29th International Cosmic Ray Conference Pune (2005) **00**, 101-104

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

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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 fufilled. 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, McDonald et al. 2003). 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.

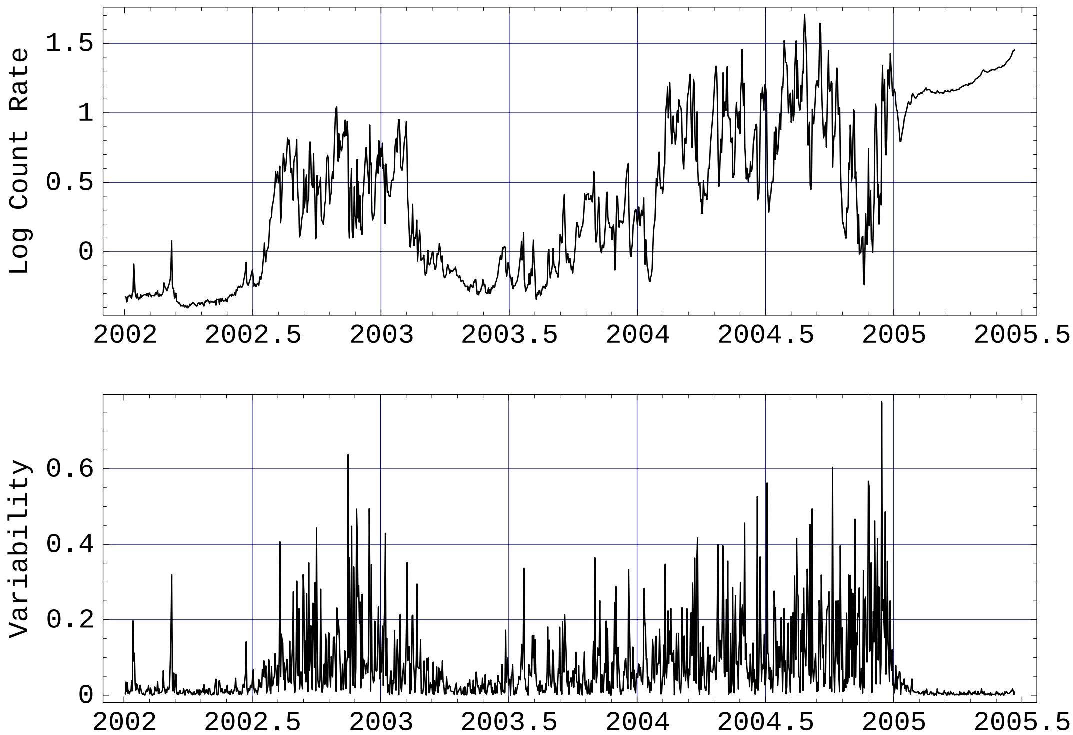

Figure 1. Time history of > 0.5 MeV ion count rates (top) and of day-to-day variability (bottom). For details, see in text.

Ion count rates for energies above 0.5 MeV are shown in the top panel of Figure 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 bottom plot of Figure 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.

The ongoing, apparently accelerating increase in the > 0.5 MeV integral channel is quite puzzling. It is even more pronounced in CRS differential channels at somewhat higher energies, but the fractional increase appears to peak around 10 MeV or even below. 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 data 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.

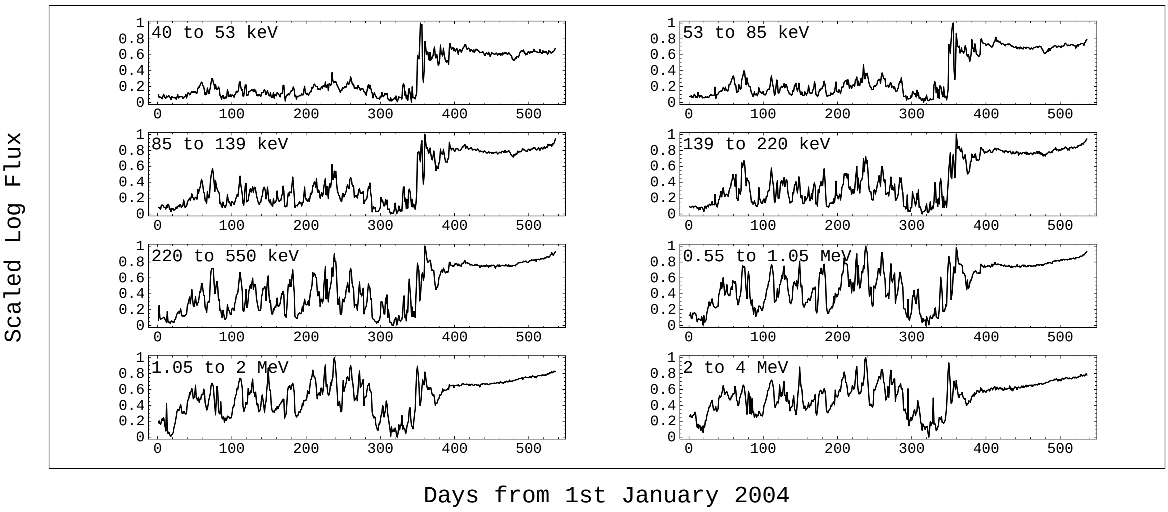

Figure 2. The variation of scaled logarithmic omnidirectional daily mean ion fluxes as measured by the V1/LECP instrument from January 2004 to late June 2005.

The change in the character of the plots following the shock and the subsequent transitory period is quite conspicuous. All characteristics of the curves vary smoothly with energy. The heights of the peak near shock transit relative to earlier high fluxes gradually decrease with increasing energy (indicating a soft spectrum for the shock peak). The post-shock section of the flux curve becomes increasingly smooth as energy increases. The 2004 enhancement (from about February to late October) has at least three main periods of activity, with marked quasi-periodic substructure. During that period correlation coefficients of data sets for subsequent energy bins are high (well over 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, and Decker *et al*., 2004). A detailed discussion on how the directional distribution of energetic particles changed with energy and time far exceeds the allowed length of this contribution, thus only some salient points will be mentioned here, and more detail will be displayed on the poster.

First, intensive outward streaming along the nominal Archimedean spiral field appears typical for both periods, particularly for the higher LECP energies. There are, however, some shorter periods of reverse streaming as well. 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 a strong tendency of more intense streaming for high intensity peaks, but that rule appeared to change later. Anisotropy was also quite high during some of the low-flux periods, e.g. during the month preceding shock crossing.

After the shock crossing, anisotropy decreased substantially, and it averages to practically zero for the whole time period elapsed so far. On shorter time scales, however, a quasi-periodic change with periods of about 20 days appears to be present, although the anisotropy amplitude is much smaller than during the 2004 enhancements.

Both high intensities and low anisotropies are consistent with general expectations for a turbulent post-shock medium, but details still have to be understood.

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. There is a good chance that V2 will also soon gather useful information about the foreshock region, both about energetic particles and later also about plasma properties. It is imperative that both probes should be kept alive as long as possible, because any replacement mission involves huge time delays. Although research on magnetospheric boundary regions teaches us that even thousands of crossings do not suffice for complete understanding, the two Voyager probes will clearly much enhance our knowledge on the plasma regions separating our local SW bubble from the rest of the Universe.

6. Acknowledgements

Financial and organizational support of the International Space Science Institute (Bern) is gratefully acknowledged. Voyager-1 LECP and CRS teams are acknowledged for making data available. R.B. Decker is particularly thanked for useful communication.

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