# Passage of a large interplanetary shock from the inner heliosphere to the heliospheric termination shock and beyond: Its effects on cosmic rays at Voyagers 1 and 2

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[1] Using data from the charged particle telescopes on V1 and V2 we have followed the progress of a large interplanetary shock as it passes V2 at a distance of 79 AU at about 2006.16, then later crosses the heliospheric termination shock finally reaching V1 at a distance ~100 AU. A decrease ~15% is observed in the V2 >70 MeV rate starting at 2006.19 and three smaller decreases starting at 2006.29, 2006.50 and 2006.86 are observed at V1. From the timing of the first two decreases at V1 we are able to determine that the average shock speed slows down at the termination shock from ~600 km s$^{-1}$ to 210–270 km s$^{-1}$. Decreases of ~30–50% in anomalous He and galactic H are observed at V2 when the shock passes this location inside the termination shock. Smaller decreases are observed for both of these components when the weakened interplanetary shock passes V1 at 2006.50. These results define the extent and magnitude of solar modulation effects on cosmic rays caused by transients both inside and beyond the termination shock. **Citation:** Webber, W. R., A. C. Cummings, F. B. McDonald, E. C. Stone, B. Heikkila, and N. Lal (2007), Passage of a large interplanetary shock from the inner heliosphere to the heliospheric termination shock and beyond: Its effects on cosmic rays at Voyagers 1 and 2, *Geophys. Res. Lett.*, *34*, L20107, doi:10.1029/2007GL031339.

## 1. Introduction

[2] On December 16, 2004, Voyager 1 crossed the Heliospheric termination shock (HTS) at a radial distance of 94 AU from the Sun, becoming the first spacecraft to explore the heliosheath beyond the HTS [*Stone et al.*, 2005; *Decker et al.*, 2005; *Burlaga et al.*, 2005]. Since that time V1 has continued to move outward to its current (2007.5) location at ~104 AU, 35°N Heliolatitude, about 15 AU beyond the presently estimated location of the HTS. V2 is now at ~83 AU and 27°S Heliolatitude, still inside the HTS. These two spacecraft thus provide a unique opportunity to study interplanetary shocks and their cosmic ray effects as they move outward from the Sun, interact with the HTS and continue moving outward through the Heliosheath region. Here a "shock" is defined as a sudden increase in solar wind speed. The plasma detector on V1 is no longer operational, but it has been shown on numerous occasions that the onset of intensity decreases of both galactic and anomalous cosmic rays may be used to define the arrival times of these events at both V1 and V2 [e.g., *McDonald and Burlaga*, 1997; *Webber and Lockwood*, 2004]. Thus the V1-V2 cosmic ray detectors may be used to track the progress of these *events* outward in the heliosphere, helping to determine their propagation speed. In particular it is now possible using this data to make an estimate of the propagation speed of these transients beyond the HTS. This is important from the theoretical point of view [e.g., *Zank*, 1999] as well as for estimating the location of the Heliopause (HP) based on measurements of VLF radio waves [e.g., *Gurnett et al.*, 1993]. For example, these estimates typically use an average shock speed beyond the HTS = 0.7 times the average shock speed inside the HTS [e.g., *Gurnett et al.*, 2003; see also *Zank et al.*, 2001].

[3] Figure 1 shows the intensity-time history of >70 MeV cosmic rays at V1 and V2 since 2004, with the time of HTS crossing by V1 indicated. Since this HTS crossing the intensities at both spacecraft have increased rapidly at first, indicative, in part at least, by the relaxation of the 11-year solar modulation effects from the minimum intensities observed between 2001–2004. Superimposed on this longer term intensity increase are several transient intensity decreases. A notable decrease, ~10% in the >70 MeV rate, occurred at V2 at 2004.33. This decrease is probably related to the arrival of the large shock from the "Halloween" events at the Earth, which occurred at about 2003.82 or ~0.51 year earlier. The events at the Sun and the Earth during this time period were some of the largest ever recorded and produced a maximum average shock speed ≥1500 km s$^{-1}$ between the Sun and the Earth for the specific Halloween event. The travel time of 0.51 years from the Earth to the location of V2 at a distance ~73 AU implies an average propagation speed ~670 km s$^{-1}$. This speed compares with the maximum solar wind speed of ~560 km s$^{-1}$ actually measured by the plasma detector on V2 at the time of the shock arrival. This Halloween event and its effects at V2 has been extensively discussed in the literature [e.g., *Richardson et al.*, 2005; *Intriligator et al.*, 2005]. This Halloween event was not as sharply defined in the cosmic ray data at V1, still upstream of the HTS at ~92 AU, but its arrival [see *Intriligator et al.*, 2005] is probably associated with the overall intensity decrease of 6–7% starting at 2004.57 and reaching a minimum just before the HTS crossing in late 2004. A comparison of V1 and V2

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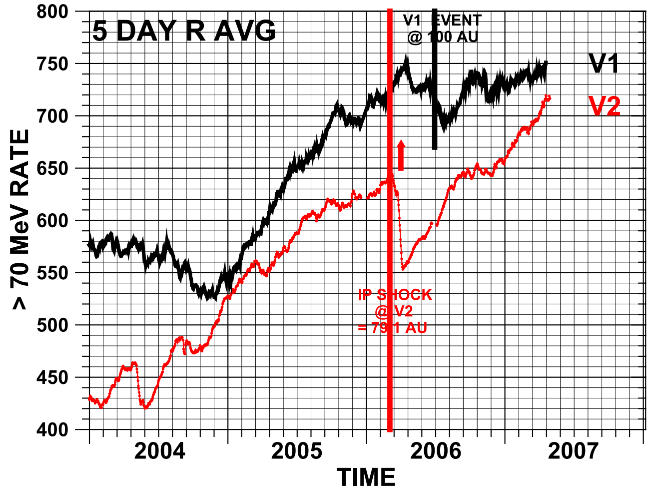


**Figure 1.** Five day running average of >70 MeV rates at V1 and V2 from 2004.0 to the present. Important times are indicated by vertical lines as described in the text.

onset times for this event with a delay ~0.24 years would imply a symmetry in the N-S shock speeds to within a few percent when allowance is made for the slowing down of the shock between the V2 and V1 locations 73 and 92 AU [e.g., *Intriligator et al.*, 2005].

[4] The event of primary interest here was first observed in the cosmic ray data at V2 at 2006.19, about two years after the Halloween event. A possible time sequence for this event, designated 2006.19, as it passes beyond the HTS and eventually reaches V1 and the implications thereof are discussed in the remainder of this paper.

## 2. Temporal History of the 2006.19 Event at V1 and V2

[5] As seen in Figure 1 this event produced an overall intensity decrease ~15% in the >70 MeV rate at V2 when it passed this spacecraft at 79.1 AU. The plasma and magnetic field characteristics of this event at V2 have been discussed by *Richardson et al.* [2006a], and we use their values for the plasma parameters. This overall decrease makes it the largest >70 MeV decrease ever seen this far from the Sun, rivaling the cosmic ray intensity decreases seen by V2 and V1 then at 36 and 47 AU, respectively after the giant transients of June and July, 1991 [*Van Allen and Fillius*, 1992; *Webber and Lockwood*, 1993]. These 1991 events went on, several months later, to produce the largest outburst of VLF radio emission ever observed by the detectors on V1 and V2, believed to originate when this IP shock later reached the Heliopause [*Gurnett et al.*, 1993].

[6] The plasma speed jump associated with the shock actually arrived at V2 at about 2006.16 several days before the cosmic ray decrease began. Also a more rapid cosmic ray decrease began at about 2006.22 at the time of the arrival of the Merged Interaction Region (MIR) behind the shock. The speed jump associated with this shock was ~130 km s$^{-1}$ making it larger than the speed jump ~110 km s$^{-1}$ for the earlier Halloween event. The maximum plasma speed ~515 km s$^{-1}$ was, however, slightly less than the maximum speed recorded at the time the Halloween event passed V2. This 2006.19 event, as observed by V2, probably represents the merging of several periods of strong solar activity occurring in August and September 2005. The related events at the Earth culminated in a large transient cosmic ray decrease 15% observed by the Climax neutron monitor on September 10. The associated shock had an average Sun-Earth propagation speed ~1000 km s$^{-1}$. This *event* was also observed at Ulysses on about September 15. The measured maximum plasma speed at Ulysses was ~800 km s$^{-1}$ (http://swoops.lanl.gov/). At this time Ulysses was at ~5.0 AU, −27° or almost in alignment with V2. The time delay between the September 10 event at the Earth and the 2006.16 arrival at V2 is ~0.47 year, less total travel time than the Halloween event although V2 was now ~6 AU further out. The average shock propagation speed is thus deduced to be about 785 km s$^{-1}$.

[7] If we follow this shock outward beyond the location of V2 at 79 AU then very shortly it should encounter the HTS. The HTS distance (at ~35°N latitude) at this time may be estimated using the method equating the variable solar wind pressure and interstellar pressure described by *Webber* [2005] [see also *Richardson et al.*, 2006b] which has previously been applied successfully for calculating the HTS location just prior to the V1 HTS crossing at 94 AU in late 2004. This updated prediction of the HTS location using 26 day average data is shown in Figure 2. In early 2006 the HTS location was estimated to be between 87–89 AU. Assuming an average IP shock speed ~600 km s$^{-1}$ beyond V2, the event seen at V2 at 2006.16 would arrive at a distance 87–89 AU, about 25–29 days later or at 2006.23–2006.25 in the S hemisphere. This time is indicated by the vertical line with the arrow in Figure 1.

[8] At 2006.29 the 1st of 3 significant intensity decreases was also observed in the >70 MeV rate at V1 in the N hemisphere and we associate this decrease with the arrival of the shock at the HTS near that location. These same three decreases seen in the >70 MeV rate were even larger in the lower energy rate dominated by 70–200 MeV protons (not

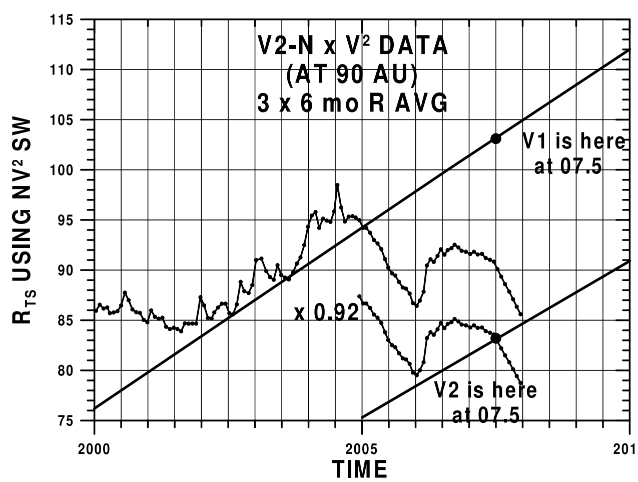


**Figure 2.** Distance to HTS location (at 35° N) based on *Webber*'s [2005] formulation with a 3 × 6 month running average for the solar wind pressure at the HTS. This N hemisphere distance × 0.92 is also shown in order to illustrate a possible 8% N-S asymmetry of the HTS distance (the HTS is closer at V2 than at V1).

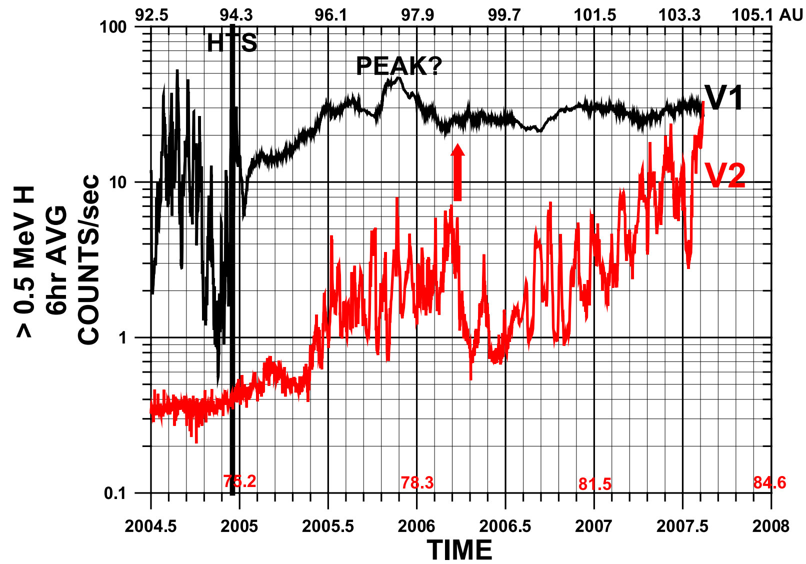


**Figure 3.** Six hour average counting rate of >0.5 MeV particles at V1 and V2 from 2004 onwards. Note the crossing of the HTS at V1 in late 2004 and the subsequent smoothing of intensity variations beyond the HTS. V2 observes an onset of these rapid intensity variations in early 2005 suggesting a proximity to the HTS. The sudden decrease in this intensity at 2006.24 shown by the red arrow is believed to be related to the arrival of the 2006.19 shock at the HTS thus moving it outward several AU. The increasing peak intensities in 2007 suggest the imminent arrival of V2 at the HTS.

shown here) and are the only significant decreases seen in this rate at V1 since the HTS crossing in late 2004.

[9] Figure 2 indicates that the arrival of this IP shock at the HTS eventually pushed the HTS outward 5 or 6 AU and as a result probably caused reverberations throughout the entire heliopause region which may have resulted in the 1st intensity decrease observed at V1.

[10] At 2006.22–2006.24 a sudden decrease of the highly irregular intensity changes of ~1 MeV particles was observed at V2 (see Figure 3). Such a decrease is consistent with the rapid movement of the HTS further away from V2 and this temporal association (delay of 0.06–0.08 years) would suggest a S hemisphere HTS location ~6–8 AU beyond V2 at this time.

[11] Together these nearly simultaneous decreases at V1 (2006.29) and V2 (2006.23) imply the near symmetry of interplanetary shock speeds at the V1 and V2 locations in the North and South hemispheres for this event as was also the case for the Halloween event [*Intriligator et al.*, 2005].

[12] The largest (~4%) of the three intensity decreases at V1 during this time period started at 2006.50. A smaller decrease (~2–3%) also occurred later at 2006.86, followed by a resumption in 2007 of the more steady general increase observed at V1 in 2005 before the arrival of the 2006.19 interplanetary shock at the HTS. At the time of the decrease at 2006.50, V1 was at 100 AU, ~12 AU beyond the estimated HTS location. The time difference between the estimated shock arrival at the HTS (+35°) at 2006.25–2006.29 and at V1 is 0.21–0.25 years. If we assume that this time difference is due to the IP shock continuing to propagate the estimated 12 ± 1 AU from the HTS to V1, the average shock speed beyond the HTS would be (240 ± 30) km $s^{-1}$ or approximately ~0.4 of the estimated interplanetary shock speed of 600 km $s^{-1}$ just before it encountered the HTS.

[13] It is tempting to associate the 3rd decrease at 2006.86 at V1 with the arrival of this same shock at the heliopause. If this cosmic ray decrease is caused by such a pulse, then the timing difference of 0.36 years between the two decreases at V1 along with an average speed of 240 km $s^{-1}$ implies a HP location not more than 18 ± 2 AU beyond V1 or 118–120 AU. This distance is less than the distance of ~150 AU determined using VLF radio measurements [e.g., *Gurnett et al.*, 2003].

[14] The effect of this shock on the intensity of various species of cosmic rays at V1 and V2 is also very interesting. Figure 4 shows these effects for anomalous He ≡ He* (27–69 MeV/nuc He) as well as galactic cosmic rays (130–240 MeV H). At V2 this decrease is very rapid and well defined

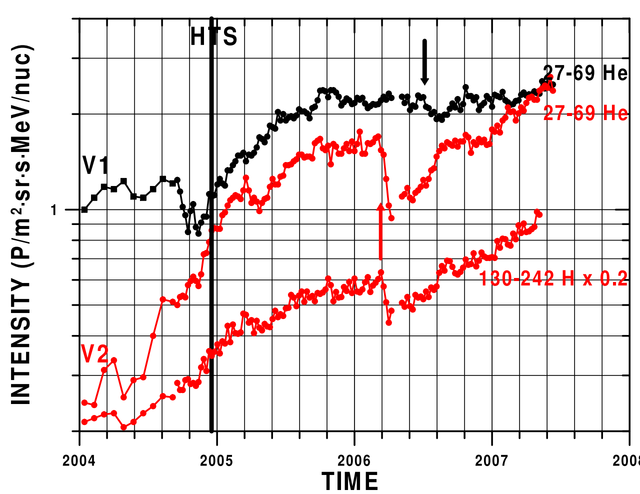


**Figure 4.** Weekly average rates at V1 and V2 for 27–69 MeV He* and 130–240 MeV H from 2004.0 to the present. V2 data is in red; V1 data is in black. The vertical arrows show the onset of the 2006.19 cosmic ray decrease at V2 and V1 according to the >70 MeV channel.

and is ∼45% for He* and ∼30% for galactic H. At V1 only the decrease at ∼2006.50 is clearly observable in the data and is ∼10% for both He* and galactic H. These intensity decrease ratios ∼4:1 for the two species at V1 and V2 are about the same as the ratio between the decreases at V1 and V2 observed in the >70 MeV channel. Note that both He* and galactic particles are still modulated by roughly the same amount by this IP shock at V1 although V1 is well beyond the HTS at this time.

## 3. Summary and Conclusions

[15] This paper presents and discusses the time sequence of events related to the large transient decrease of >15% in the >70 MeV cosmic ray rate (and the associated large jump ∼130 km $s^{-1}$ in solar wind plasma speed observed at 2006.16) which is observed to start at V2 at ∼2006.19 when this spacecraft was at 79.1 AU and 27°S heliospheric latitude. This event most likely had its origin in the high solar activity occurring in August–September, 2005, which culminated in a large decrease ∼15% in the intensity observed by the Climax neutron monitor on September 10th, several outbursts of solar cosmic rays between September 7–9, and a strong shock observed at the Earth on September 10th. The travel time of this shock from the Earth to V2 is estimated to be ∼0.47 year implying an average propagation speed ∼785 km $s^{-1}$.

[16] This event can be followed outward to V1 which is at ∼100 AU and some 12 AU beyond the estimated location of 87–89 AU for the HTS at 35°N at this time. Using an average propagation speed of ∼600 km $s^{-1}$ beyond the location of V2 at 79 AU gives a travel time 25–30 days between V2 and an HTS location at 88 AU and assuming a N-S symmetry of this propagation speed thus gives an arrival at a 35° northern hemisphere-HTS location of 88 AU at 2006.24. The decrease of a few percent observed in the >70 MeV rate at V1 starting at 2006.29 is assumed to be associated with this HTS arrival.

[17] A larger intensity decrease ∼4% at 2006.50 marks the likely arrival of this shock at V1 and the transit time of 0.21–0.25 years between the estimated HTS location and V1 gives an average speed 240 ± 30 km $s^{-1}$ for the IP shock beyond the HTS. This corresponds to an average speed beyond the HTS which is ∼0.4 times the estimated speed just prior to reaching the HTS.

[18] If the final decrease at 2006.86 at V1 is related to the arrival of this shock at the Heliopause then a distance of not more than 118–120 AU is obtained.

[19] This event is observed as an unusually large decrease of He* (∼45%) and galactic H nuclei (∼30%) when it passed V2. At V1 the decrease at 2006.50 is much smaller, ∼10% for both components, indicating a weaker but still significant modulation beyond the 100 AU location of the V1 spacecraft.

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