements of two, nearly radially aligned, spacecraft.

INTRODUCTION

The inward and outward movements of Venus' bow shock and ionopause in response to varying solar wind conditions have now been reliably established by the studies, for example, of *Brace et al.* [1980], *Slavin et al.* [1980], *Hartle et al.* [1980], *Vaisberg et al.* [1980], *Elphic et al.* [1980], *Mihalov et al.* [1980], and *Taylor et al.* [1981]. Such variability, of course, came as no great surprise since it has long been known [cf., *Binsack and Vasyliunas*, 1968] that the earth's bow shock and magnetopause respond to solar wind variability. In this context an ionopause and magnetopause share a fundamental physical reality, namely, a pressure balance (plasma plus magnetic) required to establish a contact surface between the external, shocked solar wind and the internal plasma and/or magnetic 'obstacle' that produces the bow shock in the first place. Also, it has recently been confirmed [*Smith et al.*, 1981] that these boundaries at Jupiter also respond in phase with variability of that planet's solar wind environment. Not unexpectedly, it has been suggested that the bow shocks and magnetopauses of Mercury and Saturn also fit this 'rule.' Similarly, at Mars, *Intriligator and Smith* [1979] have suggested that the variability of the solar wind conditions is the key to the changing nature of the basic planetary interaction process at work at any given moment, i.e., whether the Martian 'obstacle' is magnetospheric or ionospheric.

As yet, however, the variability of these fundamental planetary boundaries has never been associated, unambiguously, with an explicit solar event that, when tracked through the interplanetary medium directly to the obstacle, produced the movement, inward and/or outward, of one (or both) of these boundaries. We use the word 'track' in the sense of detecting (*a*) an Hα-observed solar eruption; (*b*) the subsequent white-light coronal transient out to as far as 10 solar radii; (*c*) the in-situ shock wave caused by the transient as close as ~64 solar radii (0.3 AU); and (*d*) the in-situ shock, again, at ~156 solar radii (0.7 AU). The purpose of this paper is to present a case of Venusian ionosphere compression that was caused by a shock wave produced by a solar eruption about 44 hours earlier.

The events described here took place in May 1979, that is, some 7 months before the peak of the present solar cycle. Because of the expected solar activity at this time, and in preparation for the Solar Maximum Year, the STIP Project (Study of Traveling Interplanetary Phenomena) of SCOSTEP declared the months of May and June 1979 to be STIP Interval VI. The sun cooperated with a series of solar eruptions that were observed by remote and in-situ techniques. The P78-1 satellite (in orbit around the earth), Helios 2 (at 0.3 AU perihelion, west solar limb passage, relative to an observer at the earth), and Pioneer-Venus Orbiter (at 0.7 AU and about 112° west of the earth-sun line) play the major roles in the observations that lead us to suggest that, for the first time, a specific interplanetary shock wave can be identified (via its 'tracking' by *Michels et al.* [1980] and *Sheeley et al.* [1980*b*, 1981*b*]) as the agent that produced a compression of the dayside Venusian ionopause on May 10, 1979. Figure 1 shows, schematically, an ecliptic plane projection of the relative positions of P78-1 (at the earth), Helios 2, and Pioneer-Venus-Orbiter (PVO).

In the following discussion we will (*a*) summarize the earlier solar optical observations and the in-situ solar wind conditions that were also reported earlier in order to place the Venusian ionopause observations in perspective; (*b*) present the relevant ionopause observations during PVO orbits 150–161 (May 3–14, 1979); and (*c*) finally discuss some ideas concerning implications of propagating disturbances downward into the ionosphere, of ion current disruption at the ionopause, and of ion pickup in the ionosheath.

DISCUSSION

In order to provide background on the solar activity and interplanetary solar wind plasma relevant to the Venusian response to variable ambient conditions, we first review the observations reported by the P78-1 white light (Naval Research Laboratory) coronagraph experimenters, the solar wind plasma experimenters (MPI/Lindau) on Helios 2 and the solar wind (NASA/Ames) plasma experimenters on PVO.

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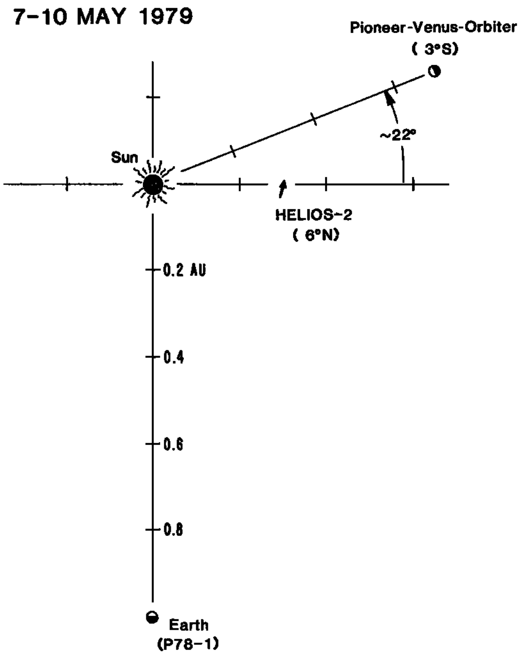

Fig. 1. Schematic sketch (ecliptic plane projection) of the relative positions of the earth (P78-1), Helios 2, and Venus (PVO) during the period May 7–10, 1979. [Note: The 3°S latitudinal figure shown for PVO should read ~0°.]

Solar Optical Observations

The solar eruption that is most relevant to our discussion took place on the southwest limb of the sun at ~0810 UT on May 8, 1979. Shown in Figure 2 is the series of cool ($<10^4$ K), dense ($\sim 10^{11-12}$ cm^{-3}), partially ionized hydrogen gas as observed in Hα (6563 Å) at the Astronomical Observatory, Wroclaw, Poland. The prominence is observed to be stationary at 0652:54 UT and 0704:44 UT; its eruption is initiated at ~0812:54 UT, when the uppermost blob, called 'A' in Figure 3, begins to move outward. Subsequent frames show additional blobs ('B,' 'C,' etc.) moving outward, some falling back to the surface during 1030–1045 UT. The entire ensemble, i.e., the eruptive prominence, was seen to move out to 1.5 R_S (where R_S is the solar radius, 6.96×10^5 km) as reported by *Sheeley et al.* [1980*a*], measured from the center of the sun. Figure 3 shows the acceleration of four blobs to velocities in excess of 50 km s^{-1}. Presumably, this gas becomes fully ionized at the highest levels shown and, of course, becomes invisible at the Hα wavelength. Concurrently, routine observations (by the NRL coronagraph on P78-1) of the outer corona (2.6–10 R_S) in white light (~3950–6500 Å) were taking place with a time resolution of about 10 min.

The white light coronal transient that was produced concurrently with the eruptive prominence is shown in Figure 4 [from *Michels et al.*, 1980]. The bright solar disk is blocked

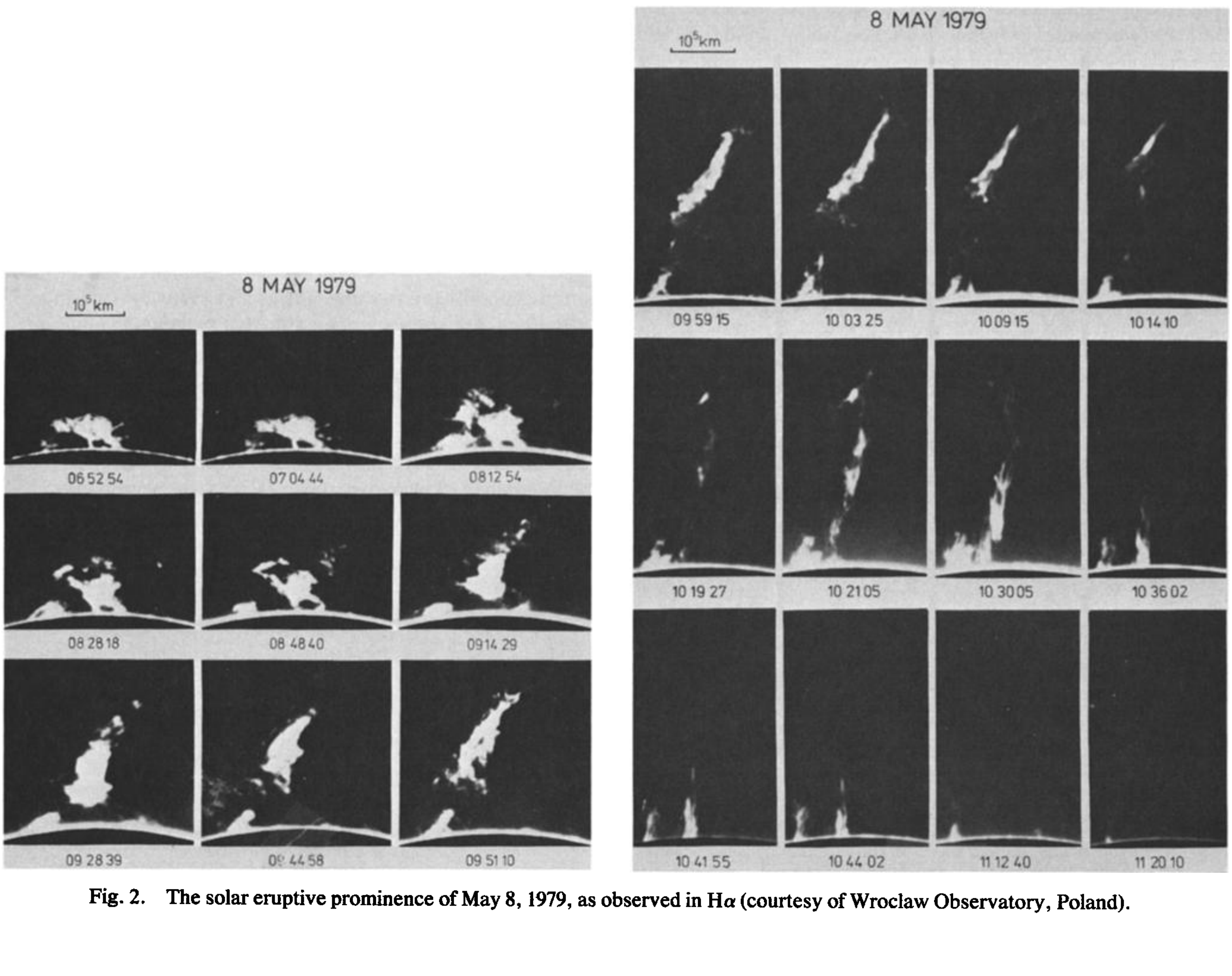

Fig. 2. The solar eruptive prominence of May 8, 1979, as observed in Hα (courtesy of Wroclaw Observatory, Poland).

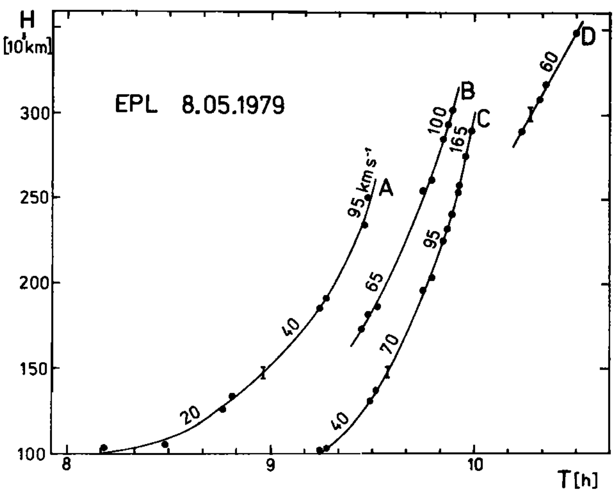

Fig. 3. Acceleration of major Hα blobs in the May 8, 1979, eruptive prominence.

by an occulting disk whose radius is equivalent to 2.6 R_S. The frames in Figure 4 are difference images, each showing coronal electron density changes (as produced by Thomson-scattered sunlight from electrons) from a reference image at 0852 UT to the times as shown. Thus bright portions (interrupted by two, dark, nearly circular annuli that are produced by polarizing filters transmitting light whose polarization is approximately radial to the plane of the sky) represent plasma density increases, and the interior darker portion represents plasma density depletions. (We remark, parenthetically, that the eruptive prominence is sometimes observed within the rarefaction region, as in the case of another coronal transient on May 24, 1979 [*Sheeley et al.*, 1981*a*].) The NRL group has also discussed an earlier transient [*Sheeley et al.*, 1980*a*] that took place on May 7, 1979 (~1522–2214 UT), from the northwest limb, as well as a much fainter loop transient on May 8, 1979 [0716 UT, *Poland et al.*, 1981] that, in our opinion, was too weak to produce any measurable solar wind effect. This earlier transient

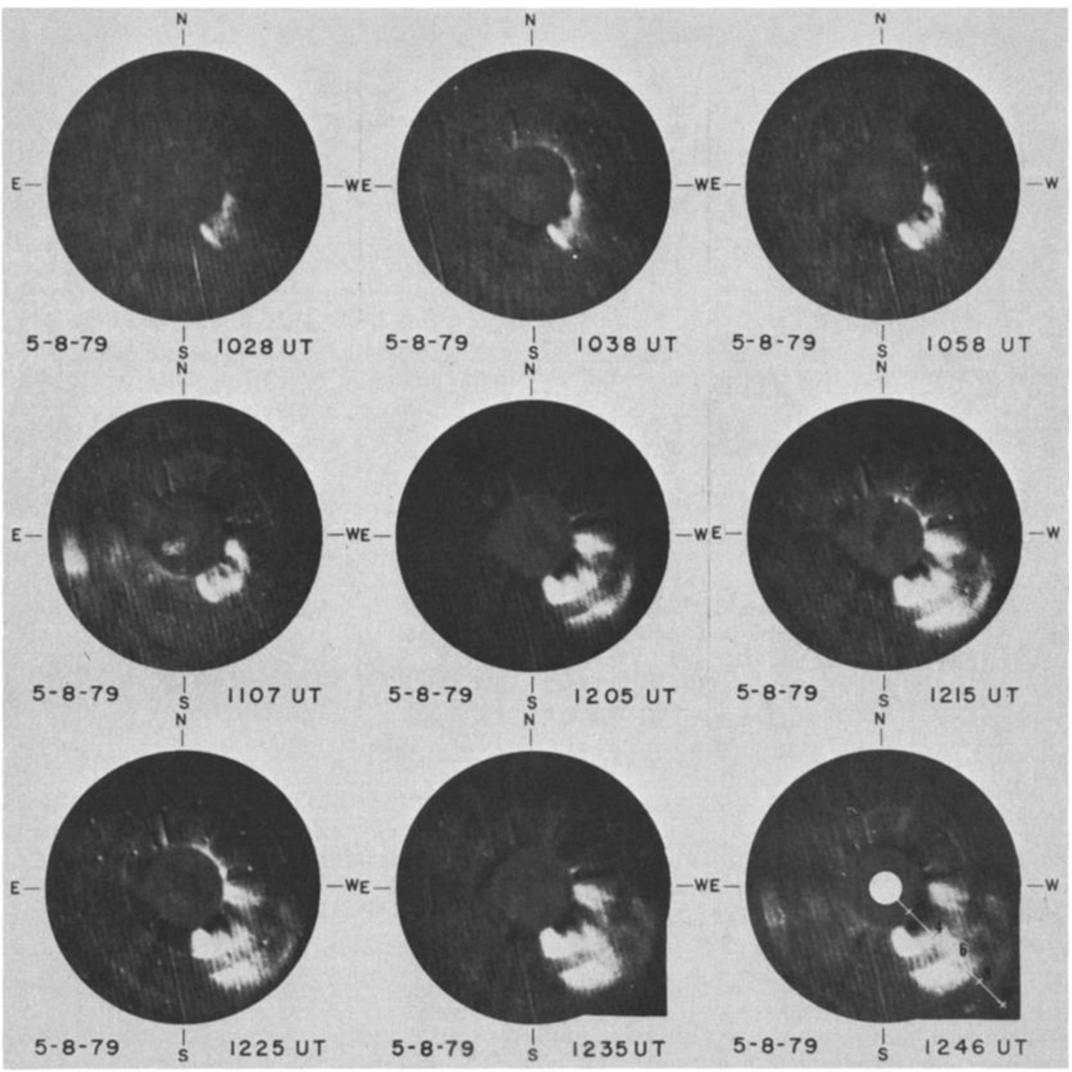

Fig. 4. P78-1 coronal transient (observed by NRL Solwind coronagraph) of May 8, 1979 [from *Michels et al.*, 1980]. The annular ring at ~5 R_S (see the scale at 1246 UT) is caused by a polarizing filter, as noted in the text, and should also be considered as equally bright as the lower and higher radial positions.

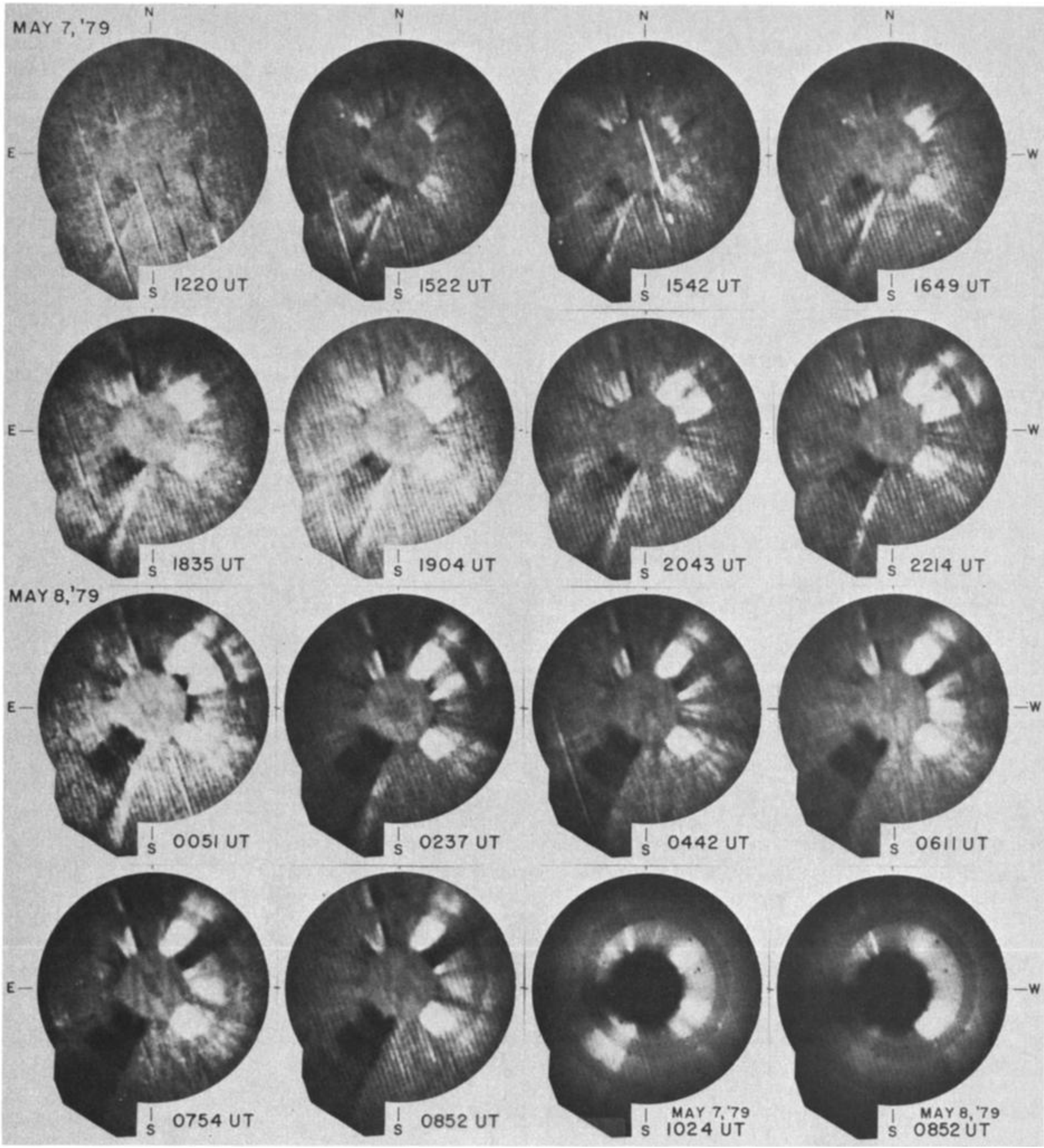

Fig. 5. P78-1 coronal transient (observed by NRL Solwind coronagraph) of May 7, 1979 [from *Sheeley et al.*, 1980*a*].

(~1522–2214 UT), shown in Figure 5, is relevant to our tentative interpretation of the Helios 2 data.

At this time, Helios 2 was located at ~0.3 AU, about 90°W of the earth-sun line (Figure 1). Also, as mentioned earlier, PVO was located at ~0.7 AU, about 112°W of this reference line. *Sheeley et al.* [1980*b*, 1981*b*] have discussed the outward propagation of a shock wave that was presumably ahead of the white light coronal transient seen in Figure 4. One can readily visualize that these two spacecraft (the former at about 6°N of the ecliptic plane and the latter in the ecliptic plane) would have been expected to sample the northern flank of the expanding shock wave from the 0810 UT solar eruption. As discussed by these authors, this is indeed what happened. (The interested reader is referred to *Wu et al.* [1978], *Dryer et al.* [1980], and *D'Uston et al.* [1981] for discussion of the 2D, MHD numerical simulation of coronal transients and propagation of interplanetary shock waves. Also, there have been two earlier observations of spacecraft associations with coronal transients, as discussed by *Gosling et al.* [1975] and *Wu et al.* [1976], that are of lower quality than the present one because of some ambiguities in viewing angle, event association, and timing.)

Thus the shock wave from the coronal transient of May 8, 1979 (and, presumably, the earlier one on May 7, 1979) was 'tracked' to 0.3 AU, where we think both shocks were observed by the MPI/Lindau solar plasma probe on Helios 2. N. R. Sheeley, Jr., et al. (unpublished manuscript, 1981) present the velocity, density, and proton temperature en-

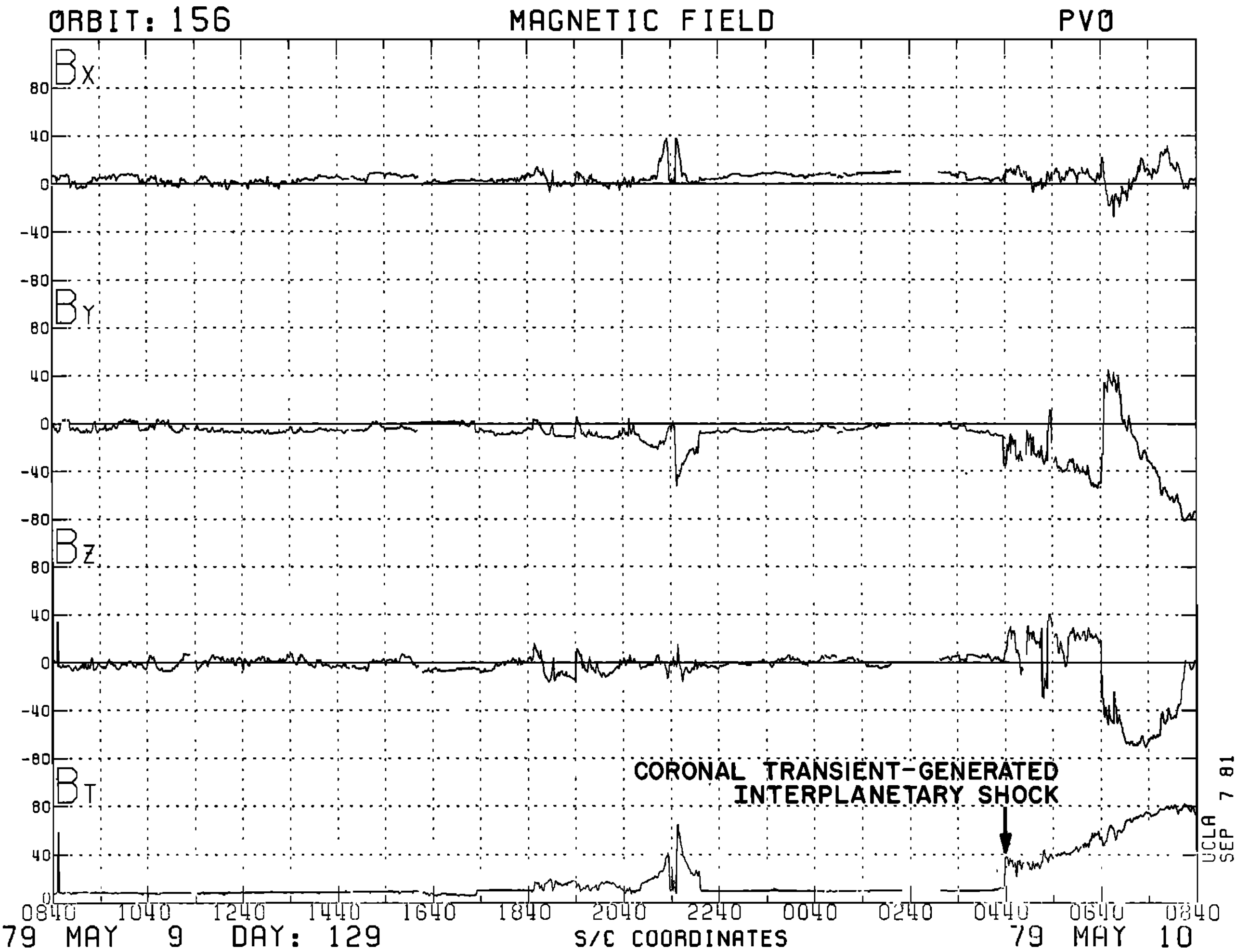

Fig. 6. Solar wind magnetometer data from PVO's magnetometer (courtesy of C. T. Russell and J. G. Luhman of UCLA) on May 9–10, 1979. The perturbation between ~2100–2200 UT is caused by Venus.

hancements that were probably caused by these two coronal transients. We believe that their largest enhancement on day 129 (approximately 0330 UT, May 9, 1979) was probably the shock wave from the coronal transient shown in Figure 4. Also, we suggest that their smaller enhancement on day 128 was possibly from the earlier transient briefly discussed by *Sheeley et al.* [1980*a*], shown in Figure 5, and discussed above. After PVO entered the solar wind on May 9, 1979, an interplanetary shock wave passed the spacecraft at 0439 UT on May 10, 1979. This shock arrival time is provided by the UCLA magnetometer data (courtesy of C. T. Russell and J. G. Luhmann) as shown in Figure 6. Figure 7 shows the solar wind velocity, density, and proton isotropic temperature from the NASA Ames orbiter plasma analyzer (OPA). Thus the average velocity of the Venus-bound interplanetary shock wave, assuming its 'birth' at ~0810 UT on May 8, 1979, and arrival at 0439 UT on May 10, 1979, is about 700 km s^{-1}. Shock impact upon the ionopause, then, could be anticipated, roughly, within minutes of its detection by PVO's magnetometer. High time-resolution magnetometer data (not shown here) suggest that several Venusian bow shock crossings (indicating several inward/outward motions of the shock) took place, starting about 1300 UT on May 10, 1979, on the inbound trajectory of PVO.

Shown in Figure 8 are the proton convective pressure, flux, and thermal pressure for essentially the same time period as that in Figure 7. The proton convective pressure, of primary importance in the present context, is seen to increase by a factor of 15 (from 4.5×10^{-8} dyn cm^{-2} to 6.9×10^{-7} dyn cm^{-2} behind the interplanetary shock wave). Similar fluctuations took place during the period of May 3–14, 1979, when ionopause motion (discussed below) took place.

Venusian Ionosphere Compression and Expansion

We will utilize only the data from the OIMS instrument for the purpose of this paper. It should be noted that the physical interaction of the solar wind with the ionosphere has, as yet, not been fully addressed in any of the papers yet published from the Venus data. This is an important point since, as a result, the agreement on the definition of the term 'ionopause' is still lacking [cf., *Vaisberg et al.*, 1980]. In addition to differences in instrument sensitivities, there is the lack of understanding of the energetic and dynamical properties of the plasma and fields involved with the interaction. Consequently, a comparison of data [cf., *Brace et al.*, 1980; *Knudsen et al.*, 1980] is not very meaningful, unless the theoretical treatment (as suggested, for example, by *Cloutier et al.* [1974, 1981]; *Pérez-de-Tejada* [1980]; *Pérez-de-Tejada and Dryer* [1976]) of the states of the interactions is incorpo-

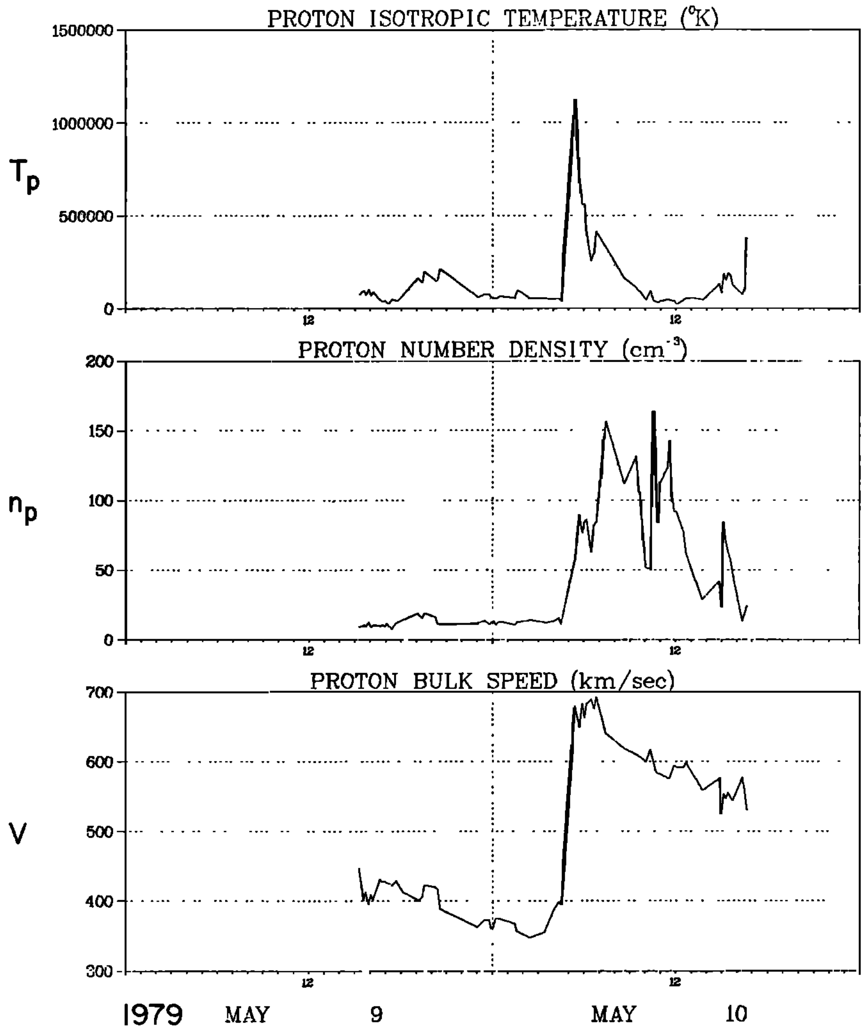

Fig. 7. Solar wind velocity, density, and temperature from PVO's plasma analyzer on May 9–10, 1979.

rated into such a comparison. This, of course, is not the intent of the present paper. Such a task, however needed, is not practical for this brief description of the response of the ionosphere to the passage of the interplanetary shock wave. Thus we confine our attention only to the ionospheric oxygen ion profiles described as follows. The height profiles of the dominant topside ion (O^+) are presented in Figure 9, in sequence for orbits 150 through 160. The ionopause height is taken to be the altitude at which the concentration of thermal O^+ ions drops to the limit of sensitivity of the OIMS, at about 5 ions/cc. We note, however, that the identification of the ionopause is somewhat complicated by the dynamic characteristics of the solar wind-plasma interaction. Analysis of the OIMS instrument response indicates that the decreasing gradient in O^+ is linked with the acceleration of the ambient ions by the solar wind interaction to velocities for which the energy of the O^+ becomes 'superthermal' (a few tens of electron volts). This process, observed to varying degrees on all orbits, indicates that the thermal or ambient upper layer of the ionosphere is converted to a superthermal ion layer. The OIMS response, primarily tuned to the thermal ions, reflects this effect by exhibiting an onset of superthermal ion currents coexistent with the decrease in the thermal ion profile.

Our major purpose in this paper is to relate the arrival of the interplanetary shock wave at Venus on May 10, 1979 (0439 UT) to the ionopause positions before and after this time. Accordingly, we show, in Figure 10, the inferred inbound (solid line) and outbound (dashed line) positions during the period May 3–14, 1979. The individual points are connected, for convenience, by straight lines during the ~24-hour orbital period when observations were not possible, since the satellite remained at altitudes above the ionopause. It is seen that the outbound and inbound movements appear to be in phase. In order to compensate (partially) for the poor temporal resolution of the ionopause height, we refer to the variability of solar wind convective pressure. Mihalov et al. show daily samples (near noon of each day) of proton convective pressure nmV^2 during 1979; the range is from about 10^{-8} to 3×10^{-7} dyn cm^{-2}. Closer inspection of the convective pressure as shown, for example, in Figure 8 shows a clear response of the ionopause to the 'waxing and waning' of the convective pressure in terms of variations such as those described earlier for the shock arrival on May 10, 1979. Table 1 shows the range of solar wind convective pressure prior to the PVO's inbound pass through Venus' bow shock wave on May 3–14, 1979. Generally, an increase of convective pressure by factors of about 2

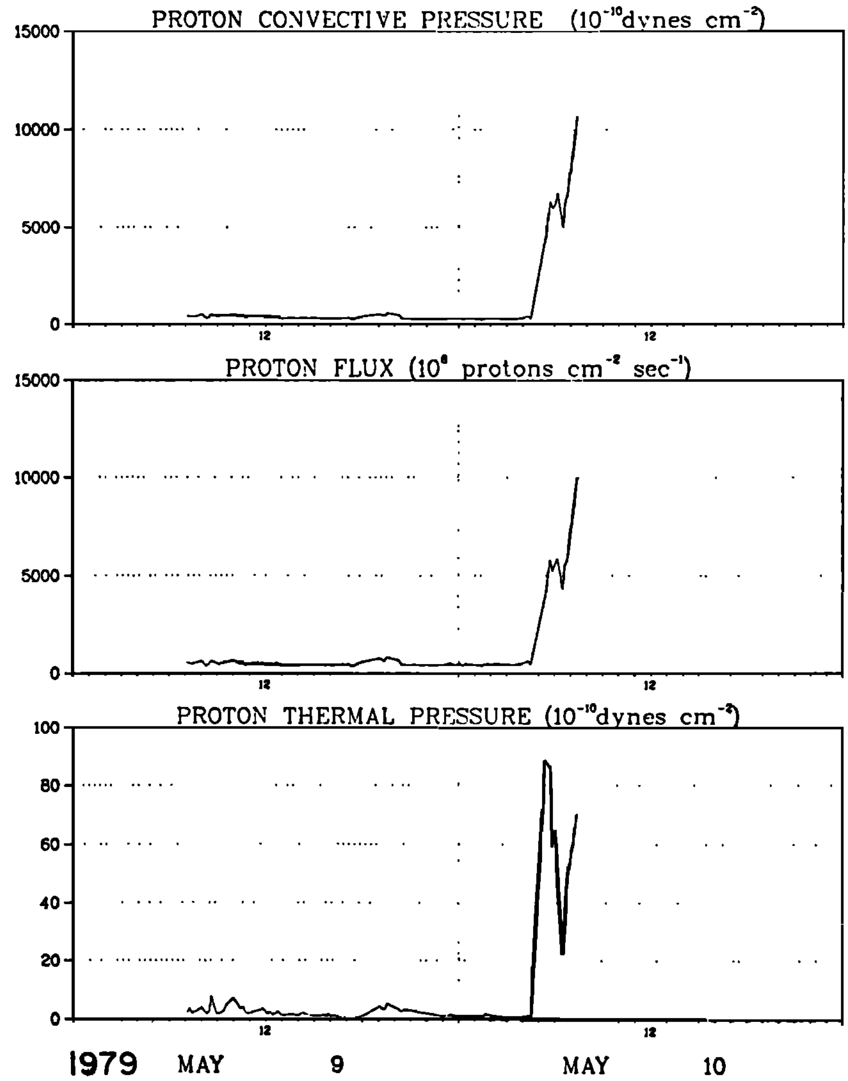

Fig. 8. Solar wind convective pressure, flux, and thermal pressure from PVO's plasma analyzer on May 9–10, 1979.

is sufficient to cause significant ionopause compression. We can, however, assert with confidence that the inward motion of the ionopause on May 10, 1979, was clearly a response to the shock impact on that day.

The PVO spacecraft was located about 6 Venusian radii behind the terminator, and 5 Venusian radii below the equator, of the planet when the interplanetary shock was detected at about 0439 UT. Considering the pre- and post-shock velocities and densities to be 400 and 650 km s^{-1} and 12 and 50 cm^{-3}, respectively, the local shock velocity was about 730 km s^{-1}. Thus the shock impact at the dayside ionopause took place about 0436 UT.

It is important to point out that the maximum and minimum positions of the ionopause, as shown by the solid circles in Figure 10 are not necessarily the true maxima and minima. Nor are the straight-line segments (solid and dashed) connecting these points necessarily the actual trajectories of the ionopause. Various studies have proposed nominal ionopause altitudes as determined from a variety of instruments. For example, for the solar zenith angles discussed here, 3°–13° (and 39°–52°), Elphic et al. (their Figure 9) give a range from about 220 to 400 km (220–600 km); Brace et al. (their Figure 12) give about 330 km (400–500 km); and Vaisberg et al. (their Figure 6) give 300 km (330–350 km) for a mean solar wind dynamic pressure condition. We can see from these previous observations that substantial variability exists. It is, therefore, not instructive for our purpose to construct a reference solar-zenith-angle dependence of the ionopause height. Thus the points and straight segments in Figure 10 are merely indicative of the inward/outward movements as sampled on, essentially, a twice-per-day passage inbound and outbound through the ionosphere. We can assert with confidence, however, that the sinusoidal-like motion is periodic on a time scale of, at most, 1 day (in response to solar wind convective pressure) and with an amplitude of several hundred kilometers.

The short time scale (minutes) response of the ionospheric ion density profile immediately after impact by the shock cannot be shown here. We can, however, suggest that the numerical, 1D, ordinary (nonmagnetic) hydrodynamic simulation of *Wolff et al.* [1982] can be instructive. These authors have clearly demonstrated the propagation of a shock wave downward into the ionosphere (with its attendant heating of the ions therein), following an impulsive pressure pulse

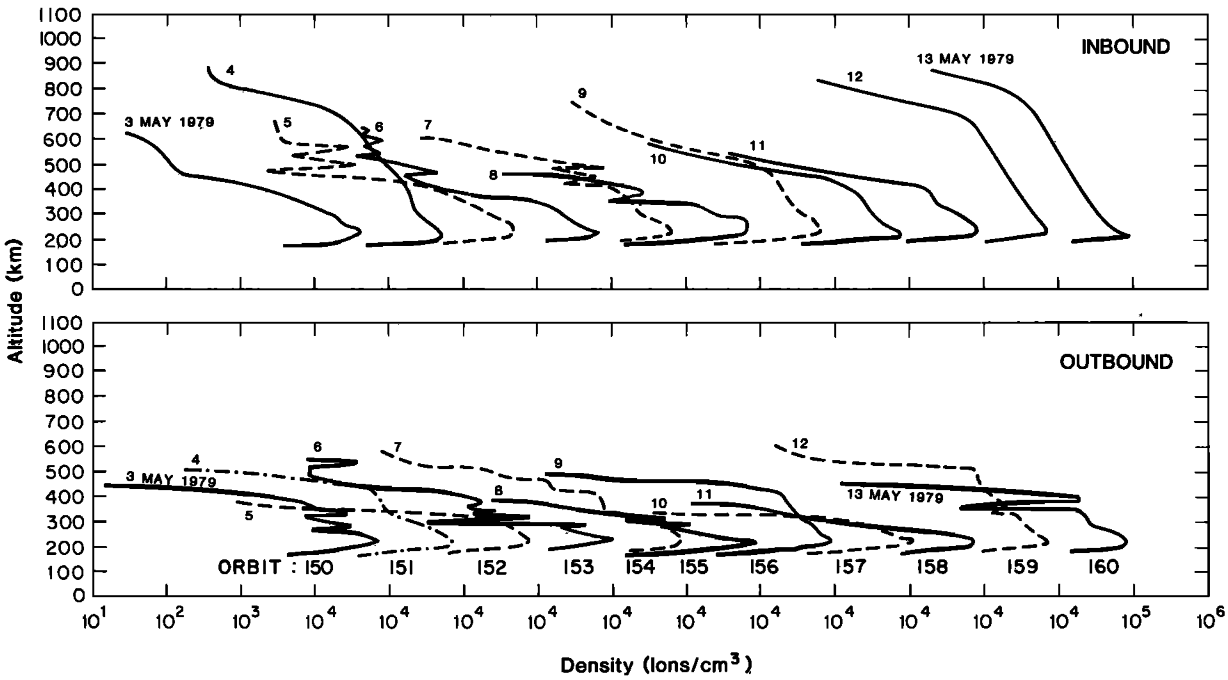

Fig. 9. Sequence of O^+ density profiles in the dayside ionosphere during orbits 150–160 (inbound and outbound) on May 3–13, 1981, respectively, from PVO's ion mass spectrometer (OIMS). Some of the profiles are drawn either with dashs or dash-dots only for convenience in guiding the reader's eye.

(such as that produced by an interplanetary shock as discussed above) at the top of the ionosphere. In a complementary numerical simulation of the convective pressure increase at the subsolar point of a magnetopause (or ionopause), following the impact of an interplanetary shock with a bow shock *Dryer et al.* [1967] showed that a twentyfold increase in peak (subsolar) pressure is possible during the impulsive period. We believe that such simulations should be encouraged, not only for the pressure pulse increases but also (as they have also done) for the simulation of the passage of a sudden solar wind rarefaction. Of course, the rippling effect of the ion density profile (as demonstrated by Wolff et al.) would be expected to culminate in an outward movement of the ionopause.

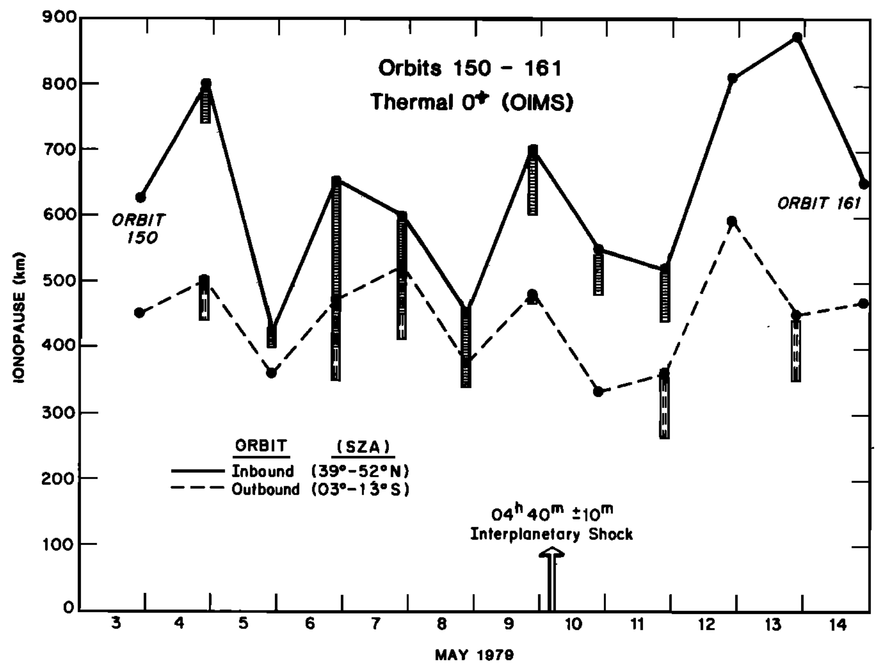

Fig. 10. Ionopause altitudes, as determined by the peak of the thermal O^+ distributions in Figure 9, for the period May 3–14, 1981. These altitudes are indicated by the dark circles. The range of superthermal O^+ ions, as detected from their onset in some cases below the ionopause (as defined here), are also indicated by the columns: the horizontally hatched columns refer to the inbound passes; the vertically hatched columns, to the outbound passes.

TABLE 1. Approximate Range of Solar Wind Convective Pressure Prior to Pioneer-Venus-Orbiter's Inbound Entry Through Venus' Bow Shock

Date, May 1979	Orbit	Temporal Duration, UT	Convective Pressure, nmV^2	
			Minimum, $\times 10^{-7}$ dyn cm^{-2}	Maximum, $\times 10^{-7}$ dyn cm^{-2}
3	150	1500–1900	0.7	1.3
4	151	1500–1900	0.3	0.5
5	152	1500–1900	0.5	1.1
6	153	1200–1800	0.4	1.1
7	154	1200–1600	0.7	1.0
8	155	1200–1700	0.3	0.6
9	156	1200–1700	0.3	0.3
10	157	1200–1600	0.6	1.0
11	158	0900–1400	0.4	2.0
12	159	0900–1400	0.1	0.3
13	160	0900–1300	0.4	2.5
14	161	0900–1300	0.3	0.6

Data obtained prior to the inbound shock crossings during this period are from the ionosheath rather than from the free-stream solar wind. The orbital orientation, with periapsis on the dayside of Venus, is responsible for this fact. However, these data are taken on the Venusian flanks, where the ionosheath has expanded back to approximate solar wind conditions of convective pressure.

CONCLUSIONS

We have summarized the 'tracking' of an interplanetary shock from a specific event at ~0810 UT, May 8, 1979, on the sun's west limb to a rendezvous with Venus at 0439 UT, May 10, 1979. By constructing the dayside ionopause's variability over an 11-day time interval (May 3–14, 1979) and comparing these positions with the solar wind dynamic pressure's variability, we conclude that this shock wave initiated (via an impulsive fifteenfold increase in dynamic pressure) an inward compression of the Venusian ionosphere. We believe that this is the first, unambiguous observation of a direct association of a specific solar/terrestrial planetary interaction via observations at the solar surface (in Hα), at 10 R_S (in white light), at 0.3 AU, and at 0.7 AU (by plasma and magnetometer observations of the interplanetary shock wave).

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