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The way out of the Bubble: implications of recent Voyager-1 data

P. Király
KFKI Research Institute for Particle and Nuclear Physics, H-1525 Budapest, POB 49, Hungary
Presenter: P. Király (pkiraly@sunserv.kfki.hu), hun-kiraly-P-abs3-sh24-poster

The Solar Bubble is the space filled by the supersonic solar wind (SW) streaming out of the solar corona and ending in the Termination Shock (TS), where the SW becomes subsonic. Since mid-2002 there has been growing awareness that intensity fluctuations of suprathermal and energetic particles seen by Voyager-1 (V1) indicate an approach toward, or possibly even some passages through the TS. Because of several complicating factors, theoretical expectations for the strength and structure of the TS were rather vague, but such long series of "precursors" to the shock crossing were certainly not expected. A qualitatively new behaviour started in mid-December 2004, and after some transients V1 reached a slowly changing energetic particle environment by late January 2005, characterized by high fluxes, steep energy spectra, and small anisotropies. All those observations were consistent with V1 having crossed the TS in mid-December, even if some other expectations were not fulfilled. The fact of the crossing was officially announced only on 24 May 2005, after support from magnetic field and wave data were also checked. The present note will discuss some peculiarities and interesting statistical features of suprathermal and energetic particle populations seen by V1 throughout the past three years.

1. Introduction

The crossing of the TS by V1 was a long-awaited event. During the last two decades expectations for the time of the crossing were mostly upward modified, while theoretical ideas about the structure of the TS and heliosheath were becoming more and more sophisticated. Ideas about the shock precursors, however, remained rather vague. The long chain of intensity enhancements in suprathermal and moderately energetic particles between mid-2002 and mid-December 2004 was quite unexpected. The shock-passage itself that took place probably on 16 December 2004 appeared again unexpected. Actually that was the first full day in 2004 when no Voyager-1 data were received at Earth, thus substantial information about detailed shock structure may have been lost. Although it was quite clear by February 2005 that a substantial and lasting change has taken place in the radiation environment of V1, the fact of the shock passage was announced only on 24 May, i.e. more than 5 months after the actual passage, when plasma wave and magnetic field data were also available to confirm energetic particle data.

It is likely that Voyager team members and the theoretical community will discuss the mid-December TS passage and its implications in several talks during the 29th ICRC. The present poster will not aim at a comprehensive coverage, but will call attention to some unexpected features of the findings along the way of V1 out of the supersonic SW bubble. An additional unexpected recent development is that now V2 appears to see signs of enhancements very similar to those first seen by V1 at 85 AU, in 2002, although V2 is still at a much smaller heliospheric radius (about 77 AU).

2. Long-term and short-term intensity variations

One of the highlights of the previous ICRC was the realization that intensity enhancements seen by V1 from mid-2002 to early 2003 indicated termination shock effects, even if it was still controversial whether any shock crossings had actually occurred. Two Nature papers by Voyager teams in November 2003 still reflected conflicting views (Krimigis et al. 2003[1], McDonald et al. 2003[2]). As apparently no major increase in the magnetic field magnitude occurred at that time, the shock crossing idea became less favored. It was hard to explain, however, why the energetic particles were streaming predominantly outward along the Archimedean spiral field, and not from the direction of the TS where they were supposed to have been accelerated, and why their spectra were much softer than typical for the anomalous component. The apparently missing Compton-Getting effect also presented a serious problem. Various suggestions tried to explain those features, and it became uncertain whether a clear-cut shock transition would be expected at all. Even larger flux enhancements prevailed after one year, between February and November 2004, but the qualitative features and the lack of understanding remained the same. Those uncertainties of interpretation may explain why it took so long to announce that the actual passage took place in mid-December 2004.

Ion count rates for energies above 0.5 MeV are shown in the top panel of Fig. 1 from early January 2002 to late June 2005, based on regularly updated data of the V1 Cosmic Ray Subsystem (CRS) team. It is clear from the plot how different is the character of the time dependence starting with some time in January 2005, after some transition period following the shock that is now accepted to have taken place on 16 December 2004. The shock was preceded by an approximately one month low-flux period. The middle plot of Fig. 1 represents day-to-day variability, defined here as the absolute difference between log mean count rates of subsequent days. No pre-shock low-variability period is seen on that plot in spite of low fluxes, while variability decreases fast and in a quite regular manner starting from late December. It is also interesting to note that increasing variability sets in soon after the end of the 2002/3 enhancement period, earlier than substantial flux enhancements.

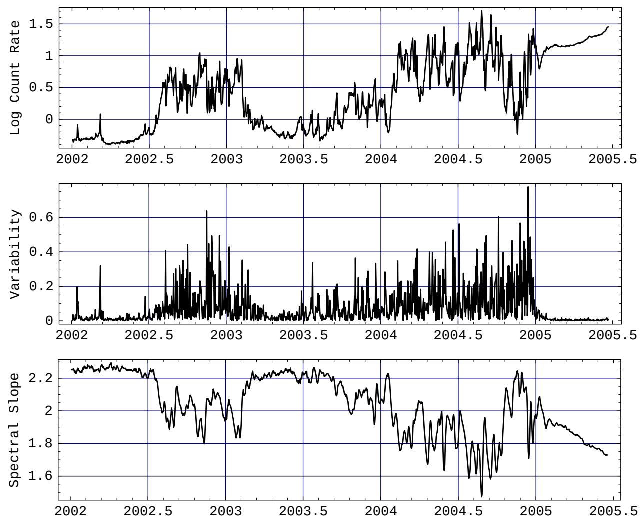

Figure 1. Time history of > 0.5 MeV ion count rates (top), of day-to-day flux variability (middle), and of the spectral slope derived from highest and lowest energy LECP ion channels.

The bottom plot shows the time history of the spectral slope derived from fluxes of the 40 keV to 53 keV (lowest) and the 2 to 4 MeV (highest) omnidirectional LECP energy channels. Here a 5-day boxcar smoothing has been applied. Large exponents (soft spectra) and small variations characterize periods without substantial flux enhancements. After shock transit a gradual hardening is seen, the exponent reaching 1.7 by mid-2005. That is harder than traditionally expected for shock acceleration. The actual value of the spectral exponent of course may also depend on propagation effects and on any kind of background counts. No attempt has been made here for background correction.

The ongoing, occasionally even accelerating flux increase in the > 0.5 MeV integral channel is quite puzzling. It is even more pronounced in LECP proton differential channels at somewhat higher energies, but the fractional increase appears to peak around 10 MeV or even below. Before the shock, there is certainly no evidence for a large component with energies above 30 MeV or so, in contrast to expectations for an anomalous component accelerated at the local section of the TS. For low energies, including the suprathermal component, the Low Energy Charged Particle (LECP) instrument provides more detailed flux data. In the next section we shall show those data in order to study the energy dependence of the 2004 flux enhancements and of the post-shock period.

3. Energy dependence

The LECP instrument has 8 differential ion channels, with a total energy range of 40 keV to 4 MeV. Directional information is also available for each energy. In this section only omnidirectional flux data will be discussed. One important technical problem is how to compare data plots for different energies, because the flux range (even the logarithmic one) is quite different for low and high energies. Here we use scaled log flux, i.e. the range of the logs of daily mean fluxes for the whole period is normalized to the (0,1) interval for each energy channel. Any data sets containing zero counts were omitted.

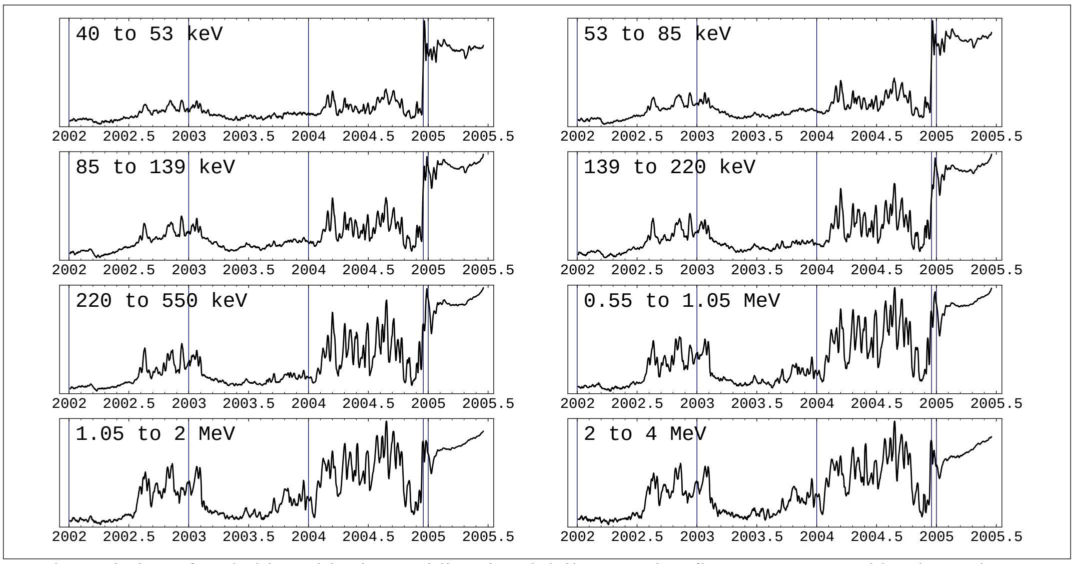

Figure 2. The variation of scaled logarithmic omnidirectional daily mean ion fluxes as measured by the V1/LECP instrument from January 2002 to late June 2005. The TS on 16 December 2004 is indicated by a vertical line.

The changed character of the plots following the shock and the subsequent transitory period is quite conspicuous. All characteristics of the curves vary smoothly with energy. Near shock transit the height of the peak relative to earlier high fluxes gradually decreases with increasing energy (indicating a soft spectrum for the shock peak). The post-shock sections of the flux curves become increasingly smooth as energy increases, although there are now indications that more complicated changes have started in early July. The 2004 enhancements (from about February to early November) had at least three main periods of activity, with marked quasi-periodic substructure. During that period correlation coefficients of data sets for subsequent energy bins were high (well above 0.9), decreasing gradually for increasing energy differences.

4. Anisotropy

Anisotropy was a common feature of both the 2002/3 and of the 2004 flux enhancements. Several papers have discussed the first period from that point of view (see e.g. Krimigis *et al.*, 2003[1], and Decker *et al.*, 2004[3]). During high-flux periods a streaming away from the sun and in a direction close to the nominal outward spiral was mostly observed. The streaming is particularly conspicuous at high energies. After the shock, anisotropy became much smaller. A detailed discussion on how the directional distribution of energetic particles changed with energy and time would far exceed the allowed length of this contribution, thus only some salient points will be mentioned here, and some more detail will be displayed on the poster.

Although outward streaming along the nominal Archimedean spiral field is typical both for the 2002/3 and 2004 high-flux periods, some shorter periods of reverse streaming appear as well. Energy-dependent Compton-Getting anisotropy is less than expected. Streaming is somewhat more intense for some periods of 2004 than was the case for 2002/3. In the first half of 2004 there was stronger azimuthally outward-directed anisotropy for higher intensities, but that tendency was less pronounced in the second half. Anisotropy was also quite high during most of the one-month low-flux period preceding shock crossing.

After shock crossing the anisotropy gradually decreased, and its direction became also rather irregular. In February and March 2005 sunward streaming became predominant, changing gradually into a weak anti-sunward streaming later on. On shorter time scales, however, a quasi-periodic change of streaming directions is apparent, with periods of 16 to 20 days, although the anisotropy amplitude is much smaller than during the 2004 enhancements of similar period lengths.

Both high fluxes and low anisotropies are consistent with general expectations for a turbulent post-shock medium, where strong wave activity is expected to be present. The detailed behavior of those quantities, however, may greatly enhance our knowledge about the structure of the heliosheath.

5. Outlook

The exploration of foreshock activity of the heliospheric TS by V1 has just ended, and the *in situ* study of particle fluxes in the heliosheath has now begun. Time histories of changes in both flux and anisotropy appear to indicate that the region where V1 crossed the TS was not a particularly active one. Energetic particles have mostly arrived from other, more active regions, both before and after shock crossing. Future changes may indicate the distance to those regions, and provide an increasingly global picture.

There are strong indications that V2 has now also entered the foreshock region of the TS. Short time-scale intensity fluctuations have been increasingly seen by V2 since May 2005 - much earlier than expected, - and anisotropy during the enhancements displays very similar features to those seen by V1 in mid-2002. It is imperative that both probes should be kept alive as long as possible, because reliance on replacement missions would involve huge time delays. Although research on the magnetospheric boundary region teaches us that even thousands of crossings do not suffice for complete understanding, the two Voyager probes will clearly much enhance our knowledge on suprathermal and energetic particle populations in the plasma regions separating our local SW bubble from the rest of the Universe.

6. Acknowledgements

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References

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