RESPONSE OF EARTH AND VENUS IONOSPHERES TO COROTATING SOLAR WIND STREAM OF 3 JULY 1979

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(Received 13 August, 1984)

Abstract. Corotating solar wind streams emanating from stable coronal structures provide an unique opportunity to compare the response of planetary ionospheres to the energy conveyed in the streams. For recurrent solar conditions the "signal" propagating outward along spiral paths in interplanetary space can at times exhibit rather similar content at quite different downstream locations in the ecliptic plane. Using solar wind measurements from plasma detectors on ISEE-3, Pioneer Venus Orbiter (PVO) and Helios-A, as well as in-situ ion composition measurements from Bennett Ion Mass Spectrometers on the Atmosphere Explorer-E and PVO spacecraft, corotating stream interactions are examined at Earth and Venus. During May–July 1979 a sequence of distinct, recurrent coronal regions developed at the Sun. Analysis of these regions and the associated solar wind characteristics indicates a corresponding sequence of corotating streams, identifiable over wide distances. The time series of solar wind velocity variations observed at Earth, Venus, and the Helios–A positions during June–July attests to intervals of corotating stream propagation. The characteristics of the stream which passed Earth on July 3, are observed at Helios-A and at Venus (PVO) about 8 days later, consistent with the spiral path propagation delay times between the locations in the ecliptic plane. On July 3, Earth and Venus have a wide azimuthal separation of about 142°. Although the planetary environments are distinctly different, pronounced and somewhat analagous ionospheric responses to the stream passage are observed at both Earth and Venus. The response to the intercepted stream is consistent with independent investigations which have shown that the variability of the solar wind momentum flux is an important factor in the solar wind-ionosphere interaction at both planets.

1. Introduction

It is now well established through numerous studies of solar wind conditions observed in the ecliptic plane that under favorable circumstances, signatures of both solar flare

Earth, Moon and Planets **32** (1985) 275–290. 0167-9295/85.15.

generated plasma streams and coherent corotating plasma streams may be observed over large radial distances within the solar system (Burlaga *et al.*, 1980; Dryer, *et al.*, 1982; Akasofu *et al.*, 1983; Suess, *et al.*, 1984). During recurrent periods of solar activity, relatively orderly and coherent plasma streams spiral outward, corotating with the Sun. Sporadic solar fluctuations such as strong flares or filament eruptions can produce bursts of outward propagating plasma streams which overtake the outward spiraling corotating stream, producing downstream field and plasma interactions which may seriously complicate the apparent signature of the original corotating stream (Akasofu *et al.*, 1983). In addition, the leading edge of the propagating corotating stream is continuously interacting with the downstream solar wind plasma, such that a shock may form at the leading edge and evolve in structure, with both time and distance (Burlaga, 1979). The interaction of these processes often results in complicated downstream characteristics in the solar wind.

The wide variety of potential complications notwithstanding, there do occur periods of relatively persistent and coherent coronal structures at the Sun for which it is possible to identify reasonably similar structures in the solar wind momentum flux at widely different times and locations. This becomes possible when corotating streams progress through interplanetary space. In this paper, we identify an evolution of solar coronal regions, and a sequence of associated corotating streams in the period June–July 1979. Subsequently, we examine the evidence of ionospheric perturbations at Earth and Venus, in response to the passage of a prominent stream which intersected Earth on July 3, and subsequently encountered Venus late in the day on July 11.

2. Identification of Recurrent Solar Coronal Regions

In an earlier paper Suess *et al.* (1984) examined a sequence of recurrent solar conditions identified in three consecutive Carrington rotations of the Sun occurring between June and September 1979. Line-of-sight photospheric magnetic field data from the Stanford Solar Observatory were used to compute potential field models of the corona. The magnetic field strength at the source surface radius to 2.6 solar radii was compared to the solar wind flow speed observed at 1 AU and kinematically extrapolated back to the Sun.

It was found that some features in the solar wind appeared in successive rotations and that these features were associated with stable, long-lived coronal structures inferred from the source surface models. The solar wind features were high speed streams, and the coronal features were relatively strong field regions on the source surface which tended also to be the location of coronal holes. The source surface data for the interval June 20 to September 9 is shown in Figure 1, together with the locations of the coronal holes.

As shown in Figure 1, the coronal hole and strong field region near Carrington Longitude 210° persisted for three solar rotations. Although not modeled by Suess *et al.*, it is evident from He_{10830} Å synoptic maps that the coronal feature was first detected at 210° on June 4 (C.R.) 1682. Thus there is evidence that the recurrent coronal hole conditions actually persisted over four rotations.

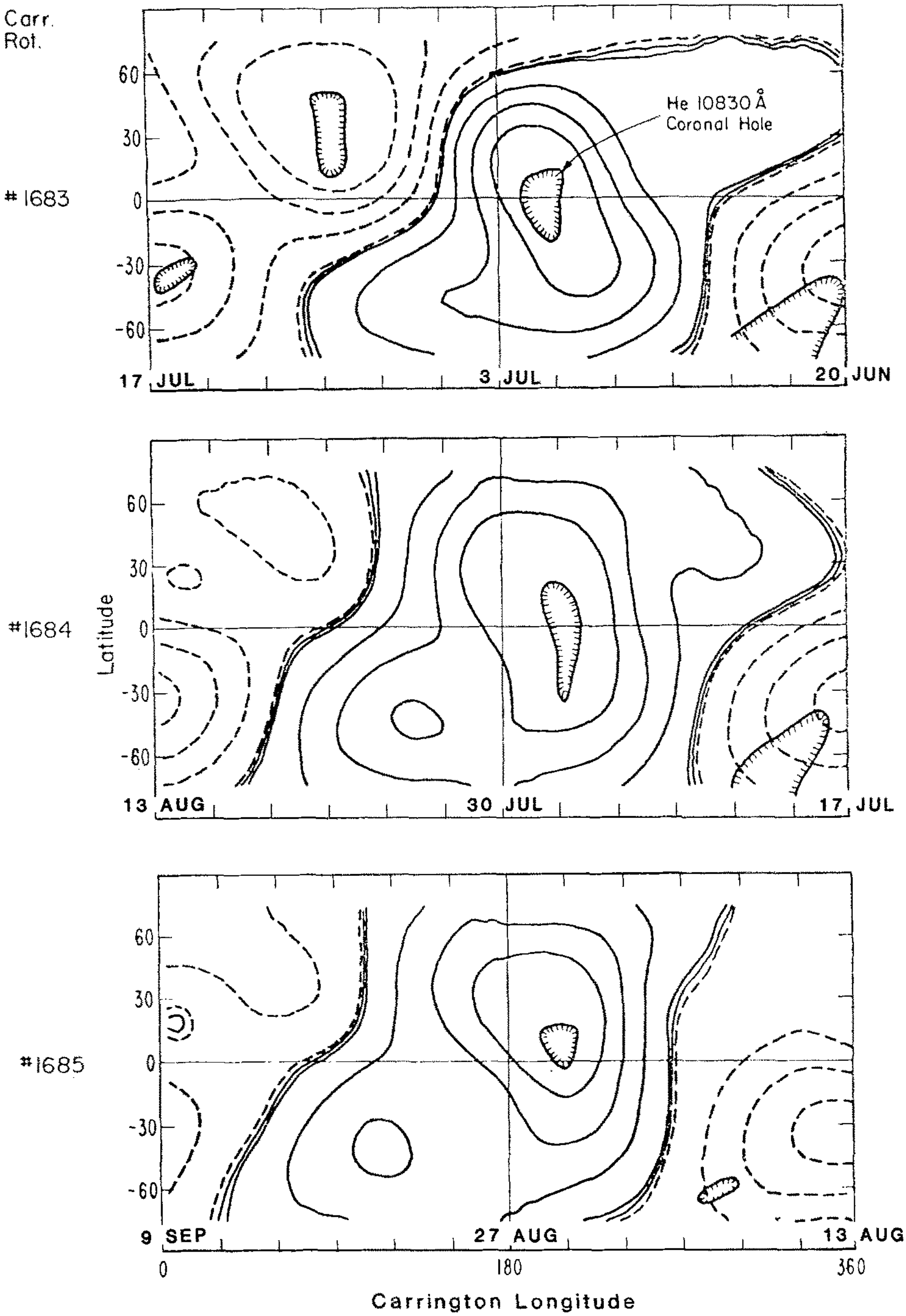

Fig. 1 Contours of constant radial magnetic field strength on the source surface of a potential field model. The source surface radius = 2.6 solar radii. Reproduced from Suess *et al.* (1984).

It may be noted from Figure 1 that the general large-scale structure in the corona between Carrington Longitudes 180° and 250° is the only long-lived, stable structure in the corona at the time. The large size suggests that a high speed emanating from the region would occupy a large solid angle. In particular, it can be expected that the stream must have a large latitudinal extent and be visible everywhere near the ecliptic. These conditions provide a stimulus for examining interplanetary data for evidence of corotating streams and their consequences. We examine in particular the solar wind conditions associated with the coronal hole identified in C.R. 1683, crossing the central meridian on July 1. We use interplanetary data from the ISEE-3, Pioneer Venus Orbiter (PVO), and Helios-A satellites to infer the presence of a corotating solar wind stream associated with this hole. Subsequently we examine the ionospheric perturbations at Earth and at Venus believed to be associated with the passage of the corotating stream at the two planets.

3. Evidence of Corotating Interplanetary Streams

Consistent with the foregoing characteristics identified in the coronal field behaviour, examination of the similarities in the structures of the down stream solar wind times series, at three distinct locations in or near the ecliptic plane provides further evidence that coherent corotating streams emanate from the Sun during the summer of 1979. The solar wind data at the Venus location are obtained from the Plasma Analyzer Experiment (OPA) on the PVO. Comparable solar wind results for Earth are obtained from the plasma detector on the ISEE-3 satellite located in a halo orbit upstream from the planet. Supporting interplanetary evidence is obtained from the Helios-A satellite at azimuth positions between Earth and Venus, in the ecliptic plane.

We first examine the period June–July, 1979, when the solar wind enchancements emanating from the recurrent coronal regions are most clearly identified in the data. During June–July, PVO and Helios–A were located at significantly large solar azimuthal angles with respect to the Earth. In Figure 2, panel (a), the trajectories of each of the satellites (also Venus, in the case of PVO) relative to the Sun is shown for the interval June 1 to July 13. The delay times in days for the arrival of a corotating spiral stream at each of the satellites, corresponding to the beginning and ending dates of the interval are also shown. The spiral paths and delay times are calculated for a constant solar wind velocity of 300 km s^{-1} and a solar equatorial-sidereal rotation rate of 25 days. It is seen that at the beginning of the interval (June 1 at Earth), a corotating stream travelling at 300 km s^{-1} would intersect Helios-A about three days earlier than Venus, with a delay relative to Earth of about four, and seven days, respectively. At the end of the interval, due to their different rates and trajectories, Helios-A and Venus are closer together with respect to the Earth and the spiral propagation time from Earth to the two locations differs by only about one day. By July 13 (at Earth) the delay for propagation to Helios-A and Venus with respect to Earth has increased to more than eight days for the two locations.

In panel (b) of Figure 2, the spiral paths and corresponding delay times are shown

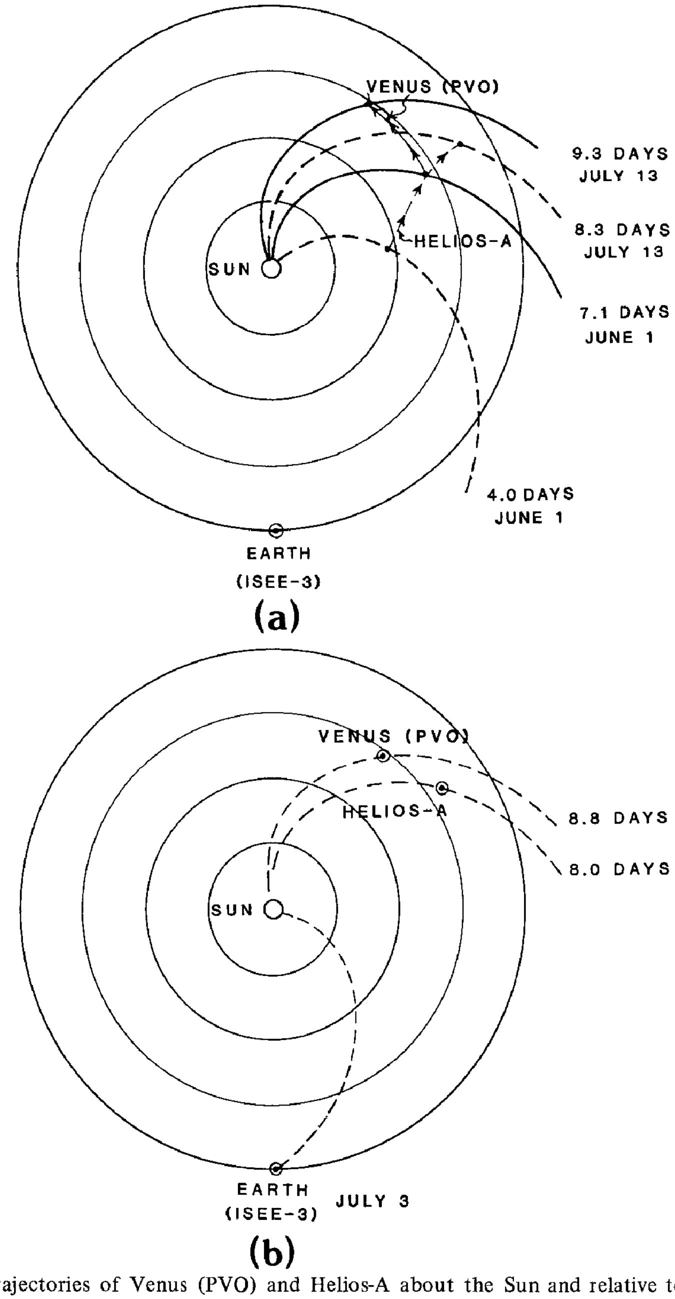

Fig. 2. (a) Trajectories of Venus (PVO) and Helios-A about the Sun and relative to a fixed Earth position all projected into the ecliptic plane. The trajectory segments are determined for the Earth interval June 1 to July 13, 1979. The spiral stream propagation paths illustrate the delay times (and corresponding dates for a corotating stream passing Earth on June 1 and July 13, respectively, to later intersect the paths of Helios-A and Venus. Spiral propagation paths and delay times are calculated assuming a constant solar wind velocity of 300 km s^{-1} and a solar equatorial-sidereal rotation rate of 25 days. (b) Illustration of spiral paths and delay times for the propagation of a corotating stream passing Earth on July 3 to intersect the positions of Helios-A and Venus (PVO).

for a specific solar wind stream passing first at Earth on July 3 then passing Helios-A (+ 8.0 days) and Venus (+ 8.8 days). These stream paths illustrate that for the stream passing Earth on July 3 and Venus 8.8 days later, late on July 11, the azimuthal separation was about 142°.

This relatively large separation in azimuth requires that the coronal source of the high speed stream be reasonably persistent in order for similar corotating stream effects to be encountered at the different locations. Fortunately as indicated by the earlier study of Suess *et al.* and from the evidence that follows, the coronal structure was sufficiently persistent that evidence of comparable coherent interplanetary variations are indeed recognized at the different positions and times.

The extended time series of V_{sw} illustrating the comparable evidence of the individual solar wind streams observed at Earth, Venus, and Helios-A for the interval June 1–July 13 (Earth) and June 10–July 22 (Venus and Helios-A) are shown in Figure 3. Noting first the solar wind data for Earth we observe apparent recurrent structures detected late on June 6 and subsequently early on July 3 with an approximately 27 day separation due to the solar rotation. Between these two most prominent features several smaller enhancements in V_{sw} occur, including a relatively prominent increase on June 22.

Examination of the corresponding solar wind variations at the locations of Venus and of Helios-A shows that while details of the velocity variations sometimes differ, the overall broad features of the recurrent perturbations in V_{sw} are fairly well identified at each of the other locations. The corresponding time series of V_{sw} detected at Venus (PVO) and Helios-A are plotted with a time shift of nine days to facilitate particularly the intercomparison between Earth on July 3 and Venus and Helios-A on July 11–12. Since the positions of Venus and Helios-A change considerably relative to Earth across the overall interval, the three V_{sw} time series are closely aligned only near the July 3 (Earth) region indicated in Figure 3. If one considers the differences in trajectory for Venus and Helios-A, it can be appreciated that the individual patterns in V_{sw} are variably shifted in time, relative to each other across the interval. Also, owing to evolving solar activity, it is quite probable that a number of associated perturbations are superimposed upon each V_{sw} time series. Allowing for such differences, it is apparent from the V_{sw} data that the prominent and recurrent enhancements seen at Earth on June 6–7 and July 3, and later with appropriate propagation delays at Venus and Helios-A, are very likely the consequence of streams emanating from the coronal holes described earlier.

Having noted the broad features indicating the sequence of corotating stream structures, we look closer at the details of the V_{sw} signatures associated with the particularly prominent stream which intersected Earth on July 3. As noted earlier in Figure 2, the delay times for the July 3 (Earth) stream to reach Helios-A and Venus are about 8.0 and 8.8 days, respectively. In Figure 4 we plot the time series for V_{sw} at each of the three locations, allowing approximately for these time spiral propagation delay times. Note that the prominent enhancement in V_{sw} observed early in the morning of July 3 at Earth is subsequently detected late in the night of July 11 at Venus. This delay, indicated by the similarities in the observed V_{sw} characteristics, is very close the the delay expected

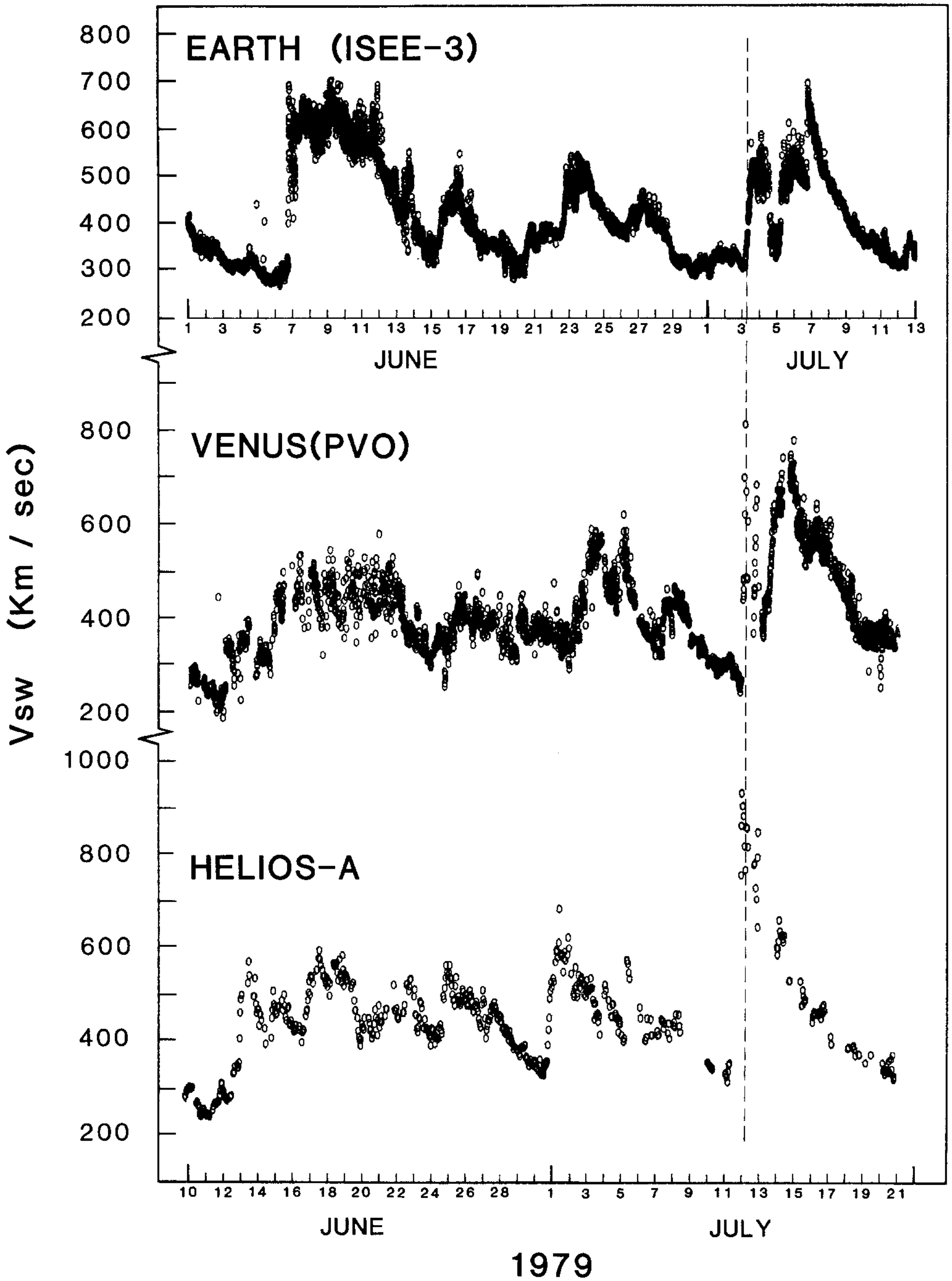

Fig. 3. A comparison of the time series of the solar wind bulk velocity V_{sw} detected at the positions of Earth, Venus, and Helios-A during the interval June 1–July 13 (Earth) and June 10–July 22 (Venus and Helios-A). The date intervals for Venus and Helios-A are shifted by nine days (later) to reflect the corotating stream delay time appropriate for July 3. The dashed line indicates the similar enhancement seen in each time series. Since the positions of Earth, Venus, and Helios-A are constantly changing the true time relationships between similar events during the interval is variably distorted, and thus the data are best aligned only for comparing the observations of the stream which passed Earth on July 3 and later passed Helios-A and Venus on July 11.

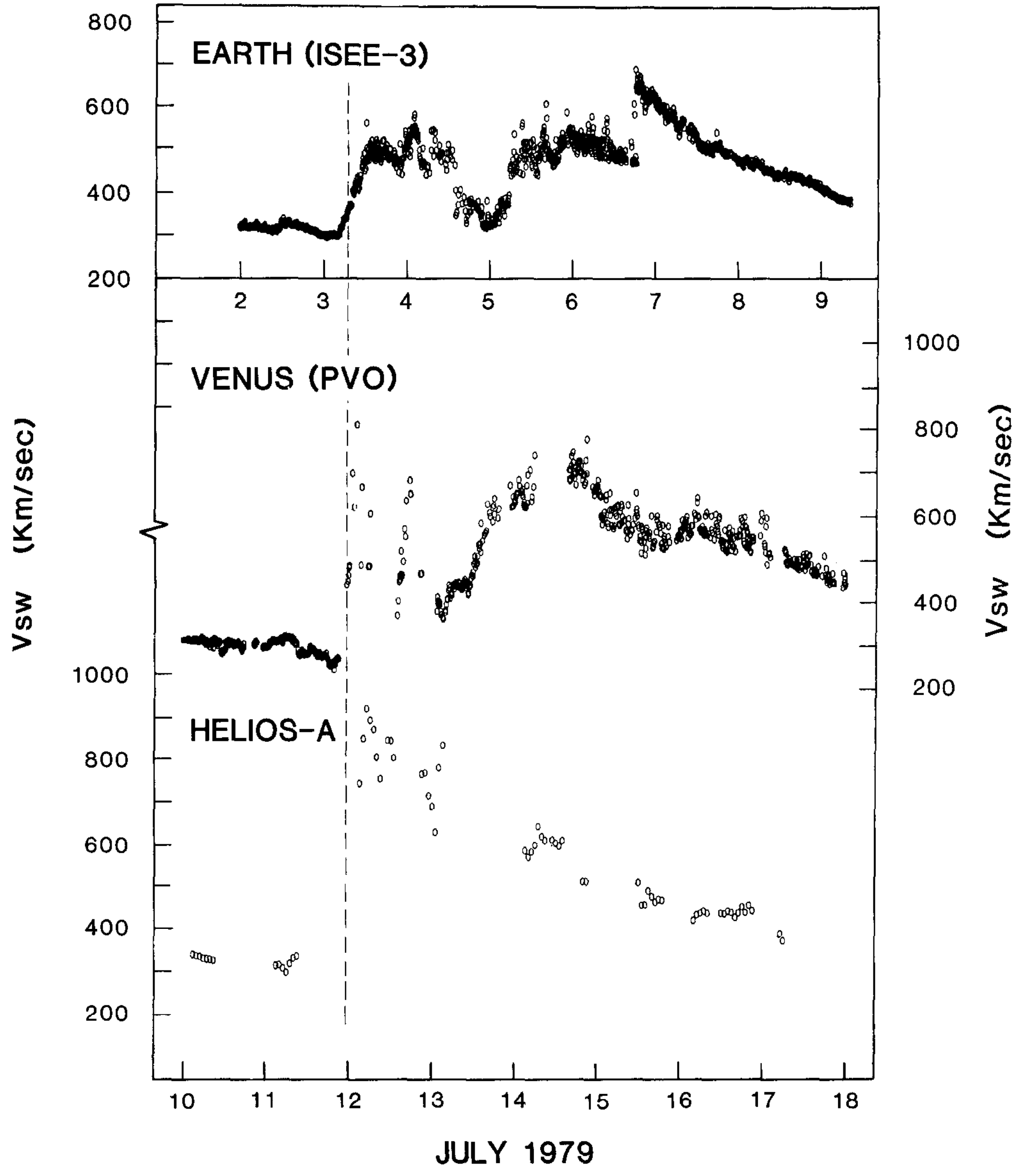

Fig. 4. A comparison of the details of the time series of V_{sw} detected at the positions of Earth, Venus, and Helios-A for the solar wind stream passing Earth on July 3 and seen later on July 11 at the other two locations. The dashed line indicates the abrupt onset of the shock-like feature in V_{sw} at each of the interplanetary locations.

from the calculated spiral stream propagating time of about 8.8 days. At the Helios-A position the details of the V_{sw} enhancement is not fully identified due to gaps in data, yet the overall pattern of V_{sw} recorded at the Helios-A position shows that a similar, large scale velocity perturbation arrived there about one day earlier. This time of arrival at Helios-A is also constant with that calculated for a corotating stream propagation.

Although we have not analyzed the solar wind and interplanetary magnetic field parameters in detail to determine that the Rankine–Hugoniot conditions classically associated with a shock are satisfied, we consider the closely related solar wind behaviour observed at the three locations to be suggestive that a corotating shock wave is formed at the leading edge of the corotating stream. While not shown here for brevity, a more detailed analysis of the solar wind and the related solar coronal field conditions for this particular event (Suess *et al.*, 1984) adds confidence that we are observing the passage of a corotating solar stream linked to a relatively persistent coronal configuration at the Sun.

Not all of the solar wind disturbances emanating from the sun during the first week of July are attributable to the coronal hole. In particular, a series of flares and erupting filaments occurred on the visible disk of the the Sun on July 4 and 5. These events may be associated with some of the structure evident in V_{sw} detected by ISEE-3 on July 6 and 7. Results of these disturbances are apparently not seen at Venus, since the planet was beyond the west limb of the Sun. While these and other active events on the Sun may have produced perturbations interspersed with the corotating stream events, we believe that the coherent nature of the correlations shown supports the inference that the events identified on July 3 (Earth) and July 11–12 (Venus) are the result of a corotating high speed solar wind stream.

4. Comparable Earth and Venus Responses to Corotating Streams

We next examine the relative responses of the ionospheres of Earth and Venus to the passage of the July 3–11 corotating stream. First, to illustrate the overall response at Earth, we use the time series of the planetary magnetic disturbance index, K_p, as a simple global indicator, and compare variations in this parameter with those of several solar wind parameters, in Figure 5.

It is seen that the momentum flux (ρv^2) increases significantly just in advance of the arrival of the shock-like enhancement in V_{sw} indicated by simultaneous jumps in the proton density (n_p) and temperature (T_p). At the time of the largest increase in V_{sw} near 0600 UT on July 3, the largest increase in ρv^2 also occurs, indicating the peak of the energetic interaction, at least as measured by these parameters. Note that the sharp peak in ρv^2 is accompanied by the largest enhancement in the Earth magnetic field disturbance indicated by K_p also seen near 0600 UT. Note that n_p drops sharply, and T_p correspondingly increases just after the dramatic increase in ρv^2 and rise in V_{sw}. This is characteristic of shock front interactions (see, e.g. Dryer and Steinolfson, 1976).

After the stream passage on July 3, the momentum flux decreases to very low values for several days then, subsequently, several additional significant enhancements occur on July 6 and 7. These perturbations appear to be associated with the sequence of flare and filament activity noted earlier. Note that the K_p time series indications of magnetic disturbance tracks several of the large enhancements in ρv^2 rather well, and does not reflect others.

To illustrate the ionospheric response at Earth much more directly we show the per-

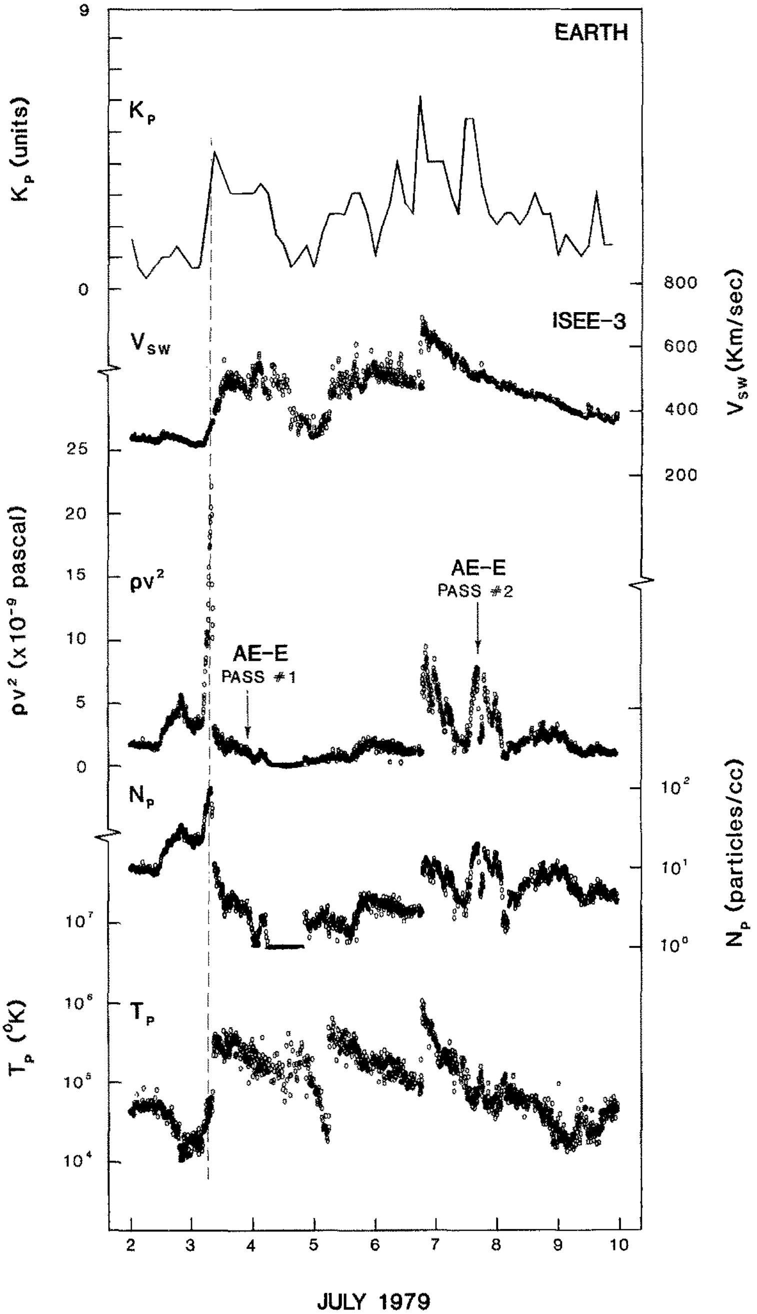

Fig. 5. A comparison of the time series of the solar wind parameters measured from ISEE-3 at Earth in the interval July 2–10 and the corresponding time series of K_p. The arrows indicate the times of the two AE-E ionospheric samples illustrated in Fig. 6.

turbations of the equatorial ionosphere, sampled by the AE-E satellite, which during this time was in a circular equatorial orbit with a perigee of 450 km. The dominant topside ion, 0^+, was measured by the Bennett Ion Mass Spectrometer (BIMS). In Figure 6 measurements of $n(0^+)$ across the noon–midnight local time sector illustrates two examples of perturbations, relative to the average distribution observed for the month of July. On the events of July 3 and 7, respectively, the upper F-layer concentrations of 0^+ near 2000–2400 h are seen to have decreased significantly relative to the average level. In particular, on July 3 $n(0^+)$ has decreased by three orders of magnitude below the average. Though not shown for clarity, the pass six hours earlier on July 3 exhibited an $n(0^+)$ distribution very close to average in concentration in the same local time region. Unfortunately, there are no AE-E passes available just prior to or immediately after the strong disturbances identified on the two disturbed days. For this reason we cannot determine the rates of onset and recovery of the 0^+ distribution as further characteristics of this event.

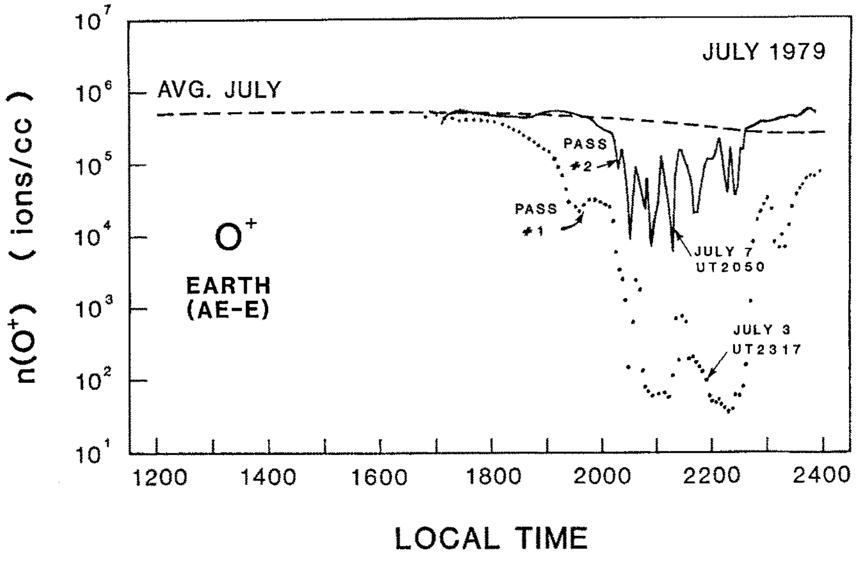

Fig. 6. A comparison of profiles of $n(0^+)$ measured from the AE-E satellite in the noon–midnight local time interval during July 1979. The average of all profiles observed near 450 km is shown by the dashed curve. The distributions identified for July 3 and 7, respectively, illustrate the strong depletion of $n(0^+)$ associated with solar wind perturbations occurring earlier in each day.

At Venus there is no evidence of an intrinsic planetary magnetic field and we have no global, plasma related index comparable to K_p. The Venus ionospheric response is, however, well identified from daily observations of the 0^+ distributions measured by the Bennett RF Ion Mass Spectrometer (OIMS) on the PVO. In Figures 7 and 8 we compare day-to-day variations observed at Venus in the solar wind parameters and associated responses in $n(0^+)$, respectively.

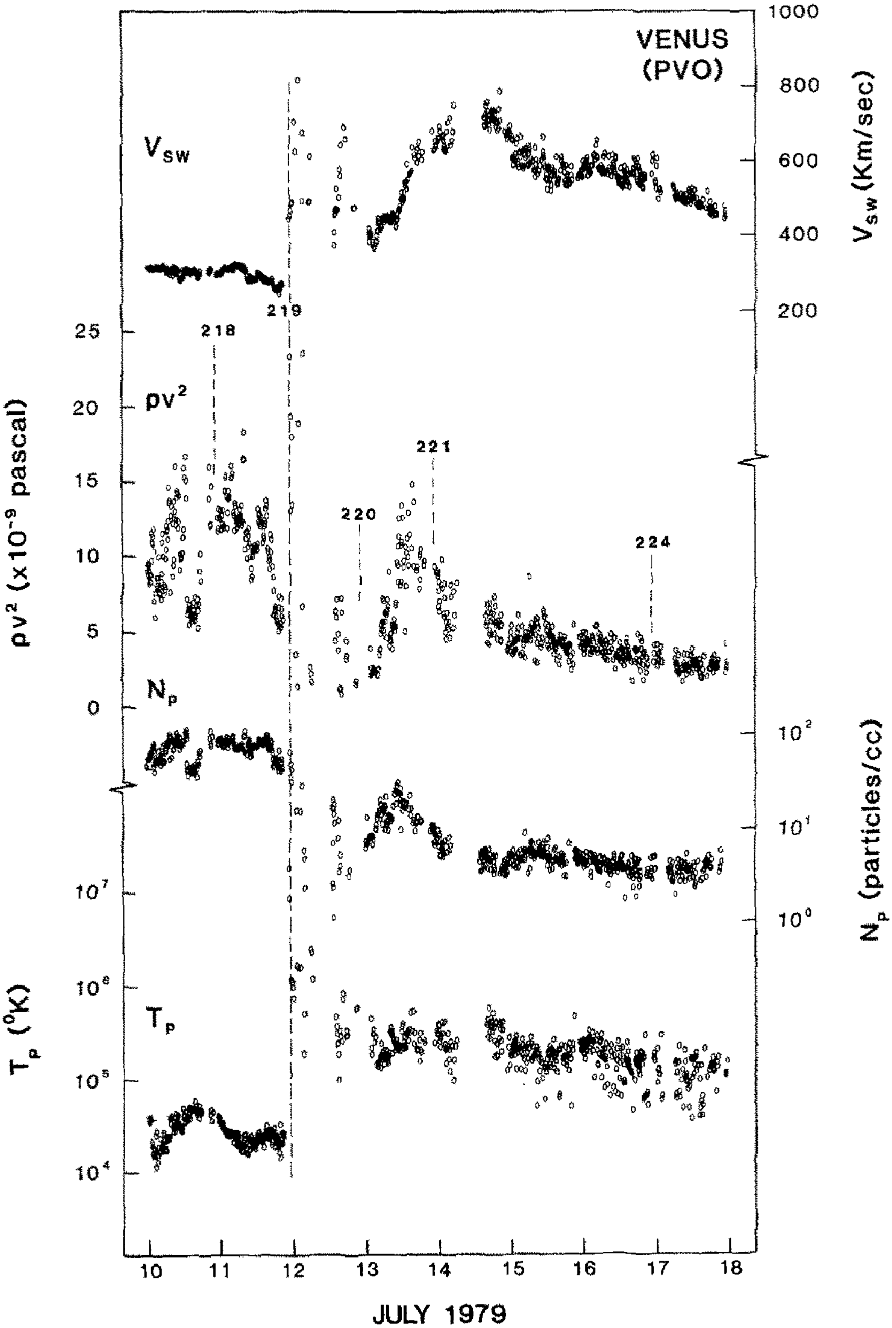

Fig. 7. A comparison of the time series of solar wind parameters measured from the PVO at Venus in the interval of July 10–18. The dashed line indicates the abrupt change in all parameters associated with the passage of the solar wind stream. This stream is interpreted as being the same event which produced the analogous perturbation marked in Figure 5 at Earth. Arrows indicate the times of PVO ionosphere measurements shown in Figure 8.

In Figure 7 the time series of the solar wind parameters exhibits similarities relative to those exhibited at Earth. Noticeable enhancements in ρv^2 occur in advance of the arrival of the large, abrupt enhancement in V_{sw}, observed near 2200 UT on July 11. Also as in the case for Earth, the arrival of the shock front in V_{sw} is associated with the largest enhancement in ρv^2, which is also observed at about 2200 UT on July 11. Also as noted at Earth, an abrupt decrease in ρv^2 follows the initial enhancement at the shock front.

Because of the high degree of variability in the solar wind, and the rapid response time of the Venus ionosphere, it is necessary to consider the *timing* of the PVO passes through the ionosphere, relative to the timing of the ρv^2 events. In Figure 7 we have marked the ρv^2 time series to show the periapsis times associated with the series of corresponding ionospheric 0^+ profiles shown in Figure 8. The sequence of individual time series of $n(0^+)$ portrays the day to day variability of the ionosphere observed as PVO (in a near polar orbit) makes a once daily periapsis pass. The atomic oxygen ions dominate the day-side upper ionosphere and the altitude and latitude extent of these profiles indicate the size of the thermal ionospheric 'envelope'. Note that the ionosphere appears to expand and contract with large differences in the altitude of the abrupt depletion in $n(0^+)$, referred to as the ionopause.

The strongest compression of the ionosphere is observed on July 11 in the midst of the shock front passage where the largest enhancement in ρv^2 occurs. In sharp contrast, the next day, on July 12, ρv^2 drops to very low values and the ionosphere is seen to have expanded significantly. A comparison of the marked PVO periapsis intervals in the ρv^2 time series of Figure 6 with the corresponding variations in the $n(o^+)$ extent shows that the Venus ionosphere is highly responsive to the solar wind momentum forcing, as noted by Dryer *et al.* (1982 and references given therein) and by Wolff *et al.* (1982). Theoretical studies indicate that the compression of the ionosphere occurs rapidly in response to enhancements in ρv^2, and that the recovery time for the lower ionosphere during a period of sustained reduction in ram pressure should be of the order of at most a few hours (Cloutier *et al.,* 1983).

5. Discussion

Although we realize that the detailed structure of solar wind perturbations depends in a complex way on field-particle interactions within the propagating stream (e.g., Burlaga *et al.,* 1980), we believe that the bulk of the solar wind perturbation event we have examined can be characterized as a high speed stream, preceded by a corotating shock, emanating from a coronal hole region. The time period we have examined appears to be conducive to our interpreting the interplanetary disturbances as evidence of corotating streams, both through the analysis of the solar coronal behaviour of Suess *et al* (1984) as well as by virtue of the orderly recurrent features in V_{sw} observed at the different interplanetary locations.

The detailed characteristics of the time series of both the V_{sw} and ρv^2 at Venus and Earth indicate that regardless of the label applied to the particular solar wind event we

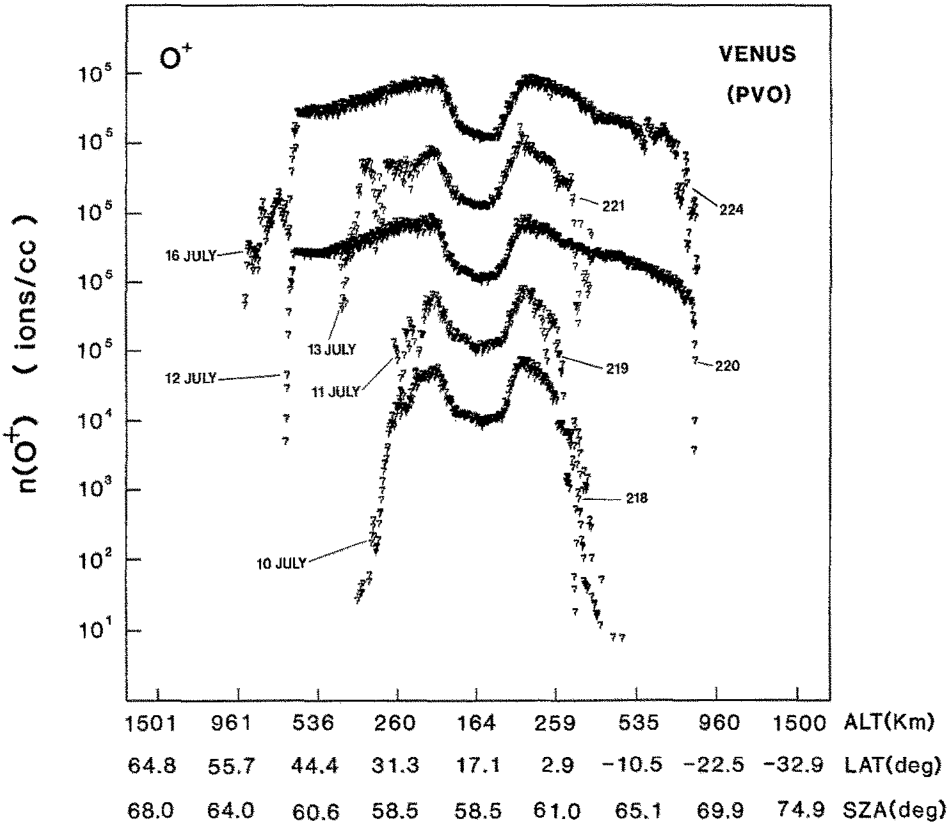

Fig. 8. An illustration of the day-to-day variability in the extent of the Venus ionosphere, observed in association with perturbations in the solar wind momentum flux. The dayside upper ionosphere is dominated by 0^+ and thus the extent of the profiles in latitude and altitude are indicative of the dimensions of the ionosphere, and its short term variability. On July 11 (orbit 219) the ionosphere is extremely compressed even more than the substantial compression indicated on July 10. In contrast, the ionosphere has expanded to extreme dimensions on July 12 and 16. The correlation between ionosphere compression and solar wind enhancement is evident from comparisons with Figure 7.

have examined, we are dealing with rather similar solar wind forcing conditions at both planets. Given the similar inputs, we have shown that for pronounced solar wind perturbations, the ionospheres of Venus and Earth can respond in pronounced and somewhat similar ways.

From our brief investgation it is evident that the solar wind momentum flux is one of the important parameters for determing the timing as well as magnitude of the ionospheric response. This evidence is consistent with many previous investigations of the independent behaviour of each of the individual planetary ionospheres e.g. Burlaga (1975); Taylor, *et al.,* (1980). We note that behaviour along these lines has also been suggested in the case of comets, e.g. Dryer *et al.* (1976). The signature of the response observed in the equatorial upper *F*-layer at Earth is interpreted as the consequence of the upward expansion of the ionosphere, resulting in turn from auroral heating occurring during the magnetic storm indicated by the K_p variation. This type of atmosphere–ionosphere response to solar wind-magnetic storm perturbations is discussed by Rishbeth (1975), Tanaka (1979), Mayr *et al.,* (1980), Benson and Brinton (1983), and many others. In general, auroral heating stimulates the flow of equatorward thermospheric neutral winds, and through ion-neutral drag, ion motions are guided equatorward along magnetic field lines. Due to field line curvature, this process results in an upward expansion of the *F*-region. Since AE-E is at a fixed altitude, upward motions of the *F*-layer can appear as abrupt local depletions of the ionosphere, as indicated in Figure 6. This happens because the underside of the *F*-layer is in the form of a sharply decreasing gradient in plasma density and on expansion, this gradient moves up to the AE–E altitude, causing a local plasma decrease. Thus, what appears as an ionospheric depletion or loss is actually only a redistribution of plasma.

The ionospheric response detected at Venus is consistent with numerous published results which show that the ambient ionosphere distribution is highly dynamic, responding critically to variations in solar wind forcing e.g. (Taylor, *et al.,*1980; Brace *et al.,* 1980; Cloutier *et al.,* 1983). Significant compression of the ionosphere, similar to that attributed to the high speed stream on 11–12 July, can also occur in response to the passage of solar flare associated solar wind shocks, as shown by Dryer *et al.*, (1982). Together, the intermingling of corotating streams and shocks from solar active regions provides a continuing flow of complex solar wind variations past the planet, and the overall ionospheric response can be highly variable, i.e. like a candle flame flickering in the wind.

At Venus, like Earth, the apparent ionospheric depletion associated with the solar wind stream passage is probably also simply a redistribution of plasma. The solar wind ram pressure indicated by the ρv^2 intensification is understood to result in a downward compression of the ionopause, which in turn drives horizontal plasma convection away from the compression zones. The enhanced convection may increase the day to night redistribution of plasma, but does not necessarily result in any net depletion of plasma.

Thus, in a simplified picture, we can appreciate that during persistent solar coronal conditions, coherent corotating streams propagate over large distances in the ecliptic plane. These disturbances may produce rather analagous ionospheric perturbations at Earth and Venus (albeit for somewhat different reasons) where large scale redistributions of plasma are stimulated. These variations are in part, though not totally, stimulated by large variations in the solar wind momentum flux associated with the stream. Clearly, the presence of the geomagnetic field at the Earth and the characteristics of the IMF draped about Venus present additional complications in determining detailed redistributions of plasma. We recognize that this brief study bypasses potentially interesting complications involving other parameters not considered. However, we trust that the results may encourage further efforts toward detailed inter-comparison of planetary responses to both recurrent and individual solar perturbations.

Acknowledgement

We acknowledge and are grateful for the use of the solar wind data from the ISEE-3 and Helios-A plasma experiments, which was made available through the facilities of the National Space Science Data Center in Greenbelt, Maryland.

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