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Cosmic rays in the heliosphere: Observations

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ABSTRACT

This contribution to the 100th commemoration of the discovery of cosmic rays (6–8 August, 2012 in Bad Saarow, Germany) is about observations of those cosmic rays that are sensitive to the structure and the dynamics of the heliosphere. This places them in the energy range of 10^7–10^{10} eV. For higher energies the heliosphere becomes transparent; below this energy range the particles become strictly locked into the solar wind. Rather than give a strict chronological development, the paper is divided into distinct topics. It starts with the Pioneer/Voyager missions to the outer edges of the heliosphere, because the most recent observations indicate that a distinct boundary of the heliosphere might have been reached at the time of the meeting. Thereafter, the Ulysses mission is described as a unique one because it is still the only spacecraft that has explored the heliosphere at very high latitudes. Next, anomalous cosmic rays, discovered in 1972–1974, constitute a separate component that is ideally suited to study the acceleration and transport of energetic particles in the heliosphere. At this point the history and development of ground-based observations is discussed, with its unique contribution to supply a stable, long-term record. The last topic is about solar energetic particles with energies up to $\sim 10^{10}$ eV.

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1. The Pioneer/Voyager missions to the outer heliosphere

It is appropriate to start this historical oversight of cosmic rays in the heliosphere with the Pioneer/Voyager missions because these missions are just over 40 years old, and puzzling results on Voyager 1 since the middle of 2012 indicate that the ultimate goal, to reach the edge of the heliosphere, was happening during the conference (6–8 August, 2012, Bad Saarow, Germany).

Pioneer 10 was launched on 2 March 1972, Pioneer 11 on 6 April 1973, while Voyager 1 was launched on 5 September, 16 days after Voyager 2 on 20 August 1977. Pioneer 11 lasted until 30 November 1995, and Pioneer 10 until 23 January 2003. At the time of this conference, the two Voyagers were still operational. Voyager 1 crossed the termination shock of the supersonic solar wind at 94 AU in December 2004, while Voyager 2 did so at 84 AU in August 2007. Since then, the spacecraft have been operating in the heliosheath where the solar wind flow is subsonic or sub-Alfvénic.

Fig. 1 summarizes how the intensity of 150–380 (average 265) MeV/nucleon Helium on Voyager 1 has increased throughout its mission towards the edge of the heliosphere. This figure is an extract of a more comprehensive one by McDonald et al. [1] that includes similar data for Voyager 2 and the two Pioneers. This graph has historical significance because it is the culmination of results first reported at the 13th International Cosmic-Ray Conference in 1973 in Denver, Colorado. That conference had a special symposium on the results of Pioneer 10, described in Refs. [2–4], and there was great interest to hear and see that, indeed, the >70 MeV intensity had increased with 3 ± 1%/AU by the time Pioneer 10 had reached about 3 AU Results for other species were still inconclusive, however, with radial gradients of 3 ± 7%/AU for 27–69 MeV H; 5 ± 7%/AU for 27–69 MeV/n He; and 0 ± 50%/AU for electrons. At the time, these relatively small gradients could be understood from the simple expression $g_r = CV/\kappa$, with typical values of the solar wind speed V, the diffusion coefficient κ of cosmic ray in the heliosphere, and the Compton–Getting spectral factor C (see, e.g. [5]). The relative smallness of the gradients indicated that the heliosphere was likely to be much larger than a few, or even several AU.

The graph clearly shows the cosmic-ray modulation cycle, with three cosmic-ray maxima observed during the periods of minimum solar activity in 1977, 1987 and 1998. The two lines show that the radial gradient is of the order of 1%/AU at solar minimum conditions, and twice as large during solar maximum. It is noteworthy, however, that there is little indication of a modulation cycle or a cosmic-ray maximum in 2009 in the heliosheath, after Voyager 1 crossed the termination shock (marked TSX). Instead, the intensity lingers at the solar maximum value. This is probably due to the fact that the subsonic solar wind speed drops off there, so that the turbulence in the field that causes the modulation is less effectively convected away. This slow-down was confirmed by Krimigis et al. [6] with the so-called LECP detector, indicating an average decrease of −18.8 ± 1.5 km/s/yr. This paper also indicates that

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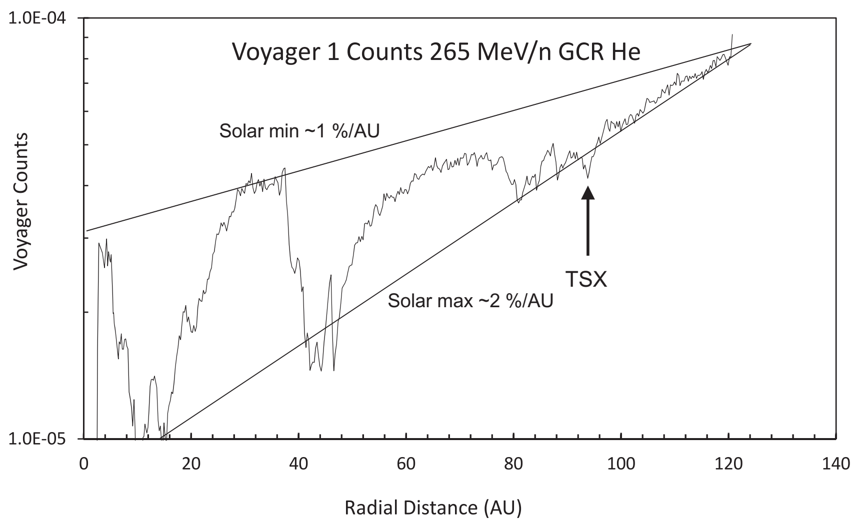

Fig. 1. Voyager 1 counting rate for He as function of radial distance. The termination shock crossing is marked as TSX. Data courtesy of F.B. McDonald and the CRS collaboration [1].

since the middle of 2010, the radial solar wind flow has essentially stopped, but that there was still a significant transverse flow of the order of 40 km/s, which has also now decreased to almost zero. This contradicts the expectation that there should be a meridional flow immediately inside the heliopause, and the region is therefore viewed as a transition region with as yet unknown properties [7].

This solar wind profile suggests that Voyager 1 must now be nearing the modulation boundary, and this justifies the construction of the two lines so that they meet at ~130 AU. Hence, this value is a first estimate of the cosmic-ray intensity in the local interstellar spectrum (LIS).

The last few points on the graph show, however, that there was a sudden increase of about 30% that happened in two steps. The first was in the beginning of May 2012, and the second one in the first week of August. These sudden increases were accompanied by even more dramatic "dropouts" in the intensity of >0.5 MeV/n ions, which are particles that mainly originate from the sun. For these particles the intensity decreased (and recovered) by almost an order of magnitude in a matter of hours. This unexpected result indicates that this new region outside the solar wind holds new surprises. Post-conference results in November 2012, see e.g. [8], indicate that there is definitely a modulation boundary, but to what extent it can be characterised as the heliopause or the outer boundary of the heliosphere is still under investigation.

Another unexpected result is that, mainly from neutral particle imaging [9], it has become clear that the heliosphere moves so slow relative to the interstellar medium that there may not exist a bow shock around it.

The project scientist of the Voyager mission, E.C. Stone, put the mission in perspective with his recent remark that 40 years ago it started with a dream, that nobody really had an idea what would be seen, when it would be seen, and whether the spacecraft would last long enough to see it. It is quite appropriate that this 40-year milestone was reached almost exactly on the 100th anniversary of the discovery of cosmic rays.

2. The Ulysses mission toward the heliospheric poles

Ulysses was a unique mission because it is the only spacecraft that has viewed the sun and the heliosphere at high latitudes, of up to 70°. It was a joint ESA/NASA mission, launched on 6 October 1990, and lasted almost 19 years, until 30 June 2009. During its lifetime it made three passes over the solar poles, the first and third at near-solar minimum conditions in 1994/5 and 2007/8, and the second one in 2000/1 near solar maximum. Its trajectory is shown in Fig. 2.

The three primary results were on the latitudinal dependence of the solar wind, the heliospheric magnetic field and its turbulence, and the cosmic-ray intensity. These three quantities are plotted in curves B, C and D of Fig. 3, taken from [11], and it highlights their latitude dependence during the first latitude scan to the two poles. Each of them revealed the following:

During this first scan, the solar wind showed two distinct states. There was a fast high-latitude wind of the order of 750 km/s, which only occasionally extended down to low latitudes. At low latitudes there was a slower wind of typically 400 km/s, centred about the heliospheric equator. This fast solar wind above the extended polar coronal holes was much more typical than was thought before the mission, and the separation between the fast and slow wind was much sharper. A more detailed exposition of this profile is given in [11]. At solar maximum, during the second pass in 2000/1, things were more complex, with many high and low-speed streams at all latitudes, making it hard to distinguish any particular region from another. It was also discovered that co-rotating solar-wind stream structures with forward and reverse shock waves produce effects extending to the highest latitudes explored by Ulysses [12].

For the heliospheric magnetic field it was discovered that the magnitude of its radial component was almost independent of latitude [13]. This deviates from a typical dipole character, and it is ascribed as due to the fact that the polar solar wind undergoes significant non-radial expansion. This in turn implies that there are large deviations from the typical Parker spiral magnetic field. In addition, there are large MHD fluctuations right up to the highest latitudes. These effects, including differential rotation on the solar surface, have been modelled in the so-called Fisk field [14] as an extension of the simpler Parker spiral. On the other hand, Ulysses did discover the nice simplicity during the solar maximum pass in 2000/1 that from one magnetic cycle to the next, the dipolar bar of the sun simply rotates through 180° [15].

Prior to the mission, it was thought that the Parker spiral would allow much easier access of galactic cosmic rays via the poles, to such an extent that the almost unmodulated galactic intensity would be seen there. But due to the vastly different magnetic field and turbulence situation at polar latitudes, the situation was quite

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