Some implications of energetic particle and plasma data at both Voyagers

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***Abstract*. Voyager-2 crossed the heliospheric termination shock late in August 2007, just after the last ICRC. The crossing(s) occurred at a smaller heliocentric distance than for Voyager-1 in mid-December 2004. Energetic particle fluxes and their directional distributions behaved differently in several respects for the two spacecraft, but the most important new discoveries were made in the field of the unexpected behaviour of the solar wind and of suprathermal particles. A comparison will be made between the characteristics of both shock transits and of subsequent records, updated to the most recent data sets available. Some tentative implications of the new findings will be discussed.**

***Keywords*: Distant Heliosphere, Energetic particles, Solar wind**

I. Introduction

After the 16th December 2004 shock crossing of Voyager-1 (V1), there were great expectations for the Voyager-2 (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 used instead, but it 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, the TS was apparently moving inward fast during the V1 transit, thus there was probably only a single crossing. A luckier configuration was hoped for in the case of V2.

Voyager-2 first crossed the TS on 30 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. At the time of the 30th ICRC in Mexico, the increase in energetic particle intensities already indicated the possibility of an imminent crossing [1]. The TS transit was officially announced only in December 2007, while the first definitive papers by the Voyager teams were published only in the 3rd of July 2008 issue of Nature (see [2], [3], [4], [5], [6]). The time period covered by that first set of papers extended mostly to the end of 2007. Subsequent papers covered some of the more recent developments ([7], [8], [9]), but up-to-date accounts on the differences between the environments of V1 and V2 during the present extended solar minimum are certainly justified.

II. Energetic ion 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. 1 (TS crossings for both spacecraft are also indicated).

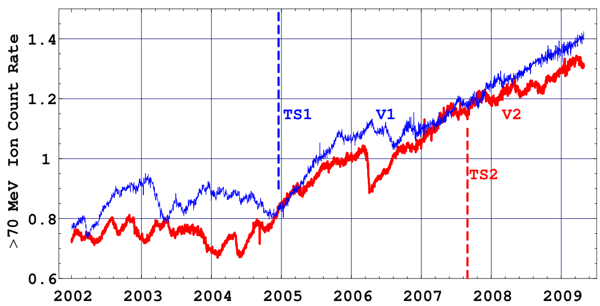

Fig. 1: High-energy ion count rates (per second) for V1 (upper curve) and for V2 (lower curve) from 2002 to late April 2009. TS crossings are indicated by dashed lines. No shock peaks are visible at TS crossings.

With the decline of solar activity, > 70 MeV count rates started to increase from mid-2004 for V2 and from late 2004 for V1. The more than 60% increase since then is due to the low and extended solar minimum period of solar activity cycle 23. Recent data show a smooth, linear increase for V1, while the increase for V2 is slower and less regular.

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 110 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 more related to the position of the spacecraft relative to the TS than to the phase of the solar cycle. Fig. 2 displays those changes for both Voyagers.

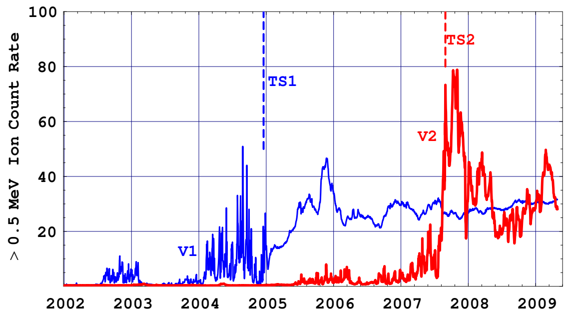

Fig. 2: MeV count rates for V1 (thin line) and V2 (thick line). Intermittent pre-shock fluctuations, shock peaks and post-shock increase are visible for both curves, but many details differ.

Pre-shock activity lasted for about 2.5 years for both V1 and V2. Periods of activity were interrupted by quieter periods in both cases, mostly due to passages 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 almost a year, while at V2 it took only about a month. Fluctuations were attenuated afterwards for both spacecraft, but much more slowly for V2 than for V1. Those differences might be partly explained by the different positions of the trajectories of the two probes relative to the nose direction of the heliosphere (V1 is closer).

The day-to-day variability of count rates (more precisely, the absolute value of the base 10 logarithm of the ratio of count rates on subsequent days) visualises how the pre-shock and post-shock fluctuations for the two probes differ. Both curves are displayed in Fig. 3.

Differences in day-to-day variabilities between the two probes are probably also due to their different positions relative to the nose of the heliosphere. It is quite surprising, how fast the variability dropped following the shock transit of V1, and how low it has been throughout the more than 4 years elapsed since the shock crossing of V1. In fact a slow decrease in variability is still apparent. One may expect more fluctuation again when V1 or V2 approaches the heliopause, or when they cross some reconnection regions where anomalous cosmic ray (ACR) acceleration may occcur [8].

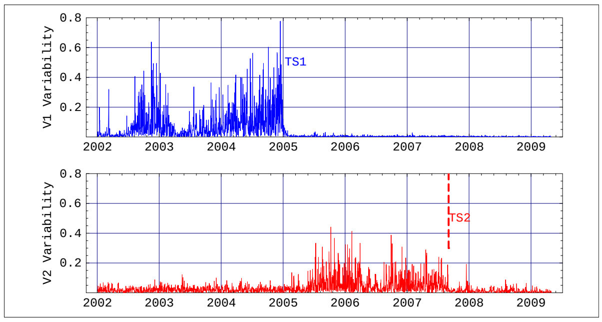

Fig. 3: Day-to-day variability of low-energy count rates for V1 (upper panel) and for V2 (lower panel). Pre-shock variability is much more pronounced for V1, while post-shock variability is more pronounced for V2.

III. Ion Fluxes and Anisotropy

The ion count rates discussed above have good statistical properties (small Poisson noise), thus they are useful for characterising some general features of the time variation at low and high energies. Of course fluxes in narrow energy bins and those arriving from different directions provide much more information, although at higher noise levels. Magnetic field and wave data have also much to offer. Here we shall only briefly discuss the time dependence of some fluxes and their anisotropies, and refer the readers to our previous work [1], [10] and to the other referenced papers for more detail.

Ion flux data as measured by the Low Energy Charged Particle [LECP] experiment 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 almost 32 years of the hardships of space - a very respectable achievement indeed. Although instrumental background has not been subtracted from the publicly available data, the raw data more or less correctly illustrate the energy dependence and the directional behaviour of suprathermal and low-energy ions. For a precise calculation of energy spectra, however, data exclusively available for Voyager team members are needed.

A large step-like flux increase at shock transit was observed for the lowest energy bins of both V1 and V2. It is attributed to the suprathermal tail of the heliosheath particle population. An even higher jump should then apply to ions of lower suprathermal energies (those between a few keV and about 30 keV), for which no Voyager data exist. Most of the SW flow energy might end up in that low-energy suprathermal component.

Energy dependences of V2 fluxes differed somewhat from those of V1. While flux increases in the 8 energy bins started at the same time for V1, and the shape of the fluctuations was more or less similar throughout both the upstream and downstream periods, that was not the case for V2. Below about 200 keV virtually no fluctuating enhancements were seen by V2 up to about 1 month before TS transit. 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 for V1, but not for V2.

Directional distributions of energetic particles are hard to characterise and visualise. 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. The debate is still open.

IV. Unexpected solar wind results

The MIT Plasma Science Experiment (PSE) aboard the V2 spacecraft measures SW data 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 (daily means are considered as most reliable). Up to day of year (DoY) 242 in 2007, i.e. up to the first shock transit, fine resolution data were also put on the web site of the V2 PSE instrument team. Subsequently, only a fairly small number of hourly data sets were put on the web until late November, when daily sets and a new, more complete set of hourly data appeared. Fig. 4 displays the hourly SW speed data of PSE as they appeared on the web before late November 2007 ("Preliminary") and their "Final" versions posted later.

A different algorithm was probably used for estimating hourly SW parameters from raw data before and after late November 2007 (SW density and temperature data were also changed). A data gap in Fig. 4 follows the fast drop in the new SW speed data at shock transit. That may also reflect some problem in the evaluation procedure. One should appreciate that particle densities were close to the lowest measurable values around the

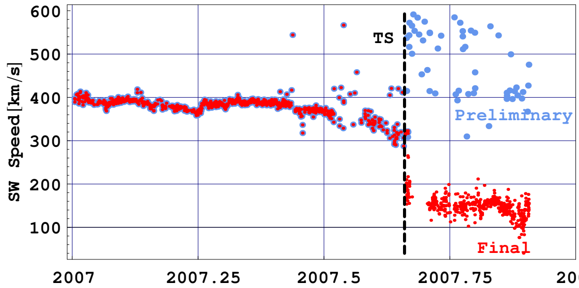

Fig. 4: Hourly SW speed data up to late November 2007, derived from data as put on the web first (Preliminary: larger dots in faint shade), and as they appeared on the web subsequently (Final: small dots)

shock, and directional distributions were very different from what the instrument and the evalutation procedures were originally optimised for.

Corrected daily data sets for the radial (Vrad) and perpendicular (Vperp) components of the SW velocity, and the root mean square (rms) thermal speed (Vtherm) are depicted in Fig. 5 (a 10-day smoothing was applied). Contrary to expectations, the thermal speed (and thus also the thermal pressure of the SW) did obviously not become dominant after shock transit. In fact, even the perpendicular velocity component mostly exceeds the thermal speed on the downstream side (as particularly conspicuous in the last 6 months).

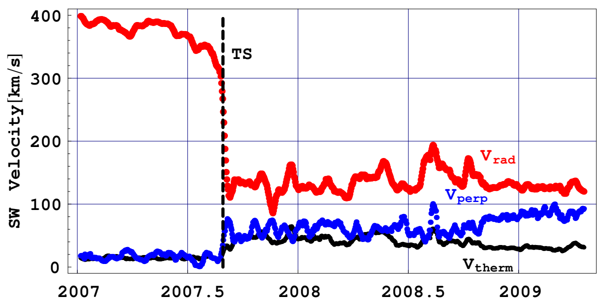

Fig. 5: Radial and perpendicular components of the SW velocity (upper and middle curves), compared to the rms thermal speed of ions characterising SW temperature (a 10-day smoothing was applied)

It is also conspicuous that SW speed (and also its dominant radial component) already started to decrease at least 3 months prior to 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 in recent years as recognised by the Ulysses team, the rather drastic decrease from 400 km/s to slightly more than 300 km/s in 3 months can not be 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 [2]. 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 to 15% 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 conversion of the bulk energy of a streaming plasma into suprathermal and energetic particles (mainly into heating and accelerating pick-up ions [7]) is certainly surprising, and might have far-reaching consequences for models of 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 was also tentatively expected. The STEREO mission indeed detected a substantial component that is attributed to that origin, and thus supports the claim of the Voyager teams [6]. More precise ENA data are expected from the IBEX mission.

It is also important to note that all solar wind parameters fluctuate quite strongly in the downstream region even after hourly or daily averaging (that is why a 10-day smoothing was applied in Fig. 5). Although there are some coherent increases in speed due to the passage of merged interaction regions of solar origin, most of the variation appears to be of a randomly varying nature. Should the fluctuations of different measured parameters be due to measurement error, then no substantial correlation among them would be expected.

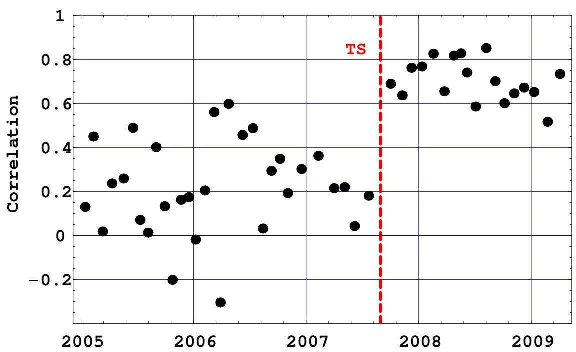

Fig. 6: Correlation between hourly temperature and log density data of ions before and after TS transit of V2. Individual points in the plot are based on correlations calculated from 200 hourly data. It is clearly seen that correlation increased substantially after TS transit.

Figure 6 shows the correlation coefficients between hourly mean SW log densities and thermal speeds, based on runs of 200 measured hourly data sets. Although there is generally some positive correlation in the upstream region as well, it is obvious that correlations are consistently larger in the downstream region. Denser regions tend to be hotter. A similar tendency is seen for dayly means as well. A systematic study of the dependence of correlation coefficients both on time scale (starting from fine resolution data) and on the time elapsed since shock transit would be useful. The compressibility and related heating of downstream SW regions on different spatial scales may provide important clues about heat deposition and transport in the uncharted heliosheath.

V. Conclusions

The two Voyagers, at solar distances of about 110 and 89 AU at the time of this ICRC, have both crossed the TS 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 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. The insight gained by those studies should also contribute to a better understanding of the miriads of astrospheres surrounding the stars of our even wider cosmic environment.

VI. Acknowledgements

Thanks are due to the Voyager teams for their efforts and for their online data support. The International Space Science Institute (ISSI) in Bern is thanked for earlier support of this research in the framework of International Team No. 70. Hungarian grant OTKA-K-62617 is acknowledged for recent financial support.

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