The Voyagers at 100 and 80 AU, on both sides of the heliospheric termination shock

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***Abstract*— Our most distant messenger, Voyager-1 crossed the heliospheric termination shock shortly after the Florence European Cosmic Ray Symposium, at a radial distance of about 94 AU, while Voyager-2 started to sense pre-shock energetic particle intensity fluctuations soon after. Thus both Voyagers are now contributing toward a better understanding of the boundary regions of the Heliosphere. Although the shock crossing itself was awaited for a long time, several features of the observed particle intensities and directional distributions were quite unexpected and are still controversial and only partially understood. A short review will be presented on the observations and on our present understanding. It is generally expected that those Voyager data and their interpretation may also have far-reaching consequences for models of particle acceleration in many astrophysical situations. A discussion of Voyager results is particularly timely, because Voyager-1 crossed the 100 AU heliocentric distance mark just two weeks before the Lisbon ECRS, while Voyager-2 crossed the 80 AU mark a few weeks earlier. The present review covers recent developments up to the time of writing, i.e. to October 2006.**

I. Introduction

Voyager-1 and Voyager-2 reached the heliocentric distances of 100 and 80 AU, respectively, just before the 20th European Cosmic Ray Symposium, held in Lisbon from 5 to 8 September 2006. More importantly, Voyager-1 crossed the heliospheric termination shock (TS) on 16 December 2004, a few months after the Florence ECRS, while Voyager-2 started to sense energetic particle precursors of the TS just half a year later, in May 2005. Although Voyager is a predominantly American project, its recent contributions to our knowledge about the Heliosphere should certainly interest European cosmic ray scientists as well. I shall shortly review some of the important developments up to October 2006.

Voyager-1 first encountered intermittent energetic particle precursors of the TS in mid-2002. The events continued until early 2003, followed by some controversy on whether the spacecraft actually crossed and re-crossed the TS during that period [1]-[2] (actually, as the TS may move faster than the spacecraft, it is better to say that the controversy was about whether the TS crossed and then re-crossed the Voyager-1 spacecraft). A new period of even more intense flux enhancements began early in 2004 and lasted to the end of that Summer. After a short pause in the Autumn, a sudden increase started in mid-December, and subsequent analysis showed that the actual TS crossing took place on 16 December 2004. Actually, the shock crossing was not officially announced until 24 May 2005. By that time magnetic field data were also evaluated, and were found to support the claim. The first set of refereed papers on the shock crossing were published even later, in September 2005 [3]-[7]. Before that, during the 29th International Cosmic Ray Conference in Pune, India, it was also announced that since May 2005, Voyager-2 was also sensing flux enhancements similar to those seen by Voyager-1 three years earlier [8]-[9].

The TS is a major component of heliospheric structure, separating supersonic and subsonic solar wind regions. It is also considered as the traditional acceleration site of the anomalous component of cosmic rays. Its role in the modulation of galactic cosmic rays is also a much-debated issue. Magnetic field effects, back-reaction of particle acceleration processes, and generation of turbulence are just a few of the complicating factors that might modify the properties of the shock. Thus expectations were high for gaining in-situ information about the shock transit.

There were several unexpected features of the 16 December 2004 shock crossing, of the pre-shock enhancements, and of the subsequent period of Voyager-1 spent in the subsonic solar wind of the heliosheath. It was unfortunate that 16 December was the only day in 2004 when no Voyager-1 data were recorded due to a technical problem. Thus some fine details of the transition were clearly lost. Before the shock crossing, energetic particle intensity enhancements in the foreshock region lasted longer than expected, and the maximum of the first harmonic anisotropy pointed in an unexpected direction. Although the energetic particle streaming was more or less aligned with the Parker spiral field, the highest flux did not arrive inward along the spiral as expected for shock-accelerated particles, but mostly from the opposite direction. That feature may indicate a fairly systematic distortion of the shape of the TS, so that local field lines connect to the TS mostly in the inward direction. For Voyager-2, the anisotropy direction is apparently mostly opposite. Energy spectra of the flux-enhancements were also softer than expected if

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anomalous cosmic rays of fairly well-established characteristics were mostly produced at the termination shock.

In spite of all those unexpected features, there were also several clear signs of the shock crossing. In what follows we shall review the recently measured energetic particle data of Voyager 1 and 2, but some aspects of magnetic field and solar wind data will also be discussed.

II. ENERGETIC PARTICLE RATES

A. *Low-energy rate data*

The Voyager Cosmic Ray Subsystem (CRS) group provide rate data for ions with energies above half MeV, and above 70 MeV, respectively, with time delays of only a few days. The low-energy count rates are characterized by large day-to-day fluctuations during the approach toward the shock, and much smoother variation after the shock. Figure 1 shows the logarithm of count rates and a measure of their variability.

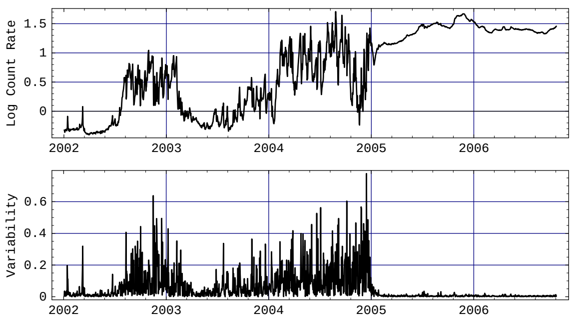

Figure 1. Logarithmic count rates (top), and their day-to-day variability (bottom) characterized by the absolute values of the differences of log count rates for subsequent days. The decrease of variability after the shock transition late in 2004 is particularly conspicuous.

It is important to note that count rates in Figure 1 are sufficiently high to minimize Poisson errors. For count rates in a narrow energy bin and for ion species of low intensity our variability measure would be dominated by the Poisson error, showing high (spurious) variability when count rates are small.

B. *High-energy (cosmic ray) rates*

Rate data for particles with energies higher than 70 MeV are usually interpreted as characterizing the modulated low-energy galactic cosmic ray component. This interpretation is not obvious on the approach to and beyond the shock, because the anomalous component supposed to be accelerated in the vicinity of the shock may reach even higher energies. Actual data, however, appear to be consistent with the galactic cosmic ray interpretation.

High-energy rates between 2002 and October 2006 for both Voyager 1 and 2 are shown in Figure 2.

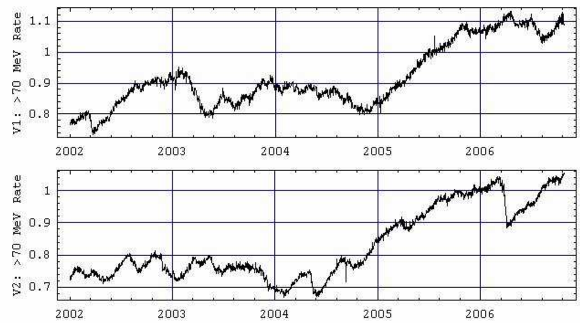

Figure 2. High-energy (E > 70 MeV) count rates for Voyager-1 (top) and Voyager-2 (bottom). Voyager-1 is now about 20 AU farther from the Sun than Voyager-2, thus solar events may reach Voyager-2 earlier. While the general increase subsequent to 2004 is mostly due to the decline of the solar activity cycle, some features, better seen on the time-shifted plots in Figure 3, indicate a common origin.

The change of galactic cosmic ray intensity with radial distance from the Sun is due to a combination of effects. One important contributor is turbulent magnetic field. When such turbulent regions move outward with the solar wind, they partially shield the inner regions of the Heliosphere from low-energy cosmic rays. Some of the turbulent regions extend to a fairly large solid angle, thus, in spite of the large angular separation (about 100 degrees) of the two Voyagers, the same events can affect both of them with an appropriate time delay. Tentatively we take the time delay as 100 days (corresponding to a solar wind speed of 350 km/s). Figure 3 shows the two plots of Figure 2 with such a time delay.

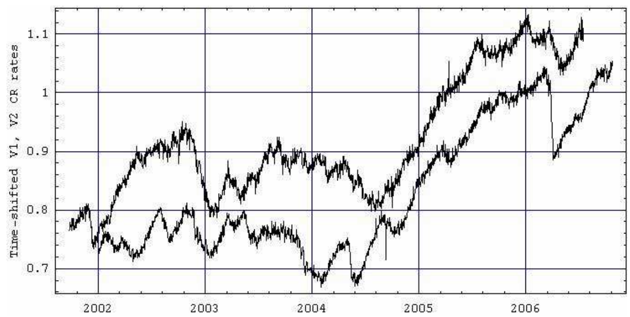

Figure 3. The same as Figure 2, but the upper count rate (for Voyager-1) was shifted to the left by 100 days relative to the lower curve (Voyager-2). The similarity of the two curves, subsequent to 2004, is thus more conspicuous. The huge Forbush-type decrease caused by a shock that arrived at Voyager-2 in early March 2006 [10] is now also seen for Voyager-1, but with smaller amplitude and duration. Before 2004 solar activity was higher, and several poorly related turbulent regions affected cosmic ray intensities at both spacecraft.

The low- and high-energy rate data are poorly correlated, and thus do not indicate how energetic particle fluxes change with energy. Now we are going to discuss the energy dependence of omnidirectional ion fluxes.

III. OMNIDIRECTIONAL PARTICLE FLUXES

A. LECP low-energy ion fluxes

Voyager LECP omnidirectional and some directional ion flux data are also refreshed more or less regularly on their web site, even if not as frequently as the CRS quick-look data. We shall first discuss omnidirectional data.

The Voyager-1 plots show that precursor activity is present at all energies, even if it becomes more conspicuous with increasing energies. Precursors at Voyager-2 are virtually absent below about 200 keV. The huge peak in early March and some subsequent peaks are visible on all Voyager-2 plots. They are not TS precursors, but almost certainly result from shocks caused by merged interaction regions of solar origin.

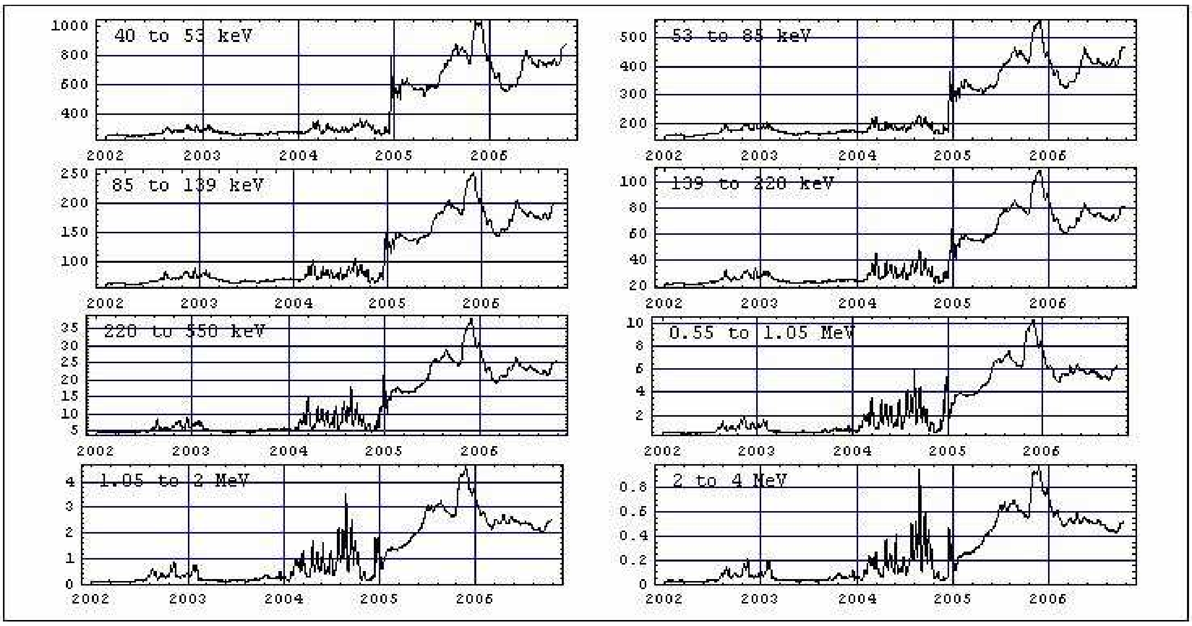

Figure 4. Omnidirectional Voyager-1 low-energy LECP ion fluxes in usual flux units, particles/(cm^2 s st MeV).

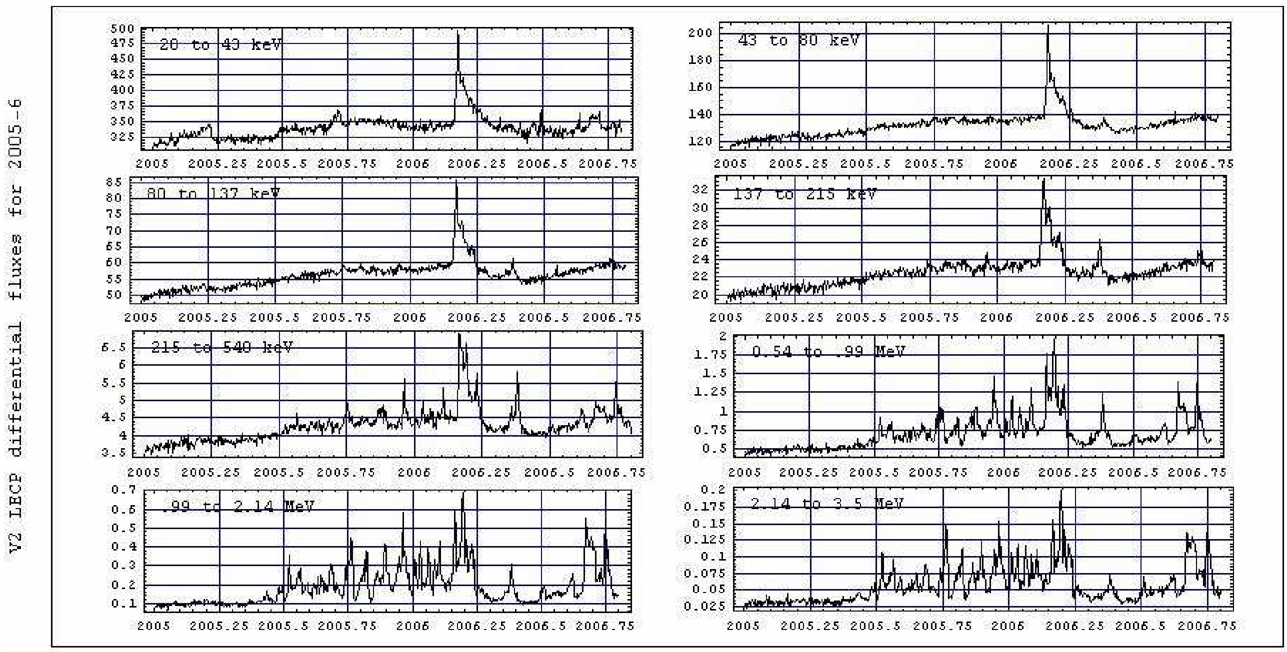

Figure 5. Omnidirectional Voyager-2 low-energy LECP ion fluxes in usual flux units, particles/(cm^2 s st MeV).

There are some interesting similarities and differences between the Voyager-1 and Voyager-2 data sets.

The position of the early March intensity peak at Voyager-2 shows an interesting energy dependence. At the lowest energies a sharp peak appears close to the arrival time of the solar wind shock. At higher energies it splits up, then the second peak becomes predominant. while the starting point of the increase shifts to earlier times. The peak at even higher energies, together with solar wind parameter changes, is shown in Figure 8.

For Voyager-1 the TS spike is first decreasing with energy, then appears to increase again. The post-shock intensities peak late in November 2005 for all energies, then start to decrease again, but some subsequent increases also occur, mainly at low energies. The gradual decrease is smoothest at the highest energies of that LECP data set.

B. LECP higher energy fluxes

Higher energy proton fluxes at Voyager-1 show the gradual change of the precursors and of post-shock intensities with energy (Figure 6). Precursor peaks decrease, but are still marginally visible at 20 to 30 MeV. The shock spike continues to decrease with energy. Post-shock intensities follow more and more the general cosmic ray increase due to solar cycle phase related changes in the modulation. Starting from mid-2006 a Forbush-type decrease is visible at all energies above a few MeV, probably due to the flanks of the strong shock of solar origin clearly seen by Voyager-2 in early March. The full recovery of the fluxes lasts at least until October.

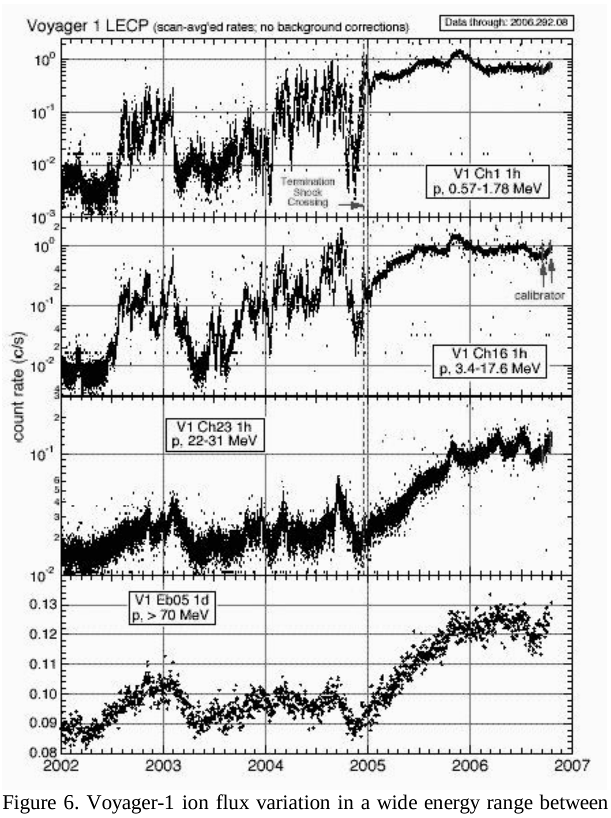

Figure 6. Voyager-1 ion flux variation in a wide energy range between 2002 and October 2006. The TS is marked by a dashed line (taken from LECP data plots)

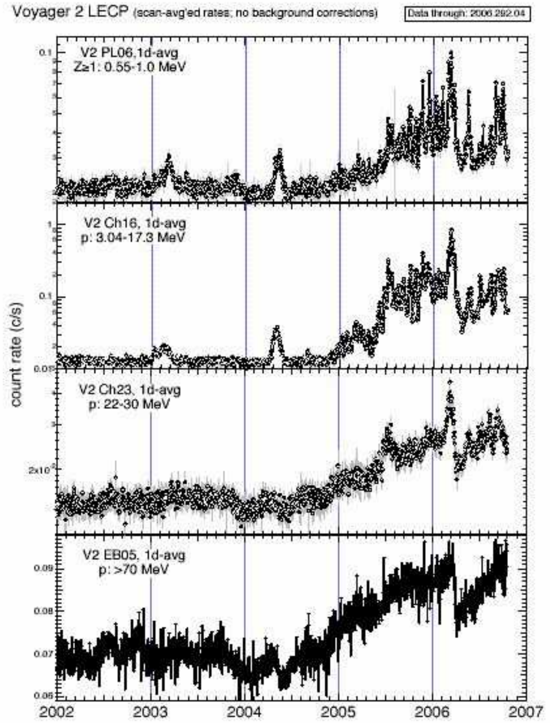

Figure 7. Voyager-2 ion flux variation in a wide energy range between 2002 and October 2006. The effects of the early March shock are seen at all energies. (Taken from LECP data plots)

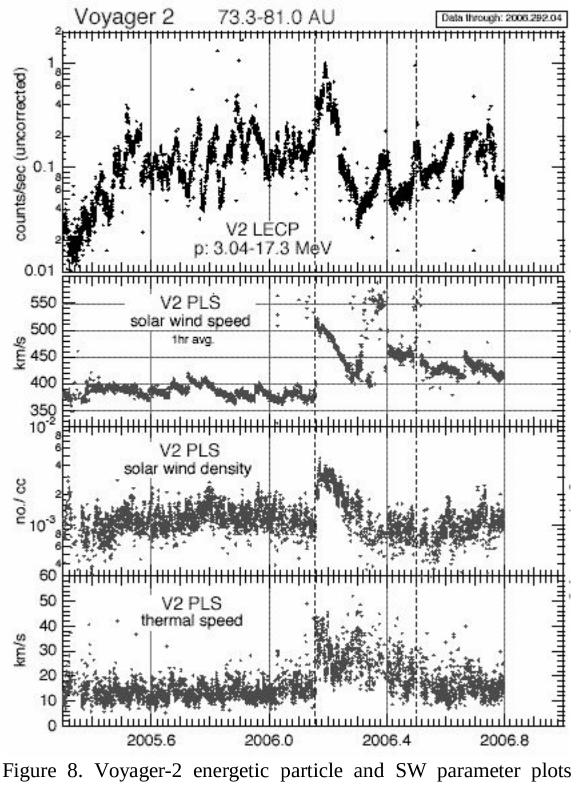

Figure 8. Voyager-2 energetic particle and SW parameter plots around the SW shocks after early March 2006. (taken from LECP data plots)

IV. DIRECTIONAL FLUXES AND ANISOTROPIES

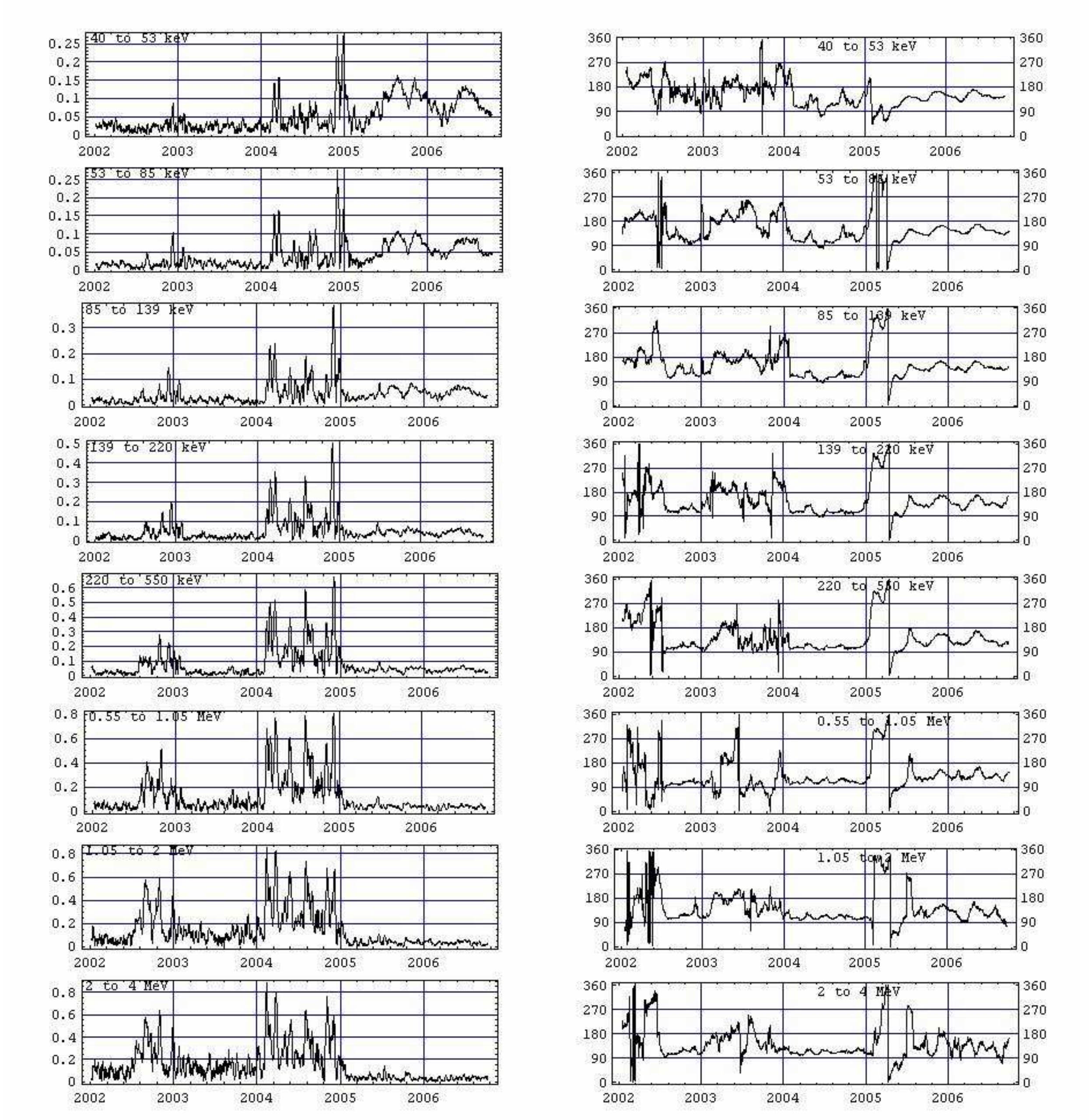

Figure 9. First harmonic amplitudes (left-hand panel) and phases (right-hand panel) of smoothed Voyager-1 low-energy daily LECP directional ion fluxes. A 90^0 phase corresponds to a streaming outward along the spiral field, 270^0 to field-aligned inward streaming. Radial streaming towards or away from the Sun correspond to 0^0 and 180^0, respectively.

In addition to omnidirectional count rates and differential fluxes, the Voyager data sets also contain information about the streaming direction of the "gas" of energetic particles with respect to the spacecraft. No Compton-Getting-correction was applied for taking into account the motion of the spacecraft with respect to the solar system rest frame. The anisotropy pattern of the particles is of course generally more complicated than a simple streaming, but the simplest directional information (the first harmonic anisotropy) represents a simple streaming.

The Voyagers can measure only the component of the streaming in a plane containing the radial and azimuthal (i.e. approximately the projected spiral) directions. The scan plane is subdivided into 8 sectors, one of which is inactive. We tentatively reconstructed the fluxes in the 8^{th} sector by averaging the directional fluxes of the two neighboring sectors. The 8 directional fluxes were then normalized to their mean, and a first harmonic anisotropy vector was calculated for each day and energy. A 10-day smoothing of the vectors was applied for calculating anisotropy amplitudes, then the magnitude of the resulting vector was taken. A 30-day smoothing was applied for phases (directions). The results are given in Figure 9.

There are several interesting points in Figure 9. In the pre-shock region the anisotropy amplitudes are highest in the regions of high pre-shock activity. The amplitudes are drastically reduced after the shock, particularly for the higher energies. Just as the day-to-day variability of omnidirectional rates that has been shown in Figure 1, the anisotropy amplitudes also clearly separate the pre-shock and post-shock regions. It is of some interest that post-shock streaming is non-negligible at the lowest energies, and it may justify some theoretical modeling efforts.

The phases (directions) of streaming are also of interest. The streaming is mostly close to the outward spiral direction during times of high pre-shock activity (perhaps with the exception of the lowest energy). The shock was followed by a 3 to 4 month period of inward streaming. One possible but doubtful explanation is that the shock was moving so fast inward at that time that the solar wind was practically stopped. From the point of view of the outward moving spacecraft the solar wind was then moving inward. Due to the strong and turbulent magnetic field the particle fluxes were also convected inwards.

The 18-month period subsequent to April 2005 is characterized by outward streaming in directions between the outward spiral and the anti-solar direction. Directional variations, however, are larger than during the pre-shock intensity enhancements.

V. MAGNETIC FIELD DATA

Magnetic field data were considered crucial in deciding whether the change in energetic particle fluxes in December 2004, at a radial distance of 94 AU from the Sun, was really due to the long-expected TS crossing. While with hindsight that may have been excessive caution, magnetic field variations are certainly important for a better understanding of the underlying physical processes.

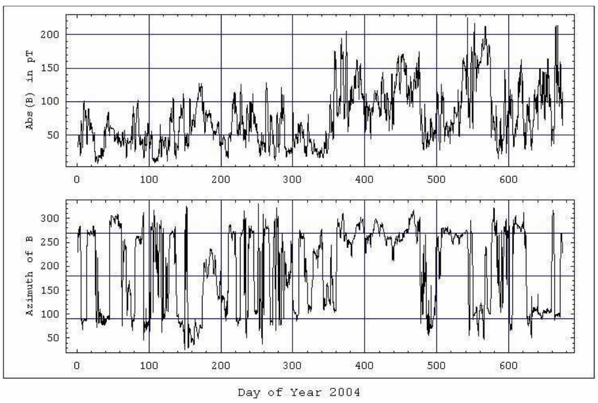

Figure 10. Field strength (top) and azimuth angle (bottom) of the interplanetary magnetic field at Voyager-1 in 2004/2005

The MAG experiment aboard both Voyagers measures three components of the magnetic field, from which the physically more relevant field strength and the heliographic azimuth of the field can be inferred. Figure 10 shows 12-point smoothed plots of hourly data for Voyager-1, between early 2004 and DoY 308 of 2005. The data were taken from the currently available NSSDC data at COHOWEB. There is a considerable time delay between the generation and the availability of the data, because raw magnetic field data need to be corrected for spacecraft-generated fields. Rolling maneuvers of the spacecraft are needed for such corrections, and those are rather fuel-consuming. For Voyager-2 no data after mid-2004 are currently available. The magnetometer was originally designed for measuring stronger fields, and it is a real achievement that it can still provide useful data at solar distances beyond 75 AU.

One can see in Figure 10 that the mean field strength is definitely higher after the TS on DoY 251 than before. Based on the whole currently available periods after and before the shock, the ratio is about 2. When magnetic data were first presented for the shock region [7], a somewhat higher ratio was suggested. As to the heliographic azimuth of the field, it is clearly seen that the directions around the Parker spiral azimuth of 90^0 and 270^0 are preferred. There are, however, small deviations: the first maximum of the frequency plot of azimuth values is at about 100^0, not at 90^0. In the present solar cycle the 90^0 azimuth corresponds to the predominant direction of the southern heliospheric fields, while Voyager-1 is at a northern latitude of 34^0. The above deviation might be due to some distortion of the southern magnetic domains penetrating into the northern hemisphere.

The long period of unipolarity following DoY 360 lasted for about 110 days. This more or less coincides with the period when low-energy particles were streaming inward (towards the Sun) as shown in Figure 9. A quasi-periodic variation with approximately the solar rotation period, however, is also visible. The very long unipolar region might be explicable by the inward motion of the shock and the stopping of the solar wind, although the period appears somewhat too long for that explanation. Unfortunately the solar wind detector of Voyager-1 was damaged during the Saturn encounter, thus solar wind speed cannot be directly checked.

Ness et al. [10], and Burlaga et al. [7], [11] discussed the distribution of hourly averages of the magnetic field magnitudes both before and after the TS. Before the TS a lognormal distribution fitted the data, while after the TS a better fit was found with Gaussian or Tsallis distributions. Their post-shock analysis, however, was mostly restricted to the long unipolar region. With the more extended period presently available one finds somewhat different distributions. If only data after the unipolar period are considered, the distribution appears rather similar to the pre-shock lognormal one.

Evidence for the reconnection of oppositely directed fields following the long unipolar region, suggested in [11], is also of interest, and similar periods should be looked for when more data are available.

Although there were several sector boundaries in the period following the unipolar region, sector changes occur slightly less frequently than before the TS.

With progress towards minimum solar activity in 2007, the waviness of the current sheet should decrease. One might expect that northern hemispheric fields should gradually become dominant for Voyager-1, while southern polarity should predominate for Voyager-2. That expectation will be worthwhile to check

VI. Conclusions

Voyager-1 crossed (or was crossed by) the TS on 16 December 2004 at a radial distance of 94 AU and at a northern heliospheric latitude of 34^0. It has now passed the distance mark of 100 AU and continues to explore the heliosheath. Except for its solar wind plasma monitor, most instrument groups continue to provide data, and are hoped to do so for more than another decade.

Before the shock crossing Voyager-1 recorded shock-precursors in the foreshock since Summer 2002. Surprisingly, most of the precursor ion fluxes were moving along the outward-directed magnetic field. It was also somewhat surprising that the full spectrum of the anomalous cosmic rays was not seen after shock crossing, although some of the higher-energy component was gradually building up later. It was also unexpected that the solar wind or at least the energetic particle flux virtually stopped for a few months after shock crossing.

Voyager-2 also started to observe intermittent enhanced precursor fluxes in May 2005, and continued to do so until an intense solar wind shock early in March 2006 presumably pushed the TS further out and temporarily stopped the activity. Precursor activity re-started after a few months, and still increases intermittently in intensity. Precursor fluxes are predominantly inward directed along the spiral field, i.e. they are traveling in opposite directions to those observed at Voyager-1. Precursor fluxes were detected at somewhat higher energies than at Voyager-1. In fact, the intermittent increases were not seen at the lowest energies.

The early March 2006 solar wind shock at Voyager-2 caused a huge increase in dynamic pressure, thus probably pushed out the TS considerably. The subsequent Forbush-decrease of energetic particles and cosmic rays took at least half a year to recover. A similar Forbush-decrease was also seen at Voyager-1, although with a more gradual intenstiy decrease and shorter recovery. The merged interaction region causing the strong shock at Voyager-2 was a "partially global" event: it did show some effects at both of the widely separated Voyagers, but at very different levels.

We are looking forward to new surprises in the future data of both Voyagers, and particularly to detailed data of the TS crossing (or crossings) of Voyager-2. With some luck, Voyager-1 may also provide data on the Heliopause, i.e. on the transition from the solar wind to the interstellar medium.

Acknowledgment

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