Recent Voyager data and unexpected properties of the heliospheric termination shock

P. Király

***Abstract*—Energetic particle precursors of the termination shock (TS) were first observed at Voyager-2 soon after the December 2004 TS crossing of Voyager-1. Intermittent flux enhancements lasted until August 2007, when count rates of >0.5 MeV ions sharply rose and finally exceeded the highest values measured by Voyager-1 by about a factor of 2. Although Voyager-2 supplied data on the plasma component of the solar wind as well, preliminary data appeared to show no sharp decrease of solar wind speed, as was expected for a TS transit. Solar wind data corrected in late November 2007 finally confirmed that the transit really took place at the end of August. However, the temperature and the thermal pressure of the post-shock plasma turned out to be much lower than expected. The contribution of the suprathermal component to the pressure thus should be more important than previously thought. Spectra, day-to-day variabilities, as well as streaming directions of suprathermal and energetic particles were also different for the two Voyagers both before and after their TS crossings.**

1. INTRODUCTION

VOYAGER-2 (V2) first crossed the solar wind (SW) termination shock (TS) on 30th August 2007, just 10 days after celebrating its 30th birthday. As it turned out later, there were subsequently at least 4 more shock crossings (2 in both directions) within about 2 days, indicating either an oscillatory motion or a waviness of the TS.

After the 16th December 2004 shock crossing of Voyager-1 (V1), there were great expectations for the V2 transit on at least three accounts. First, the plasma detector of V1 was damaged during its Saturn encounter, thus no direct information was available on the change of plasma parameters during the TS transit. Indirect information on SW speed, based on energetic particle anisotropy, was somewhat suspect. Second, there was no data transfer from V1 to the ground stations on 16th December 2004, thus no fine details of even the energetic particle data were available. (Incidentally, that was the only day of that year when no V1 data were received). Third, during the V1 transit the TS was apparently moving inward very fast, thus probably there was only a single crossing. A luckier configuration was hoped for in the case of V2.

The TS transit of V2 was officially announced in December 2007, while the first definitive papers by the Voyager teams were published in the 3rd July 2008 issue of Nature only ([1]─[6]). The time period covered by most of those papers extended only to the end of 2007.

As the recent Voyager results are highly relevant to both the structure of the outer heliosphere and to the more general issues of particle injection and acceleration in stellar winds, a brief summary of the results for ECRS participants is certainly justified. The paper will first discuss the unexpected changes in the SW parameters and some of their possible implications, then the behaviour of suprathermal and energetic particle intensities and directional distributions will be discussed for the TS transits of both Voyagers.

2. SOLAR WIND RESULTS

The MIT Plasma Science Experiment (PSE) aboard the V2 spacecraft measures various SW parameters every 192 seconds, and returns the results to Earth over the Deep Space Network whenever transfer is allowed. Results are then organised into hourly and daily data files, after some scrutiny. Up to day of year (DoY) 242 in 2007, i.e. up to about the shock transit, fine resolution data were also put on the web site of the V2 PSE instrument team.

Figure 1 displays the hourly SW speed data of PSE as they appeared on the web before late November 2007 ("Preliminary") and their "Corrected" versions posted later.

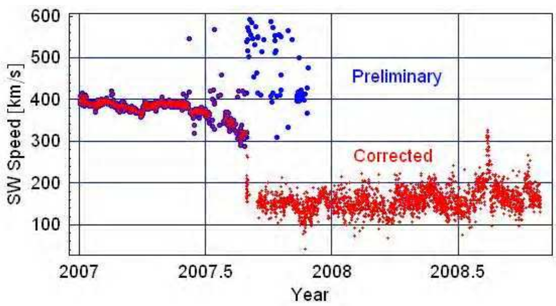

Figure 1. Preliminary (blue, larger dots) and corrected (red, smaller dots) hourly SW speed data aboard V2, as posted on the PSE web site before and after late November 2007.

Author is with the KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest 114, P.O.Box 49, Hungary (e-mail: pkiraly@mail.kfki.hu).

Obviously, a different algorithm was used for estimating hourly SW parameters from raw data before and after late November 2007 (daily data sets were not put on the web between shock transit and late November). SW density and temperature data were also similarly changed then. A data gap in Fig. 1 follows the fast drop in the new SW speed data at shock transit. That may also reflect some uncertainty in the evaluation procedure.

Corrected daily data sets for the radial (V_{rad}) and perpendicular (V_{perp}) components of the SW velocity, and the root mean square (rms) thermal speed (V_{th}) are depicted in Fig. 2 (a 10-day smoothing was applied). Contrary to expectations, the thermal speed (and thus also the thermal pressure of the SW) did not become dominant after shock transit. In fact, even the perpendicular velocity component mostly exceeds the thermal speed on the downstream side.

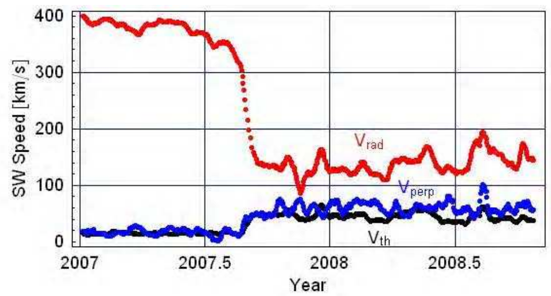

Figure 2. Radial and perpendicular components of the SW velocity (upper and middle curves, red and blue in the online version, respectively). The lowest line (black) represents the root mean square thermal speed of SW ions.

It is also conspicuous that SW speed (and also its dominant radial component) started to decrease at least 3 months before the shock transit. Although there appears to be a general tendency of decrease both in the speed and in the radial component of the magnetic field of the solar wind, recently recognised by the Ulysses team, the rather drastic decrease from 400 km/s to about 300 km/s can not be fully attributed to that effect. It seems that 30 to 40% of the bulk kinetic energy of the SW was transformed into a form of energy not seen by the plasma detector.

A further substantial fraction of the far upstream SW flow energy seems also to have “vanished” during shock transit: only about 20% of the original energy contributed to the kinetic and thermal energy of the downstream SW [1]. Barring a gross miscalculation of SW parameters by the PSE team, about 80% of energy must have gone into suprathermal and energetic particles. About 10% is indeed found in the energy range covered by the Low Energy Charged Particle (LECP) instrument (i.e. in >28 keV ions), but the rest probably resides in ions of the energy range covered neither by PSE nor by LECP, i.e. in between 6 keV and 28 keV.

Such an efficient transfer of the energy of a streaming plasma into suprathermal and energetic particles is certainly surprising, and might have far-reaching consequences for the injection and acceleration of cosmic rays. As charge exchange with interstellar neutrals should rather frequently occur in the outer heliosphere, an energetic neutral atom (ENA) signature is also expected. The STEREO mission indeed detected a component that may be attributed to that origin and thus supports the claim of the Voyager teams [6].

It is also important to note that all solar wind parameters fluctuate quite strongly in the downstream region even after hourly or daily averaging. The effect can be clearly seen in Figure 1 for the SW speed. Although there are some recent increases probably due to merged interaction regions of solar origin, most of the variation appears to be of a statistical nature. Should the fluctuations of different measured parameter values be due to poor measurement, no substantial correlation among them should be expected.

Figure 3 clearly shows that there is a genuine correlation between hourly mean SW densities (or their logarithms) and thermal speeds, and their regression lines also change with time. All hourly data from shock transit to the end of the period for which data were available (to late October 2008) were subdivided into 4 subgroups according to their time of origin (1 for the earliest, 4 for the latest). Figure 3 shows that the regression lines became steeper with the progress of time. While that tendency may not last much longer, it is clear that denser regions have so far been getting hotter in the downstream region, while no such tendency was seen for the upstream region. The apparent compressibility and related heating of downstream SW regions on different spatial scales should certainly be further studied, and the smaller time scales for which data are not yet publicly available should also be included.

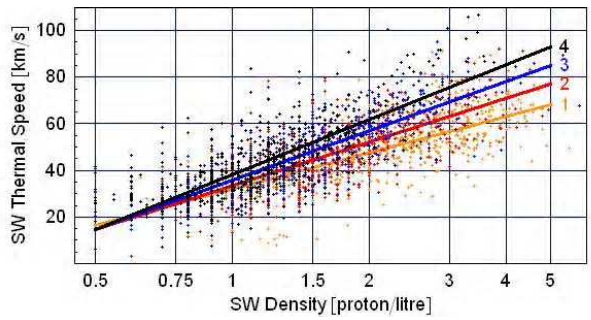

Figure 3. Scatter plot of hourly downstream SW densities and thermal speeds. Data were subdivided into 4 time intervals, with darker dots and lines representing later time periods. Regression lines were constructed separately for each data sets. It is clearly seen that the regression lines become steeper as time progresses.

3. Energetic Particle Count Rates

Quick-look data of >0.5 MeV and >70 MeV ion count rates are routinely put on the web twice or three times a week by the Cosmic Ray Subsystem (CRS) team. Those data are very useful for monitoring changes in the flux levels of MeV energetic ions of mostly heliospheric origin, and of the high-energy component of mostly cosmic ray origin.

The high-energy component is mainly influenced by general trends of solar modulation, but some solar effects (mainly the passage of merged interaction regions of solar origin) occasionally also cause both increases and Forbush-type decreases. As V2 is at a smaller heliospheric distance than V1 by about 20 AU, it is to be expected that modulation is less pronounced for V1 than for V2, particularly in years of high solar activity. High-energy count rates for both V1 and V2 are plotted in Fig. 4. TS crossings for both spacecraft are also indicated.

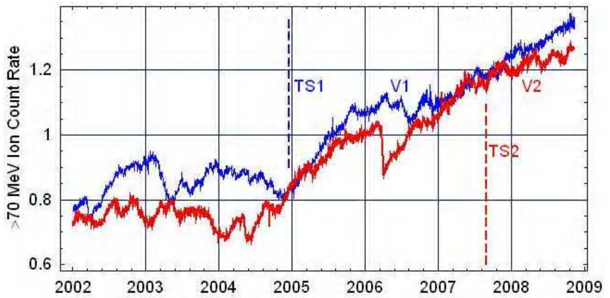

Figure 4. High-energy ion count rates for V1 (blue, upper line) and for V2 (red, lower line) from 2002 to mid-November 2008. Transits through the TS are also indicated, but no obvious shock peaks are seen.

With the decline of solar activity, count rates have started to increase from mid-2004 for V2 and from late 2004 for V1. The more than 50% increase since then is due to the low and extended solar minimum period of solar activity cycle 23.

A large-amplitude and extended Forbush-type decrease started in early March 2006 at V2. A less deep and less extended decrease started at V1 about 100 days later. At that time V1 was about 20 AU farther from the Sun and in the slow solar wind (heliosheath), thus it appears likely that the two decreases were due to the same solar event.

Changes of count rates in the 1 MeV range are much more related to the position of the spacecraft relative to the TS. Fig. 5 displays those changes for both Voyagers.

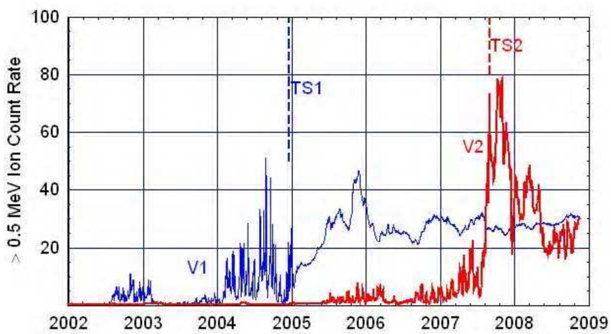

Figure 5. >0.5 MeV ion count rates for V1 (blue, thin line) and V2 (red, thicker). Intermittent pre-shock activity, shock peak, and post-shock decline of fluctuation is visible for both curves, but many details differ.

Pre-shock activity extended to a total duration of about 2.5 years for both V1 and V2. Periods of activity were interrupted by quieter periods in both cases, probably due to the passage of merged interaction regions and related increases in the radial distance of the TS. Upstream intensity fluctuations were generally more intense for V1, while the post-shock peak was much higher for V2. While the V1 shock crossing occurred at a solar distance of about 94 AU, the TS transit of V2 was about 10 AU closer to the Sun, at about 84 AU. After the shock, the maximum count rate at V1 was reached in about a full year, while at V2 it took only about a month. Fluctuations started to level off afterwards for both spacecraft, but more slowly for V2. Those differences might be partly explained by the different positions of the trajectories of the two probes relative to the nose of the heliosphere (V1 is closer).

The day-to-day variability of count rates (more precisely, the absolute value of the base 10 log of the ratio of count rates on subsequent days) provides a good visualisation of how the pre-shock and post-shock fluctuations for both probes differ. The two curves are displayed in Fig. 6.

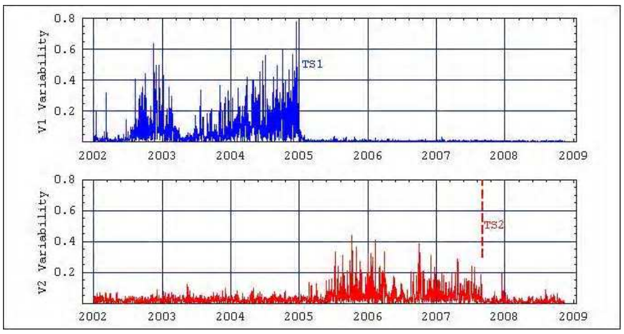

Figure 6. Day-to-day variability of >0.5 MeV count rates for V1 (upper panel) and for V2 (lower panel). Pre-shock variability is much more pronounced at V1, while post-shock activity is larger at V2.

Differences in day-to-day variability between the two probes are probably also due mostly to their different positions relative to the nose of the heliosphere. It is quite surprising how sharply the variability drops following the shock transit of V1, and how low the variability levels are throughout the almost 4 years elapsed since the shock crossing of V1.

4. ION FLUXES AND ANISOTROPY

Hourly and daily mean ion flux data as measured by the Low Energy Charged Particle Experiment [LECP] aboard both V1 and V2 are made public usually once a month in 8 logarithmically scaled energy bins between about 30 keV and 4 MeV (limits of energy bins are slightly different for V1 and V2). In addition to the omnidirectional (directionally averaged) data, 7 directional data sets are also available for each energy bin. The measurement of directional data with a single telescope is made possible by a rotating platform, still operating after 31 years of the hardships of space – a very respectable achievement indeed.

Although instrumental background has not been subtracted from the available data, they more or less correctly illustrate the energy dependence and the directional behaviour of the relatively low-energy ion data. For calculating energy spectra, however, a more careful approach is needed.

Omnidirectional daily mean fluxes for 4 of the 8 energy bins as measured by LECP aboard V1 are given in Fig. 7.

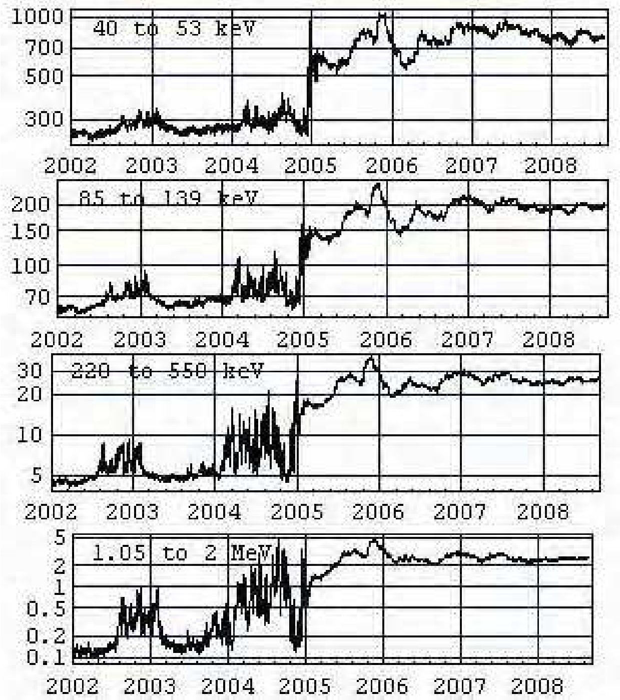

Figure 7. Omnidirectional V1 ion fluxes (in standard flux units) for 4 of the 8 LECP energy bins from 2002 to late September 2008. Upstream fluctuations (before 16 December 2004) are more conspicuous for higher energies, while a step-like flux increase is more pronounced for low energies. Far downstream fluxes are getting quite smooth for higher energies.

Intensity fluctuations in nearby energy bins are highly correlated both before and after shock transit, and correlation smoothly decreases for farther removed energy bins. The step-like flux increase at shock transit for the lowest energies may be attributed to the suprathermal tail of the heliosheath particle population (probably mostly to accelerated pick-up ions). An even higher jump should then apply to ions of lower energies, for which no V1 data exist. Most of the SW flow energy might end up in that low-energy suprathermal component.

The energy dependence of the V2 fluxes differs somewhat from that of V1. As we have seen, intensity fluctuations started at about the same time for V1 ion fluxes in a wide energy range, and the shape of the fluctuations was more or less similar throughout both the upstream and downstream periods. As the source of those upstream particles is considered to be the TS, particles with widely different energies (and thus Larmor radii) had magnetic connection to the TS through the same flux tubes. Fig. 8 shows that that was not the case for V2. Below about 200 keV virtually no fluctuations were seen by V2 up to about 1 month before TS transit. The only conspicuous increase in March 2006 was due to the arrival of a merged interaction region of solar origin, the same that also caused the Forbush decrease in the high-energy component (Fig. 4).

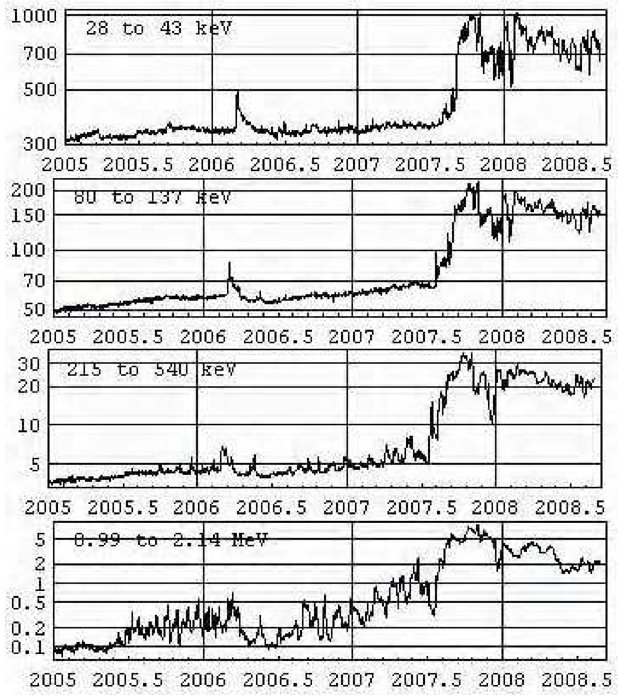

Figure 8. Omnidirectional V2 ion fluxes (in standard flux units) for 4 of the 8 LECP energy bins from 2005 to late September 2008. Early fluctuations are only visible above about 200 keV. After shock transit(s) late in August and early in September 2007, fluxes behave much less smoothly than for V1.

Directional distributions of energetic particles are harder to characterise and to visualise than was the case for the omnidirectional fluxes. One part of the problem is that the rotating platform rotated in a plane, thus no 3-dimensional reconstruction of the distribution can be inferred. A simple motional (dipole) anisotropy is often a poor approximation, particularly when field-aligned streaming is strong, or when magnetic field directions change fast relative to the rotation time of the platform (about 3 minutes). Mean particle fluxes over extended time periods in given directions, however, can still be compared, and thus a dipole-type anisotropy characterising mean streaming can be inferred. It was a surprise that particle streaming for V1 and V2 behaved in a different way. While upstream of the TS, V1 found particles streaming mostly outward along the Parker spiral, and not inward, as expected (and as was later found for V2). That strange behaviour was later rationalised by taking into account the different positions of the V1 and V2 trajectories relative to the nose direction of the heliosphere, and also by considering various distortions of the shape of the heliosphere, or assuming multiple crossings of the TS by the magnetic field. Although those speculations are certainly interesting and some of them might prove correct, the debate still appears to be open.

The amplitude of a smoothed dipole-type anisotropy, taking into account directions in the rotation plane of the platform only, provides some measure of how deviations from isotropy change with time and energy. In what follows we include only two energies (one lower, one higher) for both Voyagers.

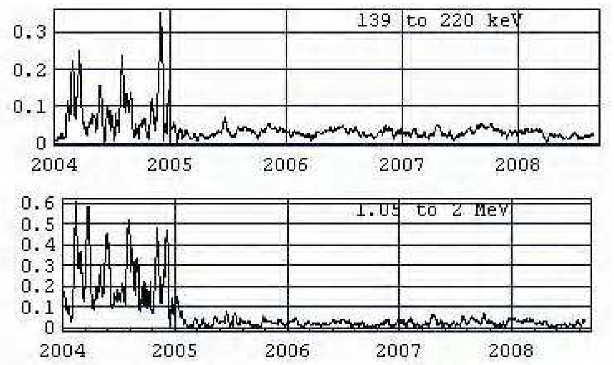

Figure 9. Dipole anisotropy amplitudes at V1 for two energies. A 10-point box-car smoothing of the daily anisotropy vectors was applied. Amplitudes decreased drastically after TS transit at both energies.

As seen in Fig. 9, the downstream region is characterised by much smaller anisotropy for both low and high energies.

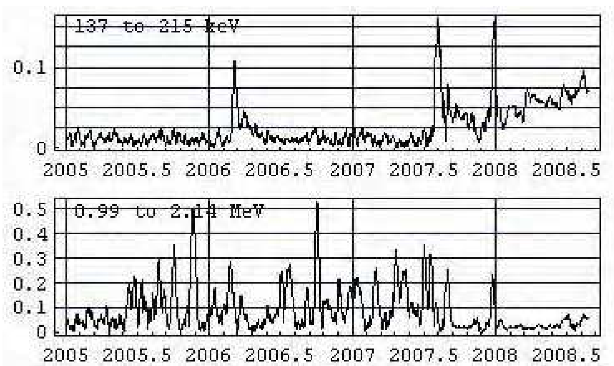

Figure 10. Dipole anisotropy amplitudes at V2 for two energies. A 10-point box-car smoothing of the daily anisotropy vectors was applied. Amplitudes increased after TS transit at low energies, and decreased at high energies.

Although both energy ranges are similar for V1 and V2, anisotropy amplitudes behave differently. Before August 2007, low-energy TS fluxes had practically no access to V2, thus they did not contribute to anisotropy either. When connection was established, anisotropy also started to increase. The peak in anisotropy in March 2006 was due to a merged interaction region, and not to TS connection. The gradual increase of anisotropy in 2008 at low energies may be due to some streaming caused by the magnetic field configuration in the heliosheath, but there is no convincing explanation as yet.

5. Conclusions

Both Voyagers have by now crossed the TS of the heliosphere and are exploring the uncharted slow SW regions of our inner heliosheath. Whether any of them will survive to cross the heliopause and penetrate into the shocked interstellar wind of the outer heliosheath, is still an open question. Their many surprising and still poorly understood findings before and after the TS crossing, however, will certainly keep theoreticians busy for the next several years. It is to be hoped that future in situ data from both probes, together with remote sensing results of the recently launched IBEX mission, will lead to a deeper understanding of the boundary regions of our heliosphere. Such an insight should also contribute to a better understanding of the many astrospheres surrounding the stars of our even wider cosmic environment.

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