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Voyagers 1 and 2 in a shrunken and squashed heliosphere

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[1] We have extended our earlier calculations of the distance to the heliospheric termination shock (HTS), which covered the period from the launch of V1 and V2 in 1977 to 2005, to the period from 2006 to 2011. During this latter period, the solar wind speed, ram pressure, and magnetic field decreased to the lowest levels in recent history, related to the sunspot minimum in 2008–2009. The HTS distance has decreased correspondingly so that V1, which was crossed by the HTS at 94 AU in late 2004, would now, in early 2011, be expected to reach the HTS at a distance of ~80 AU, when the HTS distance would be expected to be at its minimum. Similarly, V2, which was crossed by the HTS at 84 AU in mid-2007, would, in early 2011, reach the HTS at a distance of only 74 AU. These distances, in early 2011, are ~15% less than those at which V1 and V2 initially reached the HTS. The distance to the heliopause (HP) is more uncertain, but recent calculations place its equilibrium distance at between 1.4 and 1.6 times the HTS distance. Allowing for an additional 1 year for the HP to reach its equilibrium minimum distance relative to the HTS would mean that, assuming this distance remains a constant fraction larger than the HTS distance, the HP distance would be at its minimum distance of (1.4–1.6) × 80 AU = 112–128 AU in the direction of V1 in early 2012. At this time, V1 will be at a distance of ~120 AU so that there is a possibility that V1 could cross the HP and enter interstellar space at the time 2012.0 ± 1 year. If the crossing does not happen during this time period, then it is unlikely that V1 will reach this defining boundary before about 2016 because of the expected outward motion of the HTS and the HP toward their more normal distances of 85–96 and ~120–140 AU, coincident with the maximum of the new sunspot cycle.

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1. Introduction

[2] The location of the heliospheric termination shock (HTS) is determined by the pressure balance between the outward flowing solar wind and the plasma and magnetic field properties of the local interstellar medium [*Wang and Belcher*, 1999; *Suess*, 1993]. V1 first reached the HTS in late 2004 at a distance of 94 AU. This provided a normalization point for determining the HTS distance with time that was utilized in a simple empirical model to estimate the effect of solar wind pressure variations on the shock location using the available solar wind plasma data from V2 [*Webber*, 2005]. Subsequently, more sophisticated models were employed to trace the HTS location [e.g., *Richardson et al.*, 2006] and to also examine the heliosheath region beyond the HTS [*Washimi et al.*, 2007, 2011]. Basically, the prediction of all of these models is similar with regard to the variations of the HTS distance with time. Over a comparable time period from about 2002 to 2007, covering a period from maximum to minimum HTS distance, the maximum variation in each model was ~10–13 AU.

[3] At the location of V1, the HTS distance was estimated to be ~85 AU in 2001 (just beyond or outside of the V1 distance at that time) and moved rapidly outward, still just outside of the V1 location, between 2002 and 2004 [*Webber*, 2005]. Then near the end of 2004, the HTS started an inward movement and the HTS crossed V1 at 94 AU. The HTS continued to move inward rapidly and reached a distance of ~87 AU by the end of 2005, so that V1 was located ~10 AU beyond the shock in only 1 year [*Webber et al.*, 2007] (the average speed of V1 is 3.6 AU yr^{-1})!

[4] The object of this study is to determine the distance of the HTS at both V1 and V2 during the period just before V2 reached the HTS in 2007, again using V2 plasma data [see also *Washimi et al.*, 2011], and then in the time period from 2007 to 2011, to determine the HTS distance in the direction of V1 and V2, but now using the plasma data at 1 AU from the Solar Wind Electron, Proton, and Alpha Monitor (SWEPAM) instrument on ACE (http://www.srl.caltech.edu/ACE/) and the OMNI plasma data (http://omniweb.gsfc.nasa.gov/form/dx1.html) since the V2 plasma data are no longer useful in this regard after the HTS crossing. This later time period is one in

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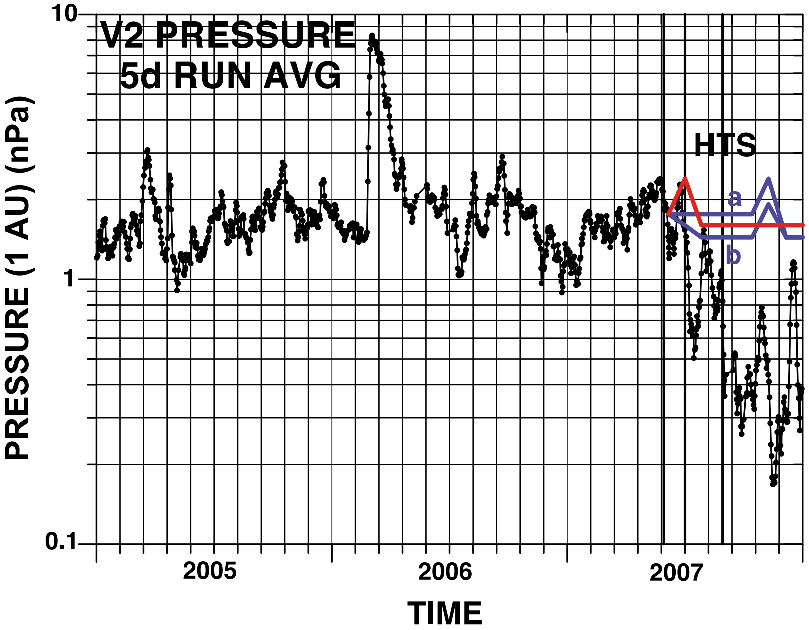

Figure 1. Solar wind ram pressure measured at V2 (density corrected to 1 AU) in 2005–2007. See text for discussion of the solar wind ram pressure profiles after 2007.4, including the a and b lines and the red line.

which the cosmic ray intensities reached an unprecedented high maximum and the solar wind speed and pressure and the interplanetary magnetic field reached unusually low values corresponding to the sunspot minimum in 2008–2009 [e.g., *McDonald et al.*, 2010; *Mewaldt et al.*, 2010; *McComas et al.*, 2008]. For this later time period, we shall also estimate the distance to the heliopause (HP), assumed to be at a distance beyond the HTS that remains a constant fraction of the HTS distance from the Sun [e.g., *Müller et al.*, 2008].

2. Data

[5] From the beginning of 2005 to the time the HTS crossed V2, we use the daily average density and solar wind speed data from the V2 Massachusetts Institute of Technology plasma experiment to calculate the time history of the solar wind ram pressure, nV^2 (see http://web.mit.edu/afs//athena/org/s/space/www/voyager/voyager_data/voyager_data.html). The 5 day running average pressure is corrected to a constant distance of 1 AU using an r^{-2} dependence for the density (no correction is made for a possible radial dependence of V). This pressure is shown in Figure 1 for the time period from 2005 to 2007 when V2 was between 75 and 85 AU. The main features of these data are the large pressure wave seen at 2006.17 and two decreases in pressure seen about 0.26 and 0.16 years prior to the HTS crossing of V2. The blue and red lines in Figure 1 show extrapolations of the pressure that may have been seen at V2 during the latter half of 2007 if the HTS were not present. They will be discussed later.

[6] After about 2007.4, the V2 data cannot be reliably used to indicate the solar wind pressure inside the HTS. For these time periods, we use the SWEPAM data from the ACE spacecraft at the Earth. The day-to-day variations of this pressure, caused mainly by density variations, is large, so in Figure 2 we show the 27 day average solar wind ram pressure at the Earth additionally smoothed with a five-period running average. These data show several broad time periods of increased pressure during the 11 year solar activity cycle and, in particular after 2008.0, show a rapid decrease in the overall solar wind pressure as the solar activity approaches its minimum. By the end of 2009, this ram pressure is less than half of the average pressure over the earlier part of the 11 year solar cycle. This time period is consistent with the low average values of the interplanetary magnetic field and the unusually low amount of solar modulation of galactic cosmic rays as described by *McDonald et al.* [2010] and *Mewaldt et al.* [2010].

[7] In Figure 3, we show the solar wind ram pressure measured at the V2 spacecraft over the same time period and with the same smoothing. The Earth-based SWEPAM data in Figure 3 are delayed by 0.87 years to correspond to an average solar wind transient time between the Earth and V2. Starting in ~2002, the broad temporal features seen at the Earth line up well with those seen at V2 using this delay.

[8] In Figure 4, we show the ratio of the ram pressure measured at V2 (corrected to 1 AU) and at the Earth, delayed by between 8 and 14 of the 27 day intervals depending on the relative spacecraft locations, over the entire time period of 1998–2007, nearly a complete 11 year solar cycle. This ratio has an average value slightly less than 1 over this time period, as might be expected from a slowing down of the solar wind speed, and also shows the large temporal variations exhibited in Figure 3. The ratio of 1, as shown by the dashed line in Figure 4, is used to approximate the temporal variations in the solar wind ram pressure that would be seen near the HTS after 2008.0 from the smoothed variations

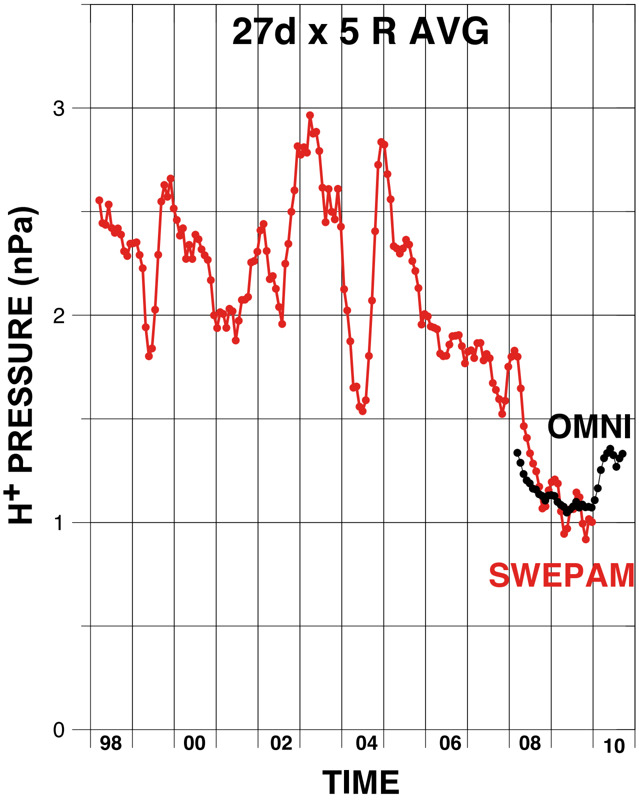

Figure 2. The 27 day average solar wind ram pressure at the Earth from ACE-SWEPAM and OMNI, from 1998 to 2010 based on the available data. Data smoothed with the five-period running average are shown. The differences between the ACE and OMNI data after ~2008.5 are relatively minor and do not affect the conclusions of this paper.

observed at the Earth by SWEPAM. These Earth data are extended to late 2010 by using the solar wind data from OMNI.

3. Responses of the HTS to the Solar Wind Pressure Variations

[9] *Wang and Belcher* [1999] and *Suess* [1993] discuss the HTS response to solar wind pressure variations. The fluctuating solar wind pressure variations make it difficult to calculate theoretically the expected HTS distance with time at any one location. Certainly, on a longer-term time scale, the HTS will be located near the point where there is equilibrium between the outward solar wind pressure and the inward local interstellar plasma and magnetic field pressure. On a shorter time scale, the HTS location will also move inward and outward corresponding to the short-term pressure variations in the solar wind. Complex latitude and longitude asymmetries in the solar wind pressure will result in a nonuniform HTS distance with respect to both heliospheric latitude and longitude.

[10] For our calculation, we consider both the short-term (~26 day) and long-term (~1 year or longer) pressure variations to calculate a typical HTS distance near the solar apex within ± 30° of the heliospheric equator. This includes the locations of V1 and V2. Possible latitude effects of the solar wind ram pressure and therefore the HTS distance, which could be important, are not considered in this analysis.

[11] The details of the calculation of the HTS location with time are discussed by *Webber* [2005]. Briefly in summary here, we note that this calculation considers both long-term and short-term pressure variations as well as the inward and outward speeds of the HTS in each 26 day interval in response to the solar wind pressure variations. For the long-term HTS variations, we take a three-period moving average of the 6 month average solar wind pressure data. This time sequencing is similar to that used by *Izmodenov et al.* [2003] in their calculation of the HTS distance in which they use a five-period moving average of the 6 month average solar wind data to calculate the HTS location and its changes with time. For the inward and outward speed of the HTS in response to the longer-term pressure variation, we used as a guide the work of *Wang and Belcher* [1999].

[12] The shorter-term, 26 day pressure variations are superimposed on the longer-term variations. Here we recognize that the average pressure difference between successive 26 day periods may change by a factor of ~2 or more. These pressure differences are usually related to the passage of large interplanetary shocks (e.g., Global Merged Interaction Regions (GMIRs)). For the inward and outward speeds during these time periods, we make use of calculations by *Whang and Burlaga* [1993] and *Lu et al.* [1999] for

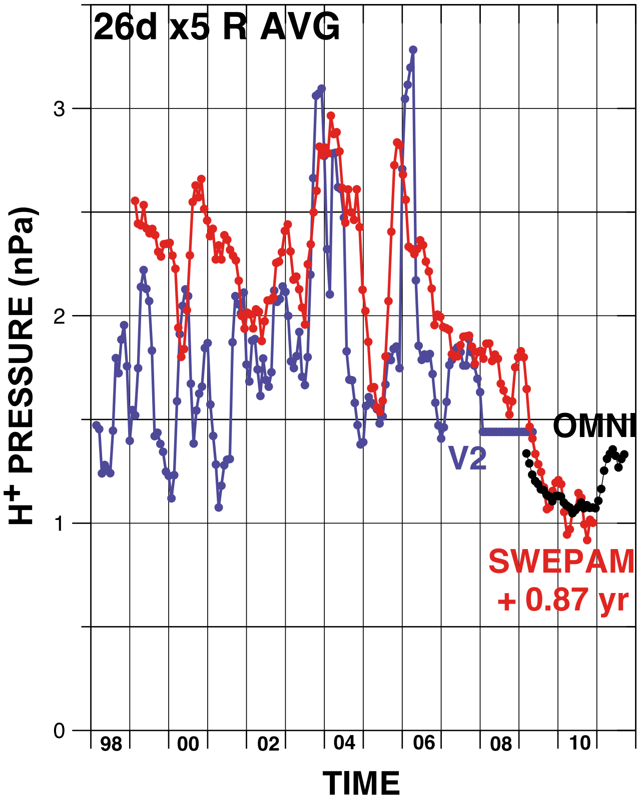

Figure 3. The 26 day average solar wind ram pressure at V2 from 1998 to 2007 (density corrected to 1 AU). V2 data are smoothed in the same way as Earth data. SWEPAM/OMNI data are shown with an average time delay of 0.87 year.

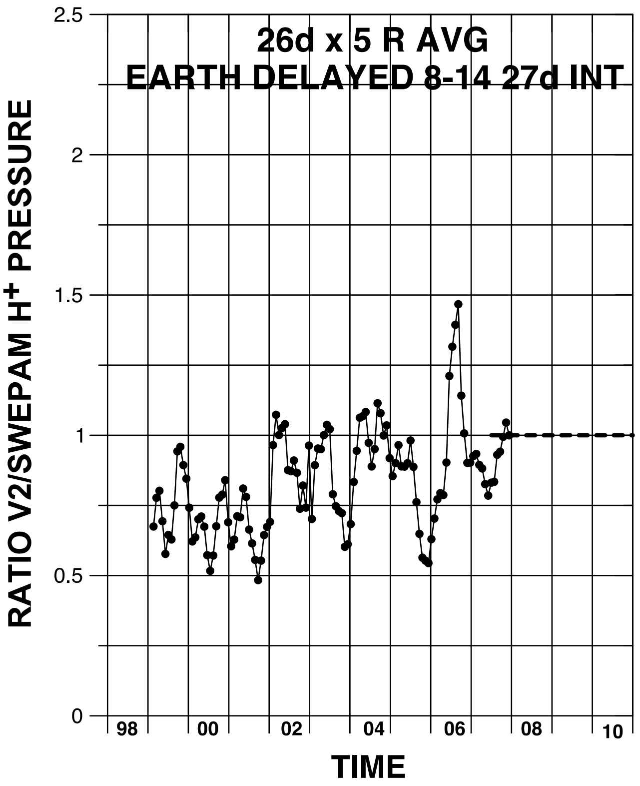

Figure 4. Ratio of solar wind ram pressures measured by V2 and by SWEPAM from 1998 to 2007.4. Note, as indicated at the top of Figure 4, that unlike Figure 3 where the average time shift for all the data was 0.87 year, in Figure 4 the time delay is not constant. The offset varies between 8 and 14 of the 27 day intervals depending on the relative spacecraft locations.

interplanetary shocks interacting with the HTS. In some cases, when the pressure difference between two successive 26 day intervals is large, outward and inward speeds of the HTS of at least 100 km s^{-1} are estimated during a 26 day period.

4. Variations of the HTS Distance at V1 and V2 During the 2002–2007 Time Period

[13] In Figure 5, we show the calculated distance of the HTS at the V1 location for the 2002–2007 time period using our method. Also shown in Figure 5 are the radial locations of V1 and V2 as a function of time. For V1, we observe that throughout 2002–2004, this spacecraft is just upstream or sunward of the estimated HTS location. This time period and its relationship to the large intensities of MeV protons seen at V1 has been discussed by *Webber* [2005; see also *Washimi et al.*, 2007]. At the end of 2004, the HTS crossed V1 during a period of rapid inward movement after the so-called Halloween 2003 shocks (October–November 2003) at the Earth [*Intriligator et al.*, 2005] reached the HTS.

[14] The behavior of the HTS at the V2 location is also shown in Figure 5. This curve, which essentially matches the V1 curve, is normalized so that the HTS crossed V2 at the observed time of 2007.66. This normalization factor, taken here to be 0.92, is a measure of the asymmetry of the heliosphere between the N-S distances at which V1 and V2 reached the HTS [see *Stone et al.*, 2008; *Opher*, 2010; *Washimi et al.*, 2011]. This asymmetry factor is of importance for comparing V1 and V2 cosmic ray intensity observations to determine a radial gradient, for example, and is often neglected. These two spacecraft are separated by about 20 AU in radial distance over this time period, and this "squashing" of the heliosphere by ~8%–10% or 8–10 AU

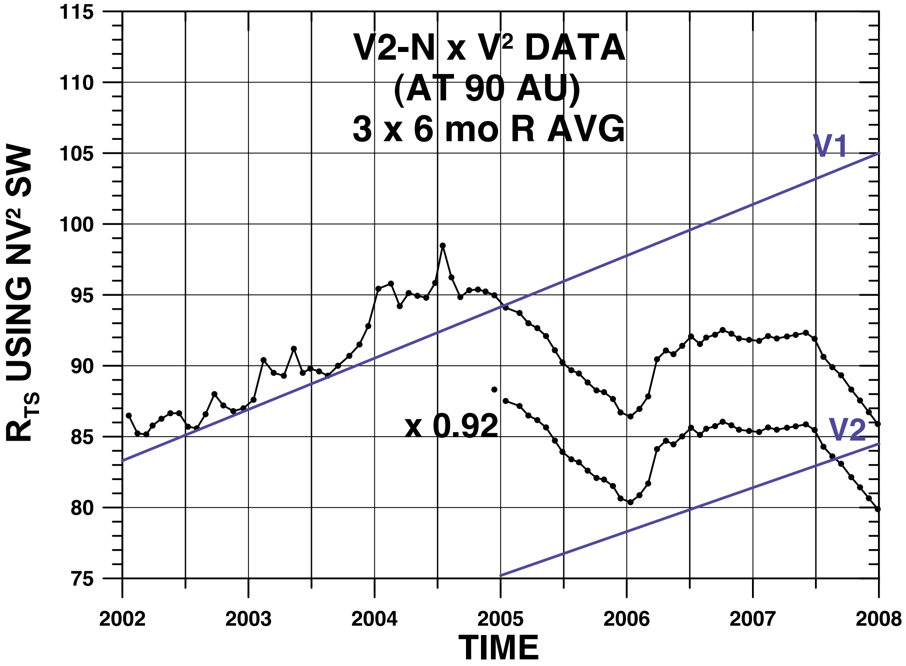

Figure 5. Calculated distance of the HTS at V1 for the time period 2002–2007 and at V2 from 2005 to 2007. The HTS distance at V2 is normalized so that V2 crosses the HTS at 2007.66.

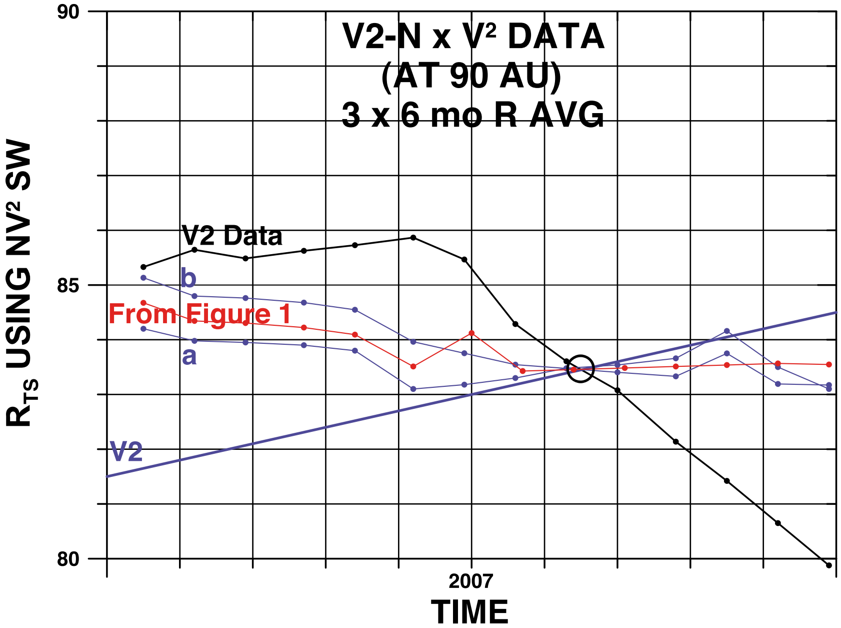

Figure 6. Calculated distance of the HTS at the location of V2 during 2007. The HTS distance for the different solar wind ram pressure profiles a and b and the red line is discussed in the text. The original V2 data profile is shown as a black line. The a, b, and red lines have been renormalized so that V2 crosses the HTS at 2007.66.

near the location of the HTS significantly changes the values of the radial gradient determined.

[15] Notice in Figure 5 that after about 2007.5, the HTS location at both V1 and V2 is rapidly moving inward. This inward motion arises from the fact that the solar wind pressure measured at V2 suddenly begins to decrease at about 2007.4, well before the arrival of V2 at the HTS itself. A second further decrease in solar wind pressure occurred at about 2007.5 so that in the time period just prior to the arrival of V2 at the HTS, the solar wind ram pressure became less than half of the average pressure observed at V2 throughout 2006 and 2007 (see Figure 1 and *Richardson et al.* [2008])).

[16] The HTS distance at V2 shown in Figure 5 is based on the V2 solar wind plasma data up to the time of arrival of V2 at the HTS at 2007.66, the same as the *Washimi et al.* [2011] calculation. If we believe that these solar wind data are affected by structures in front of (sunward of) the HTS after about 2007.4, then we have to make assumptions about the solar wind pressure at V2 for the remainder of 2007. Possible assumptions are shown by the red curve and blue curves a and b in Figure 1. In each case, the solar wind pressure is taken to be that measured by V2 up to 2007.4. For the red curve, the shock from the December 2006 events at the Earth is taken to arrive at V2 at 2007.50, the time of a large magnetic field increase indicative of a GMIR [*Burlaga et al.*, 2008] as well as a large decrease of >70 MeV cosmic rays [*Webber et al.*, 2009].

[17] This December 2006 event has also been propagated through the heliosphere by *Intriligator et al.* [2010a]. Their calculated arrival time of this shock is about 2007.72 (day 262), and the convective plasma speed increase in the heliosheath at this time is 1.15 times (from 325 to 375 km s^{-1}). The Hakamada-Akasofu-Fry Source Surface (HAFSS) model used (as discussed by *Intriligator et al.* [2010a]) does not take into account the fact that the December 2006 interplanetary (IP) shock is propagating beyond the HTS. HAFSS assumes the IP shock is always in the solar wind. Also including the effects of slowing down, we estimate the interplanetary shock as calculated by *Intriligator et al.* [2010a] arrived at V2 in the 26 day time interval centered on 2007.86 ± one 26 day interval, with a shock pressure increase of 1.3 times.

[18] An enlarged profile of the HTS behavior in the year 2007 for these different possibilities is shown in Figure 6. Instead of a rapidly decreasing HTS distance at the time of the V2 HTS crossing, we now find that the HTS distance is almost constant throughout the period before and after the shock crossing for all three possibilities. Thus, the HTS first crossed V2 at 2007.66, and V2 is slightly beyond the HTS just before 2007.86. When the interplanetary shock predicted by *Intriligator et al.* [2010a] reached the HTS, just inside V2, it pushed the HTS out to near the location of V2 during the 2007.86 26 day interval. Thus, a second HTS encounter or near-encounter could occur at that time. The HTS moved out ~1 AU at this time in accordance with the assumed solar wind pressure increase of ~1.3 times.

[19] We note that *Intriligator et al.* [2010a] have observed high-energy solar wind ions at roughly twice the average solar wind speed at V2 two times in 2007. The first time was on days 242–243 in conjunction with the HTS crossings [*Intriligator et al.*, 2010b], the second time was between days 333 and 348 (2007.91 and 2007.95). Large transient energetic plasma, termination shock particle (TSP), and anomalous cosmic ray (ACR) intensity changes were seen near these times in later 2007 by the low-energy charged particle (LECP) and cosmic ray subsystem (CRS) instruments on V2 [*Decker et al.*, 2009; *Intriligator et al.*, 2010a]. Large

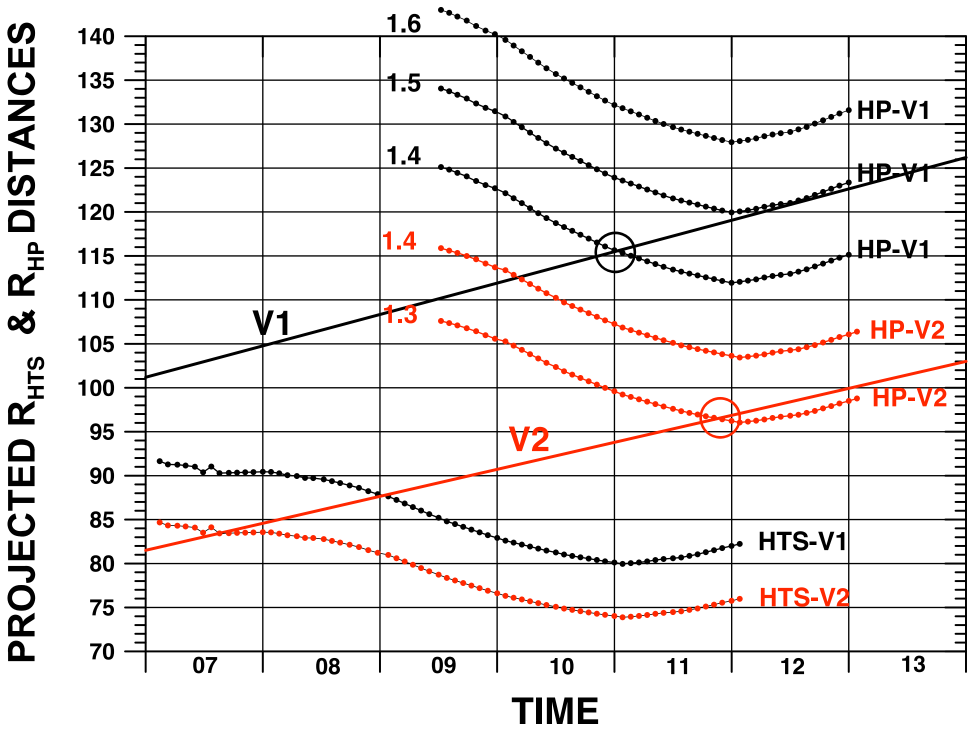

Figure 7. Distance to the HTS and the HP in the direction of V1 (in black) and V2 (in red) for the time period 2007–2013. The estimated location of the HP for this same time period is shown. It is assumed that the ratio of the HP distance to the HTS distance, delayed by 1 year, remains a constant with time with values during this time period between 1.4 and 1.6 for V1 and between 1.3 and 1.4 for V2. Circled is the point of first contact for each spacecraft: the point at which the 1.4 HP line and the V1 trajectory first cross, and for V2, the point at which the 1.3 HP line and the V2 trajectory first cross.

magnetic field enhancements were also seen near the times of the particle intensity changes [*Burlaga et al.*, 2008]. Further studies are underway to verify whether these times could be time of HTS crossing.

[20] Subsequently, in late 2008, the HTS began to move inward as the decreasing solar wind pressure associated with the 11 year solar cycle propagated out to the location of V2.

5. The Distance of the HTS and HP From 2008 to 2012

[21] The behavior of the HTS in the direction of V1 and V2 in the time period from 2008 to 2012, based on the SWEPAM and OMNI data at the Earth, is shown in Figure 7. The HTS moved inward, slowly at first during 2008, but in 2009 and 2010 moved inward by ~4–5 AU yr^{-1}, actually greater than the outward speed of V1. By 2011.0, the HTS reached a location at ~80 AU, while at the same time, V1 was at ~115.7 AU. After 2011.0, the HTS behavior will depend on the solar wind pressure at the Earth after about ~2010.0. OMNI data show that this pressure increases in the first half of 2010 and then levels off through the end of 2010. By the end of 2011, the HTS distance at V1 has increased from a minimum of ~80 to ~82.5 AU.

[22] The changes in the distance to the HP during this time period are more problematical. The studies by *Müller et al.* [2008] have shown that, for a wide range of interstellar parameters and a wide range of HTS distances, the ratio of the HP distance to the HTS distance remains roughly constant at a value of ~1.4. From this study, one might conclude that, as the HTS moves inward during the 2008–2011 time period due to solar wind pressure changes, the HP will move inward as well and that, once equilibrium is established, the HP will be at a closer distance, which is still ~1.4 times the new HTS distance. In this scenario, then, assuming that equilibrium is established in ~1 year (the travel time of an outward moving disturbance to propagate through the heliosheath [e.g., *Washimi et al.*, 2011]), by about 2012.0, the HP distance would be at its minimum of 1.4 times the HTS minimum of 80 AU, or ~112 AU, and by about 2013.0, the last point at which we have data, the HP would be at ~115 AU and moving outward at about the same speed as V1. The curve corresponding to this minimum HP distance of 1.4 times the HTS distance and an approximate equilibrium time of 1 year is shown in Figure 7. The V1 trajectory first intersects this curve early in 2011. Indeed, there is evidence in the changing pattern of the solar wind flow as of about 2010.5 that V1 may be approaching the HP [*Decker et al.*, 2010].

[23] But there is the question, how will we know when V1 is approaching or has crossed the HP? On V1, without a working plasma detector, this might be more difficult. From the energetic particle point of view, the intensities of ~100 keV plasma particles measured by the LECP experiment [*Decker et al.*, 2010], the MeV termination shock particles measured by both the LECP and CRS experiments, and the ACR particles measured in most detail by the CRS experiment [*Cummings et al.*, 2008] provide interesting possibilities for sensing the proximity of

the HP or some equivalent "outer boundary." The TSP and ACR populations have extremely high intensities in the heliosheath that are characteristic of "trapped" populations. These high intensities first appeared, more or less coincident with the HTS crossing, and have continued, even increasing intensity in the case of the ACR, up to the present time when V1 is approaching 115 AU.

[24] At some distance, near the outer trapping boundary, these intensities should begin to decrease, with the higher energies most likely decreasing first because of their longer diffusion length. Calculations relating to this problem have been made by *Ferreira et al.* [2007] in their model for the acceleration and propagation of ACR. These calculations, above a few MeV, show that the peak intensities of ACR will occur about ~5–10 AU in front of an outer boundary. This boundary need not be the HP but could be a specific "region" (e.g., the magnetic wall identified in the calculations of *Washimi et al.* [2011]), in the structure of the heliosheath. The magnetic wall itself appears to be ~10 AU inside the HP according to *Washimi et al.* [2011]. At the present time (early 2011), the intensities of ACR above a few MeV certainly appear to have reached a "peak" intensity [*Cummings et al.*, 2010].

[25] Returning to the question of the distance of the HP, V1 and V2 during the 2008–2013 time period, we also observe that there are a number of different estimates regarding the distance to the HP. Relative to the HTS, most of these estimates place the equilibrium HP distance (in the apex direction) at between 1.4 and 1.6 times the HTS distance. Thus, the *Müller et al.* [2008] value is at the low end of this range. The work of *Florinski and Pogorelev* [2009] uses an HP distance of between 1.5 and 1.6 times the HTS distance in order to describe the cosmic ray modulation in the outer heliosphere. A similar value for this HP/HTS distance ratio is obtained from the studies of *Washimi et al.* [2011] on the characteristics and structure of the heliosheath.

[26] We thus take a reasonable upper limit for V1 for the equilibrium value of the HP/HTS distance ratio to be 1.6. This is shown as the upper limit in Figure 7. V1 will not reach this limiting distance during the 2008–2012 time period. In fact, V1 will be at ~121 AU near the middle of 2012, will be at a distance that is equal to 1.50 times the HTS distance. After early 2012, the HP distance will have already started to increase in response to the increasing solar activity and solar wind ram pressure as observed by OMNI. The outward HP speed at this time will be, in fact, close to the outward speed of V1.

6. Summary and Conclusions

[27] We have extended our earlier calculations of the distance to the HTS, which covered the time period from the launch of V1 and V2 in 1977 to 2005 [*Webber*, 2005], to the time period from 2006 to 2012. We continue to use the V2 plasma data up to 2007.40 just before V2 reached the HTS. In our updated calculations for the time period between 2007.4 and 2011, we use the solar wind data from the SWEPAM instrument on the ACE spacecraft and the OMNI data.

[28] We find that to match the HTS crossing distances of 94.0 AU for V1 and 83.7 AU for V2, we require a normalization factor of 0.92 between the Northern and Southern Hemispheres. This factor represents a squashing of the heliosphere in the Southern Hemisphere relative to the Northern Hemisphere as originally suggested by *Stone et al.* [2008] and *Opher et al.* [2006].

[29] We also find that, in response to a decreasing solar wind ram pressure, the HTS moved inward after about mid-2008, reaching a minimum distance of ~80 AU in the direction of V1 and 74 AU in the direction of V2 in early 2011. Recall that the HTS crossed V1 at 94 AU in late 2004 and crossed V2 at 84 AU at 2007.66, so this represents a shrinking of this heliospheric parameter by ~15% at that time. The HTS distance will start to increase early in 2011 as a result of the increasing solar activity and solar wind pressure observed by OMNI.

[30] Our studies reveal that the HTS crossings of V2 at 2007.66 may not be unique. It is quite likely that structure just upstream of the HTS modified the solar wind ram pressure. As a result, instead of decreasing as previous calculations using the actually measured solar wind ram pressure, the HTS distance at the V2 location remained almost constant during the latter part of 2007. The arrival of the IP shock from the December 2006 events on the Sun between about 2007.50 and 2007.86 thus pushed the HTS outward just enough so that it almost reached V2, thus providing a possibility of a second V2 crossing (or near crossing) after the initial crossings.

[31] The distance to the HP is more uncertain than the HTS. Assuming that the ratio of the HP distance to that of the HTS remains constant at a value between 1.4 and 1.6 during the inward movement of the HTS, and allowing for a further 1 year delay for the HP to reach an equilibrium distance relative to the HTS, if the HP/HTS ratio is only 1.4, V1 could encounter the HP as early as the beginning of 2011 at a distance of ~116 AU.

[32] The HP continues to move inward until the early part of 2012 when it begins to move outward due to the onset of the new solar cycle. At 2012.5, V1 will be at 121 AU. This is equivalent to a distance ~1.50 times the corresponding HTS location 1 year earlier.

[33] So a nonencounter during the 2011–2012 time period would mean that the equilibrium HP/HTS distance ratio is greater than 1.50.

[34] At a nominal HP distance of 144 AU implied by a 1.6 HP/HTS distance ratio and an HTS location of 90 AU, the HP would then not be encountered by V1 until 2019, which is near the limit of the expected lifetime of V1.

[35] So will V1 reach the HP and interstellar space during 2011–2012, or will this illustrious mission be denied its final triumph? Or will it defy its makers once again and last just long enough to cross the HP and live to send the data back to Earth?

[36] **Acknowledgments.** The work at NMSU was funded by JPL/Voyager. The work at Carmel Research Center, Inc. was funded by NASA grant NNX08AE40G and by Carmel Research Center, Inc.

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