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The total modulation of cosmic rays in the heliosphere

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The remarkable exploration of the final frontier of the heliosphere started in December 2004 when Voyager 1 crossed the solar wind termination shock (TS) at 94 AU from the Sun. This was followed by Voyager 2 in August 2007 at 84 AU from the Sun. This points to a TS that moves and probably also a north-south asymmetry in the geometry of the heliosphere, apart from the predicted large nose-tail asymmetry. The most surprising observation was that the so-called anomalous cosmic rays (ACRs) were not accelerated at the TS but further away into the inner heliosheath. However, lower energy particles were clearly accelerated at the TS, including electrons around 10 MeV. The latter, exhibited amazing modulation features from the inner heliosphere, including the Jovian electrons, up to the TS and beyond. It has turned out the inner heliosheath, as the region between the TS and the heliopause (HP), acts as a steady modulation barrier to galactic cosmic rays, the lower the energy, the more so. This will be illustrated with a comprehensive numerical model in comparison with observations. The second extraordinary event was when Voyager 1 crossed the HP in August 2012 at 121.7 AU, while Voyager 2 has still not crossed it. This could however happen soon. The HP crossing by itself has produced new surprises and seems to be a wider region than anticipated. It additionally acts as a barrier through which the ACRs dropped away spectacularly while the galactic particles increased surprisingly much to what is now considered the very local interstellar values. Voyager 1 is now at 131 AU from the Sun, and Voyager 2 at 108 AU. Exploration of the whole heliosphere, and finally the crossing of the TS and later the HP have provided us with new and exciting observations, with ample challenges to theoretical and modelling approaches to the acceleration, transport and modulation of cosmic rays in the heliosphere, which will be reviewed in this presentation. And, in the process, new paradigms are put before us, to be amazed about and to enjoy studying.

Summary

It is possible for the first time to describe the total modulation of cosmic rays in the heliosphere using Voyager observations from the Earth to the heliopause, and from the PAMELA space mission at the Earth, in comparison with comprehensive numerical models, which will be illustrated and discussed for galactic electrons in particular.

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