Voyager 2 High Energy Ions Near the Outward Moving Termination Shock

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Abstract. We present results on the recurrence of High Energy Ions (HEIs) in the V2 data about 90 days after the initial sunward-moving termination shock (TS) crossings of V2 in Aug.-Sept. 2007. We associate the HEIs in Nov.-Dec. 2007 with the outward motion of the TS or with a ripple in the TS so that the TS is again near V2. Comparisons of the timings of the recurrence of the HEI detections and the simultaneous V2 convective plasma, energetic particle, and magnetic field data indicate that the variations in all these V2 data sets are consistent with the TS re-approach to V2 in Nov.-Dec. 2007. We use our three-dimensional (3D) kinematic HAFSS model to investigate whether the timing of the arrival at V2 of the increase in solar wind dynamic pressure associated with the December 2006 solar events could have been responsible for the dynamic pressure pulse that moved the TS outward toward V2 ~ 90 days after the initial TS crossings of V2. This explanation or, alternatively, a 3D solar wind inhomogeneity-caused TS ripple (on the scale of ~ 1 AU) could be viable scenarios to explain the recurrence of the HEIs in the V2 data in Nov. - Dec. 2007.
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INTRODUCTION

Previously we reported [1,2] evidence of the presence of High Energy Ions (HEIs) in the Voyager 2 (V2) Plasma Subsystem (PLS) data associated with the termination shock (TS) crossings near Day 242-244, 2007 [3-7]. V2 plasma waves also were detected [1,2,7]. It was tempting to associate these plasma waves with a two-stream instability arising from the lower energy and higher energy ion beams in the plasma. Beginning about 90 days later on Day 333, 2007 and continuing through Day 348, 2007 even more HEIs have been detected by the V2 PLS [8]. The intensity is greater and the duration is longer of these HEI detections near the end of 2007 than during the earlier interval near Day 243, 2007. These recent detections are discussed in the next section.

As in the earlier interval of HEI detections [1,2], we associate these more intense HEI detections with the proximity of the TS or its approach or a ripple in the TS. The TS ripple could be caused by three-dimensional (3D) in-homogeneities in the sunward solar wind plasma and magnetic field. During the Day 333-348, 2007 interval these HEIs also appear to be associated with significant changes in the V2 Low Energy

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Charged Particle (LECP) instrument detections and in the V2 Cosmic Ray Subsystem (CRS) detections of ions, electrons, and anomalous cosmic rays (ACRs). These variations also are associated with concurrent changes in the measured V2 convective plasma and magnetic field parameters. These particle and field variations also are consistent with the approach of the TS. These in-situ measurements are discussed in the second section below. Between the initial TS crossings of V2 near Day 242, 2007 at ~ 83.6 AU and this latter time interval (Day 333-348, 2007), V2 traveled to ~ 84.6 AU, about 1 AU farther away from the Sun. Thus, if these HEIs are associated with the TS, this implies that the TS moved outward away from the Sun or that there is a ripple in the TS on the scale of ~ 1 AU.

To investigate the possibility of the TS moving outward during this time interval, we examined the plasma dynamic pressures at 1 AU and at V2. Even though it was solar minimum in 2006 and 2007, there were variations in the plasma pressure at both locations: In December 2006 there were four solar events that gave rise to interplanetary (IP) shocks and, at V2 in Nov.- Dec. 2007, there were several increases in the plasma pressure that could be associated with traveling IP shocks and/or the TS approach. To estimate the propagation of the Dec. 2006 events from the Sun to V2 in the heliosheath (HS) we used our 3D kinematic HAFSS (Hakamada Akasofu Fry Source Surface) model [14]. The HAFSS model results and comparisons with V2 data are presented in the second section below. In the last section we discuss the implications of these analyses.

ANALYSES OF V2 HIGH ENERGY IONS IN THE PLASMA DATA NEAR THE TERMINATION SHOCK

In [1,2] we showed evidence that the V2 HEI detections near the TS were indicative of the presence of pickup ions and/or reflected ions in the plasma data on V2. These pickup ions and/or reflected ions have a unique signature of elevated readings on energy/unit charge (E/Q) step 12 (corresponding to a proton speed of ~ 554 km/s) in the L-mode of the B-Cup [8], one of the three sunward-facing cups on the V2 PLS. In the present paper we extend this work by showing that these HEIs can be used as a tracer or a fiduciary to alert us to Voyager 2's proximity to the TS.

On day 333, 2007, about 90 days after the reported TS crossings of V2 near Day 242, 2007, the elevated B-Cup readings on E/Q step 12 reoccurred in the V2 PLS L-Mode data. Figure 1 shows the B-Cup E/Q spectra as a function of average proton speed on Day 334, 2007. The presence of the two plasma components - the convective HS plasma (from the solar wind core plasma) and the HEIs (probably pickup or reflected ions) - are evident in the data. Comparable elevated B12 detections also were observed on Day 333 and on Days 335-348, 2007. As shown in Fig. 1, the elevated readings are intermittent and not present in all of the E/Q spectra.

ANALYSES OF 3D SIMULATIONS AND V2 DATA NEAR THE TERMINATION SHOCK

The 3D simulations starting at the Sun [2,9-15] can address fundamental questions of solar transient propagation in the 3D time-dependent global heliosphere. The 3D kinematic HAFSS has a well-established heritage [9 - 14] that has shown successful modeling of the propagation of solar transients to the HS. From our previous modeling of

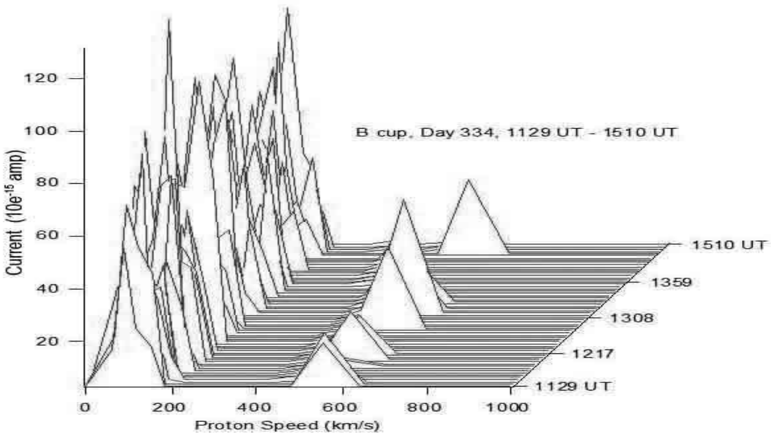

FIGURE 1. Voyager 2 E/Q spectra of PLS ion detections on the sunward-facing B-Cup in L-Mode scans [1-2] as a function of average proton speed on Day 334, 2007. Start times of some E/Q spectra are shown. The bulk convective heliosheath plasma can be seen below the average proton speed of ~ 200 km/s. The high energy ions (HEIs) are associated with the plasma detections having an average proton speed of 554 km/s. The HEIs are not present in all spectra.

our 3D magnetohydrodynamic (MHD) hybrid heliospheric modeling system with pickup protons (HHMS-PI) [2, 9-15] and comparisons with spacecraft data, we know

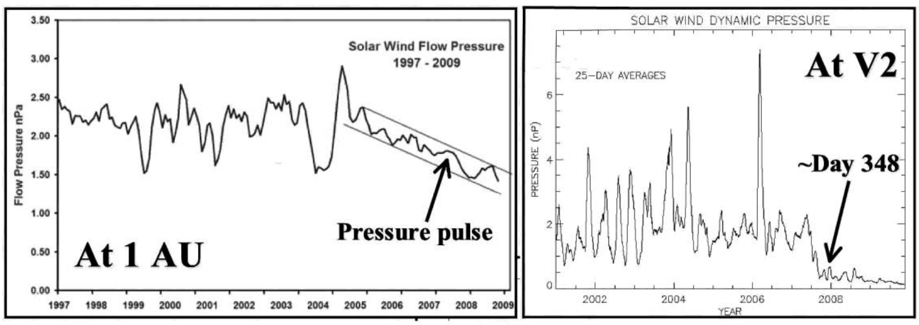

FIGURE 2. Comparison of dynamic plasma pressure at 1 AU in the solar wind and at V2 in the outer heliosphere (OH) and heliosheath (HS). Note in the V2 data near Day 242, 2007 (i.e., 2007.66) the sharp transition at the termination shock (TS) between the outer heliosphere and the heliosheath. Also note the two pressure increases in 2007 at V2 following the TS crossing.

[15] that the presence of pickup protons slows the propagation of IP shocks. We believe that such IP shock deceleration may be due to some of the IP shock energy being transferred to pickup protons.

Figure 2 shows the dynamic pressure at 1 AU and at V2. This figure shows that there are discernable variations in the pressure at both locations during the 2006-2007 time frame. In Figure 2 at 2007.66 the TS crossing of V2 is evident by the abrupt decrease in the plasma pressure as V2 exits the outer heliosphere (OH) and is immersed in the HS plasma with its associated decrease in convective speed and increase in density. At the end of 2007 there are two pressure pulses at V2 that we associate, respectively, with the arrival at V2 of the IP shock (discussed below) associated with the December 2006 solar events and the re-approach of the TS as it moves outward due to the increased solar wind pressure exerted on it from the arrival of the pressure pulse from the Dec. 2006 solar events.

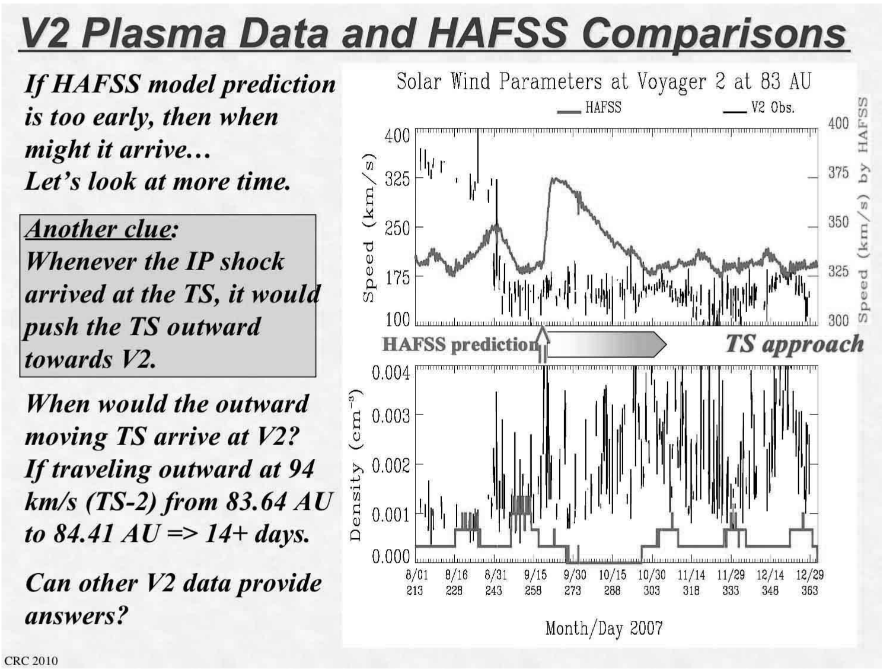

FIGURE 3. HAFSS results for the arrival of the interplanetary (IP) shock and its associated plasma parameters compared with Voyager 2 data from Day 213 to 365, 2007. In each of the panels the HAFSS simulations are the continuous line and the V2 data are shown with the vertical lines. The top panel shows the HAFSS simulated speeds (see label on right) and the V2 plasma speed (km/s) as shown on the left. The bottom panel shows the comparison between HAFSS results and the V2 plasma densities. From our earlier work we know that the HAFSS model predicts an earlier arrival of the IP shock than the more accurate 3D HHMS-PI model that takes into account the effects of pickup protons. HAFSS also predicts an earlier arrival than the spacecraft data that show the actual arrival of the events. In this case, as shown between the two panels, we estimate that the HAFSS IP shock arrival is ~ Day 263, 2007 and that the actual shock arrival in the V2 data in the heliosheath is on ~ Day 304, 2007.

Figure 3 shows the comparisons of the 3D HAFSS results for the Dec. 2006 events and the V2 plasma speed (top panel) and density (bottom panel). Our earlier comparisons [15] of the 3D HHMS-PI MHD results that take account of the effects of pickup protons have shown that the pickup protons slow down the propagation of interplanetary shocks. In the case of the Halloween events at V1 in the outer heliosphere at 93 AU, the 3D kinematic shock arrived ~ 14 days early [10]. For the Dec. 2006 IP shocks the HAFSS results in Figure 3 may indicate that the modeled IP shock arrived on ~ Day 263, 2007, and the actual IP shock may have arrived at V2 in the HS on ~ Day 304, 2007. The HAFSS result is a considerably earlier arrival (~ 41 days) than the case of the 2003 Halloween events when the IP shock arrived ~ 14 days after the HAFv2 predicted arrival [10]. On the other hand, at the time of the Halloween 2003 events, V1 was in the OH. However, for the Dec. 2006 events, V2 was in the HS so that the IP shock had to propagate beyond the TS. We anticipate that, for these events in the OH and in the HS, our future work with the full 3D MHD HHMS-PI simulations (that take account of the effects of pickup protons) [15] will greatly improve our knowledge of the significant underlying physical mechanisms responsible for the phenomena revealed in the V2 data.

Figure 4 shows the V2 magnetic field and plasma parameters from Day 220-365,

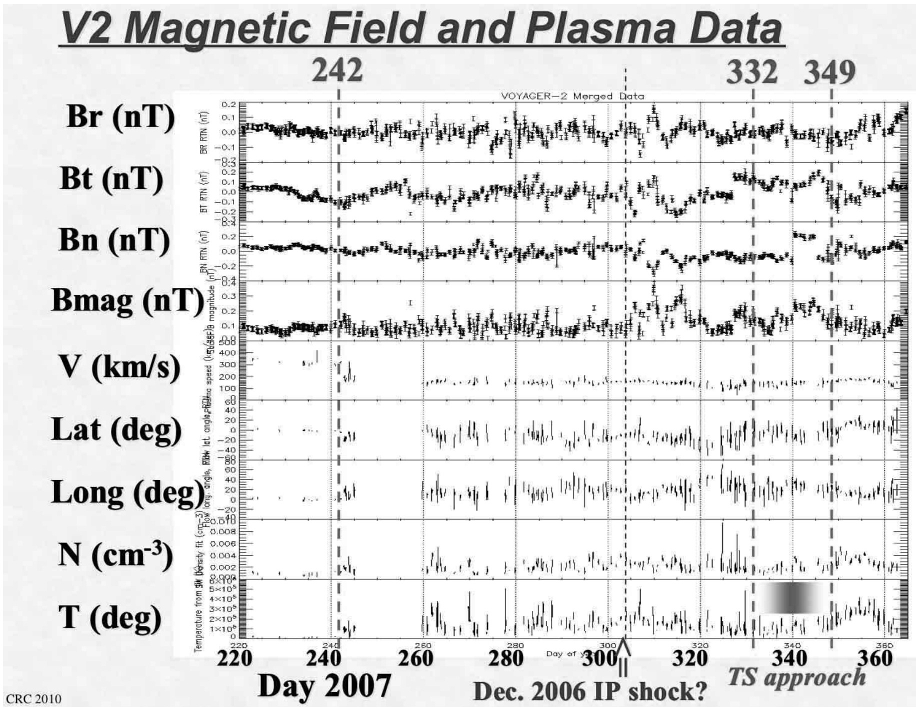

FIGURE 4. Comparisons of the V2 magnetic field and plasma data from Day 220 to Day 365, 2007. The first vertical dashed line on the left denotes the sunward-moving TS crossing of V2 on Day 242, 2007 near 83.6 AU. The second dashed vertical line on Day 304 denotes the suggested time of arrival at V2 of the IP shock associated with the Dec. 2006 solar events. The set of two dashed vertical lines on the right show the Day 333 to Day 348, 2007 time frame when the HEIs are detected by the V2 plasma probe near 84.6 AU. Note the discontinuity in the data ~ Day 340. We suggest that these HEI detections are associated with the re-approach of the TS as it moves outward toward V2 due to the pressure pulse associated with the Dec. 2006 IP shock(s). It is also possible that V2 is detecting the effects of a ripple in the TS (see text).

2007. From examination of these data it appears reasonable to suggest that the Dec. 2006 IP shock arrived at V2 on ~ Day 304, 2007 (second vertical dashed line on left). This arrival time would coincide with noticeable changes in the magnetic field orientation and increase in magnitude and with the change in plasma flow direction and increase in temperature. We also have indicated – on the right with dashed vertical lines and "TS approach" - the later time interval (Day 332-349) that encompasses the HEI detections. We associate this later time interval with the outward motion of the TS and its re-approach to V2. Note the changes in the field and plasma parameters during this interval; and following this interval the increased plasma temperature and density, and the change in flow parameters. During this interval there also are abrupt and large changes near ~ Day 340 in the magnetic field magnitude, orientation, and in the plasma data. After the interval the field magnitude decreases, and the orientation changes. All of these plasma and magnetic field characteristics could be consistent with the re-approach of the TS as a result of its outward motion toward V2 or due to V2's proximity to a ripple in the TS.

If we assume that on ~ Day 300 the TS was still near 83.6 AU, the location where it crossed V2 on ~ Day 242, 2007, and, then, that the TS eventually moved outward to 84.4 AU, where V2 was on ~ Day 333, 2007, then the TS would have moved outward a distance of ~ 1 AU. [Following the TS crossing of V2 near Day 243, 2007, it had been estimated [5] that, associated with this "TS-2" crossing, the TS moved outward at a speed of ~ 94 km/s.] If we assume this is the average speed of the outward moving TS, and if we also assume that the TS moved steadily outward without stopping or breathing inward at times, then it would have taken the TS at least ~ 14 days to re-approach V2 as V2 traveled farther out away from the Sun. Thus, in order to have the outward moving TS arrive in the vicinity of V2 on ~ Day 333, 2007 (when the HEI ions re-appear), the TS would have had to be impacted by the Dec. 2006 IP shock at least 14 days earlier (before ~ Day 319, 2007.) However, if the faster-moving Dec. IP shock reached V2 on ~ Day 304, 2007, then, if we further assume the IP shock was traveling at an average speed of ~ 300 km/s then the IP shock probably impacted the TS earlier than Day 304, for example, on ~ Day 299-300, 2007. This would imply that it took the TS about 30 days to move outward to V2 or about twice the time it would have taken if it were moving steadily outward at ~ 94 km/s without stopping or breathing inward, etc. If the Dec. 2006 IP shock were propagating more slowly in the HS than 300 km/s then it would have impacted the TS before ~ Day 300 (since then it would have taken the IP shock more than 30 days to move from the TS to V2), assuming that the TS was still at ~ 83.6 AU. Or, if the Dec. 2006 IP shock were propagating faster in the HS than 300 km/s it would have impacted the TS after ~ Day 300 (since then it would have taken the IP shock less than 30 days to move from the TS to V2), assuming the TS was still at ~ 83.6 AU. It is possible that after the sunward moving TS crossed V2 near ~ Day 243, it continued moving sunward. If this were the case, then the IP shock(s) from the Dec. 2006 events may have impacted the TS earlier than ~ Day 300 at a distance closer to the Sun than ~ 83.6 AU.

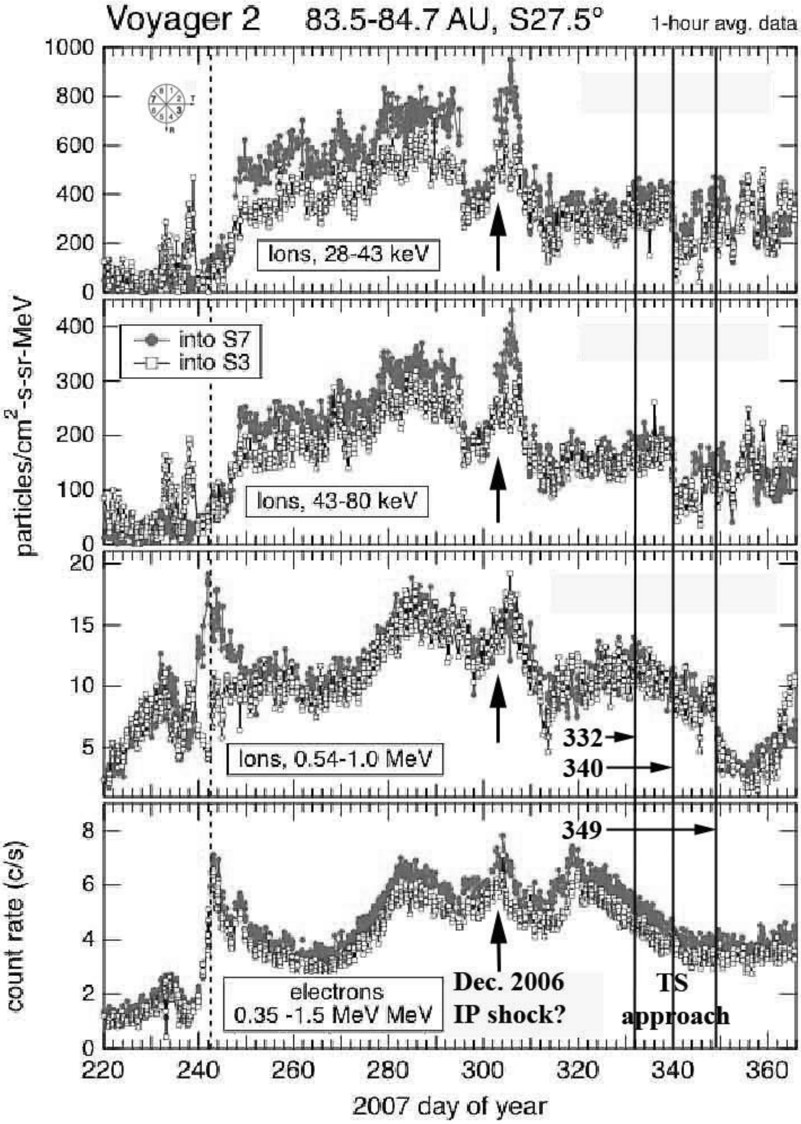

FIGURE 5. V2 LECP data for the same time interval as the magnetic field and plasma parameters in Figure 4: Day 220-365, 2007. The first vertical dashed line on the left denotes the sunward-moving TS crossing of V2. There is a peak (see vertical upward pointing arrows in each panel on Day 304) in the LECP data near Day 304, 2007 that could be associated with the arrival of the Dec. 2006 IP shock(s) at V2. The outer two solid vertical lines on the right encompass the time of the HEI detections in the V2 plasma data. Note they also coincide with slightly increased LECP fluxes in the top three panels. They also coincide with the interval we associate with the re-approach of the TS. The middle solid vertical line at Day 340 shows the time of the abrupt decrease in the LECP detections in the two lowest energy ranges in the upper two panels, coinciding with the changes in the magnetic field and plasma (see Figure 4).

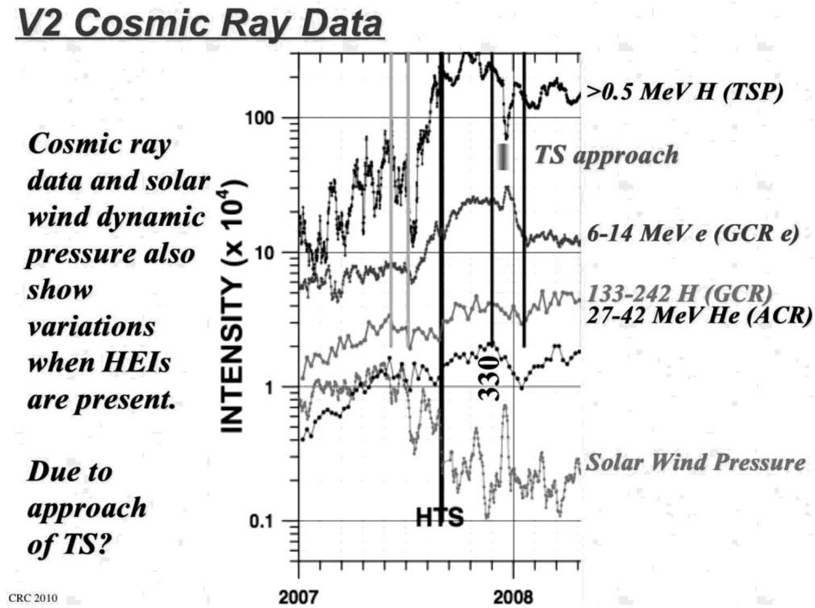

FIGURE 6. Comparisons of the V2 plasma dynamic pressure and the CRS measurements from the beginning of 2007 into 2008. The possible re-approach of the TS outward to the vicinity of V2 in Nov.-Dec. 2007 is indicated and is consistent with the changes in the CRS and plasma data seen in the figure. HTS denotes the sunward-moving TS crossing. TSP indicates the termination shock particles. GCR indicates galactic cosmic rays; e denotes electrons. ACR indicates anomalous cosmic rays.

Figure 5 shows the V2 LECP data for the same times as shown in Figure 4. These LECP data show an isolated peak at ~ Day 304, 2007. Thus, in the LECP data also, we can associate this event with the arrival of the Dec. 2006 IP shock(s) at V2. With regard to the possible re-approach of the TS near Day 332-349, 2007, we note an increase in the count rate starting at ~ Day 332 in the lowest energy ion channel (top panel in Figure 5). Note each channel shows somewhat similar behavior after ~ Day 349, to that shown in the same channel after the TS crossing ~ Day 243, denoted by the dashed vertical line on the left. The discontinuity in the LECP data on ~ Day 340 coincides with those in the magnetic field and plasma data (Fig. 4) on ~ Day 340.

Figure 6 shows the V2 CRS data and the plasma dynamic pressure from 2007 to 2008.3. Again the variations are evident in the data when the HEIs are detected (see brackets with short solid vertical line labeled "TS approach"). These cosmic ray variations also are consistent with the outward motion of the TS so that it re-approaches V2 near Day 333-349, 2007. Due to the lack of higher time resolution data in this plot, at this time we are not able to identify if the possible arrival of the IP shock associated with the Dec. 2006 solar events is observed in the V2 CRS data.

DISCUSSION

V2 was crossed by the sunward movement of the TS on ~ Day 242, 2007. We have found a prolonged interval (~ 16 days) of HEI detections in the V2 plasma data near the end of 2007, about 90 days after the ~ Day 242 TS crossings of V2. We associate these later HEI detections with the subsequent TS outward motion and re-approach to V2. The simultaneous changes in the V2 magnetic field, convective bulk plasma parameters, LECP, and CRS energetic particle observations appear to be consistent with this interpretation. We suggest that the interplanetary shock(s) associated with the Dec. 2006 solar events may have given rise to an increase in the solar wind dynamic pressure in the outer heliosphere that pushed the TS outward ~ 1 AU so that the TS re-approached V2 in Nov.-Dec. 2007. It is also possible that there is a ripple in the TS on the order of ~ 1 AU and that V2 and the ripple in the TS were in close proximity in Nov. - Dec. 2007.

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