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Where does the heliospheric modulation of galactic cosmic rays start?

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Abstract

The long outstanding question of where the heliospheric (solar) modulation of galactic cosmic rays actually begins, in terms of spatial position, as well as at what high kinetic energy, can now be answered. Both answers are possible by using the results of an advanced numerical model, together with appropriate observations. Voyager 1 has been exploring the outskirts of the heliosphere and is presently entering what can be called the very local interstellar medium. It has been generally expected, and accepted, that once the heliopause is crossed, the local interstellar spectrum (LIS) should be measured *in situ* by the Voyager spacecraft. However, we show that this may not be the case and that modulation effects on galactic cosmic rays can persist well beyond the heliopause. For example, proton observations at 100 MeV close to the heliopause can be lower by ∼25% to 40% than the LIS, depending on solar modulation conditions. It is also illustrated quantitatively that significant solar modulation diminishes above ∼50 GeV at Earth. It is found that cosmic ray observations above this energy contain less that 5% solar modulation effects and should therefore reflect the LIS for galactic cosmic rays. Input spectra, in other words the very LIS, for solar modulation models are now constrained by *in situ* observations and can therefore not any longer be treated arbitrarily. It is also possible for the first time to determine the lower limit of the very LIS from a few MeV/nuc to very high energies.

Keywords: Cosmic rays; Solar modulation; Heliopause; Local interstellar spectra; Positron excess

1. Introduction

A recent report by Gurnett et al. (2013) indicates that the spacecraft Voyager 1 has entered the very local interstellar medium. Corresponding cosmic ray (CR) observations (Stone et al., 2013; Krimigis et al., 2013) can thus be considered as indicative of what the very local interstellar spectra (LIS) could be (see also Potgieter et al., 2013a; Potgieter, 2013a). These *in situ* observations by Voyager 1 have led to a renewed interest in the long outstanding question of where exactly does the solar modulation of galactic CRs commence in terms of spatial position. At Earth, the PAMELA space detector (e.g. Adriani et al., 2013a) has been observing CR spectra since mid-2006, down to kinetic energies of $E \sim 100$ MeV, in particular also an excess of CR positrons (Adriani et al., 2013b), evident from ∼200 GeV down in energy to the point where solar modulation dominates, thus obscuring the very LIS. Where the solar modulation of CRs commences in terms of energy (or rigidity) has thus also become of interest.

This report is focused on answering these questions quantitatively. In the next section, our investigation of the energy dependence of the solar modulation of CRs, from 100 MeV up to 350 GeV will be given in order to find the energy range at which solar modulation becomes significant. In the section that follows, the spatial dependence of the solar modulation of CRs is investigated in order to establish where the modulation process begins. Does it occur from the heliopause (HP) of the heliosphere, usually assumed as the modulation boundary, or is it beginning beyond the HP?

Discussions are given in the context of the results of numerical modelling and the subsequent insight gained

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by doing such modelling. The emphasis is on the implications for the interpretation of *in situ* measurements of the very LIS of galactic CRs inside and outside of the heliosphere, including low energies $E < 1$ GeV which is of special interest to solar modulation studies. A preliminary presentation on this topic was given by Potgieter and Strauss (2013).

2. Energy dependence of the solar modulation of CRs

It is not straightforward to establish at what energy/rigidity the modulation of galactic CRs actually begins in the heliosphere. This should also change as a function of time and position, e.g. if the modulation conditions would be significantly different in the nose direction of the heliosphere compared to the tail-direction. It is not yet possible to determine observationally at what high energy (rigidity) the solar modulation of galactic CRS becomes insignificant. It can only be done precisely if the relevant very LIS for CRs were known (observed) at the appropriate rigidities, and reliable measurements are made simultaneously inside and outside the heliosphere over a relatively large rigidity range, e.g. between 10 GV and ~200 GV. Neutron monitors, observing mainly galactic CR protons indirectly (inside the Earth's atmosphere and magnetosphere) at rigidities larger than ~40 GV do observe solar related changes in the CR intensity over relatively long periods at meaningful levels of modulation, even during solar minimum activity conditions. This indicates that the modulation of CRs is occurring at higher rigidities than what is usually assumed. Also from a numerical modelling side, it is not as easy as it may seem because a so-called no-modulation limit at high energies is difficult to determine so that this required initial condition in numerical modelling is simply assumed. In the past, this assumption was many times adjusted to lower energies to save on the computational time it took to do these computations.

Most numerical models applied to solar modulation are based on what can be called standard finite difference schemes which require boundary conditions at all phase-space domains, one of which is a high energy initial condition where the LIS is specified as the unmodulated spectrum, usually between 30 to 50 GeV. This artificial condition therefore assumes no modulation above this selected energy, usually without considering what the values of the CR transport coefficients are for this assumed energy. Fundamentally, the energy at which modulation is no longer present, should be determined entirely by the values of transport coefficients at these high energies (in other words, by the physics), and should be independent of the adopted numerical scheme. Unfortunately, despite significant progress in turbulence and diffusion theory (see e.g. Shalchi, 2013), we also do not know what exactly the values of these diffusion coefficients everywhere are, inside and outside the heliosphere.

Recently, progressively more CR transport and modulation models are based on solutions of stochastic differential equations (SDEs). A reason is that the numerical scheme and process are perfectly parallelizable and is therefore very appropriate in utilizing the advantage given by large computer clusters. This approach offers the opportunity to determine the level of modulation for any given rigidity (or kinetic energy/nucleon), from very high to low rigidities. With these types of models it is possible to determine the energy at which CR modulation fades, because no energy domain boundary conditions need to be prescribed. In this section, the SDE based galactic CR transport model of Strauss et al. (2011a,b) is used to study the modulation of galactic CR protons, in particular its energy dependence. For details of this numerical method, see the work of Zhang (1999), Pei et al. (2010), Kopp et al. (2012) and references therein.

The left panel of Fig. 1 shows energy spectra at Earth for galactic CR protons, for the two modulation drift cycles, indicated as $A < 0$ and $A > 0$. For a detailed discussion of this charge-sign dependent modulation and the 22-year cycle, see also e.g. Potgieter (2013c) and Strauss et al. (2012b). These spectra were computed with the mentioned SDE model and are shown with respect to the computed LIS of Moskalenko et al. (2002), as unmodulated input to the model, specified at a distance of $r = 120$ AU from the Sun. The drift solutions are compared to observations of von Rosenvinge et al. (1979) and Balasubrahmanya et al. (1965) to validate the choice of transport coefficients as implemented, illustrating that realistic levels of modulation are obtained in this manner. For these simulations, a wavy heliospheric current sheet (HCS) with a tilt angle of $\alpha = 10^\circ$ is assumed, as implemented by Strauss et al. (2012a), along with the diffusion coefficients as discussed by Strauss et al. (2012c). This figure illustrates the general features and drift characteristics of modulated proton spectra at Earth. Of particular importance is that the LIS, according to this drift modulation model, gives two modulated spectra at Earth, produced with one set of modulation parameters but different drift cycles caused by flipping only the solar magnetic field direction every 11 years, thus creating a 22-year CR modulation cycle.

The right panel of Fig. 1 shows the corresponding modulation ratio as a function of kinetic energy, obtained by normalizing the spectra at Earth to the LIS levels; unity therefore indicates that the LIS is unmodulated (no reduction in intensity). The shaded regions respectively indicate energy regimes where less than 30% (light grey; $E > 10$ GeV) and less than 5% (dark grey; $E > 50$ GeV) modulation are computed. This modulation ratio approaches unity at high energies as expected, but does not quite reach this value at 350 GeV, where the computations were stopped, with a small fraction of residual modulation still present. Clearly, the drift modulation cycles produce somewhat different modulation ratios, becoming quite evident between 10 to 20 GeV, progressively so with decreasing energy. Note that the drift effect seems to fade at low energies but this is simply caused by the use of a