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A local interstellar spectrum for galactic electrons

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ABSTRACT

A heliopause spectrum at 122 AU from the Sun is presented for galactic electrons over an energy range from 1 MeV to 50 GeV that can be considered the lowest possible local interstellar spectrum (LIS). The focus of this work is on the spectral shape of the LIS below ∼1.0 GeV. The study is done by using a comprehensive numerical model for solar modulation in comparison with Voyager 1 observations at ∼112 AU from the Sun and PAMELA data at Earth. Below ∼1.0 GeV, this LIS exhibits a power law with $E^{-(1.55 \pm 0.05)}$, where E is the kinetic energy of these electrons. However, reproducing the PAMELA electron spectrum averaged for 2009, requires a LIS with a different power law of the form $E^{-(3.15 \pm 0.05)}$ above ∼5 GeV. Combining the two power laws with a smooth transition from low to high energies yields a LIS over the full energy range that is relevant and applicable to the modulation of cosmic ray electrons in the heliosphere. The break occurs between ∼800 MeV and ∼2 GeV as a characteristic feature of this LIS. The power-law form below ∼1 GeV produces a challenge to the origin of these low energy galactic electrons. On the other hand, the results of this study can be used as a gauge for astrophysical modeling of the local interstellar spectrum for electrons.

1. Introduction

A crucially important aspect of the modulation of galactic cosmic rays in the heliosphere is that the local interstellar spectra (LIS) need to be specified as input spectra at an assumed modulation boundary and then modulated throughout the heliosphere as a function of position, energy and time. Because of solar modulation and the fact that the nature of the heliospheric diffusion coefficients is not yet fully established, all cosmic ray LIS at low kinetic energies ($E < \sim 1$ GeV) remain controversial. This is true from an astrophysical and heliospheric point of view.

We focus on galactic electrons and approach the controversy from a heliospheric point of view. This is achievable because solar modulation models have reached a relatively high level of sophistication, including a third order tensor, supported by progress on diffusion and turbulence theory for the heliosphere. Even more important is that the Voyager 1 spacecraft is about to exit the inner heliosheath, the region between the solar wind termination shock (TS) and the heliopause (HP), while observing electrons between 6 and ∼120 MeV [1]. Together with electron observations at Earth from PAMELA with $E > \sim 100$ MeV [2], it is now possible to establish the total modulation between the heliospheric boundary and Earth, which provides a rather robust set of modulation parameters for comprehensive numerical modeling of solar modulation.

We first discuss the enduring controversy around electron galactic spectra (GS), focusing on $E < \sim 1$ GeV, and the conventional assumption that these GS are LIS. The solutions of a numerical model for the modulation of galactic electrons in the heliosphere are then presented in comparison with Voyager 1 and PAMELA observations to obtain a computed electron spectrum at the heliopause that can be considered the lowest possible very LIS.

2. Galactic spectra assumed as local interstellar spectra

Computed galactic cosmic ray spectra, from a solar modulation point of view, are referred to as spectra that are produced from astrophysical sources, usually assumed to be evenly distributed through the Galaxy, typically very far from the heliosphere. More elaborate approaches to the distribution of sources have also been followed (e.g., [3]), even considering contributions of sources or regions relatively closer to the heliosphere (e.g. [4]) and with new theoretical (e.g. [5]) and observational developments [6]. These spectra are calculated using various approaches based on different assumptions, but mostly using numerical models, e.g. the well-known GALPROP propagation model [6–8]. For energies below several GeV, which are of great interest to solar modulation studies, the galactic propagation processes are acknowledged as to be less precise as illustrated comprehensively by [9]. The situation for galactic electrons at low energies has always been considered somewhat better because electrons produce synchrotron radiation, so that radio data assist in estimating the electron GS at these low energies. For a discussion of this particular approach and some

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examples of consequent electron GS, see Langner et al. [10], Strong et al. [6] and Webber and Higbie [11]

Computed galactic spectra usually do not contain the contributions of any specific (local) sources within parsecs from the heliosphere so that an interstellar spectrum may be different from an average GS (typically as is computed with GALPROP). An averaged interstellar spectrum may be different from a LIS (thousands of AU away from the Sun), which might be different from a very LIS, say within ~200 AU away from the Sun, or what can be called a heliopause spectrum, right at the edge of the heliosphere. If known, the latter would be the ideal spectrum to use as an input spectrum for solar modulation models. This study is used to compute such an electron spectrum from a heliospheric point of view, using an existing comprehensive modulation model and the mentioned observations.

Potgieter and Ferreira [12] and Potgieter and Langner [13] showed that the heliospheric TS could in principle re-accelerate low-energy galactic electrons to energies as high as ~1 GeV so that a heliopause spectrum could be different from a TS spectrum. Principally, such a TS spectrum may even be higher than a GS spectrum, depending on the energies considered. However, because the TS was observed as rather weak [14], only a factor of ~2 increase was observed close to the TS for 6–14 MeV electrons. Since the crossing of the TS, Voyager 1 has observed an increase of a factor of ~60 on its way to the HP [1]. During the period 2009–2012, the intensity of these low-energy electrons has increased by almost a factor of 10. This means that the HP spectrum is at least a factor of ~30 higher at these energies than what had been observed by Voyager 1 at the TS, more than 8 years ago. It is thus reasonable to neglect the influence of the heliospheric TS on a very LIS when cosmic ray ions are considered, but the possibility of the re-acceleration of low energy electrons (and positrons) inside the heliosphere will have to be investigated before a decisive conclusion can be made. The latter is not addressed in this work. For a review on the solar modulation of cosmic rays see [15].

For a compilation of computed GS based on the GALPROP code for cosmic ray protons, anti-protons, electrons, positrons, Helium, Boron and Carbon and more, see Moskalenko et al. [7] and Ptuskin et al. [9]. For an update on electron LIS from an astrophysical point of view, see Strong et al. [6]. For a discussion on the contribution of Jovian electrons to the global solar modulation of electrons, see Strauss et al. [16] and Potgieter and Nndanganeni [17]. For the rest of this report, the focus remains strictly on galactic electrons.

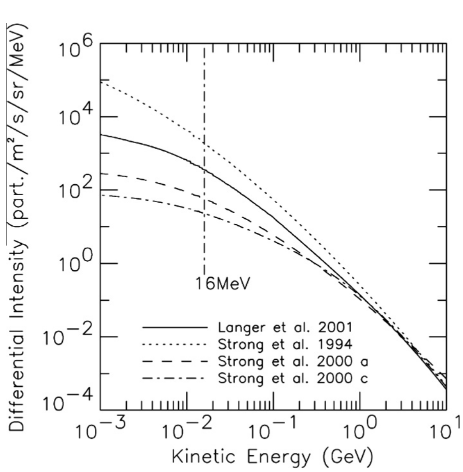

Fig. 1. Computed galactic spectra for low-energy electrons by Strong et al. [18,19] are shown in comparison with the spectra by Langner et al. [10]. Figure is adapted from Ferreira et al. [20] which focused on the solar modulation of 16 MeV electrons in the heliosphere.

Fig. 1 is presented as an example of the mentioned uncertainties in GS that were used as LIS, from a historical point of view. It shows several electron spectra as computed with earlier versions of the GALPROP propagation model, done between 1994 and 2000. The highest electron GS was reported by Strong et al. [18] and was used frequently as the LIS in earlier modulation studies (e.g. [21,22]). Later, Strong et al. [19] argued that this GS was too high and much lower spectra were computed as indicated in the Figure. Langner et al. [10] recalculated the electron GS using a phenomenological approach, including also radio data for calculations at lower energies. They found a spectrum that was between the spectra reported by [18,19]. This spectrum is shown together with the GALPROP computations in units of particles $m^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$. A feature of these GS is that all of them deviate from a power law progressively below ~1 GeV to differ substantially the lower the energy becomes. A power-law form is recognizable above ~1 GeV but at lower energies this is not the case. Evidently, the situation has been unsatisfactorily, yielding a difference of a factor of 1000 at 1 MeV. It also emphasizes that GS for electrons at these low energies have remain controversial over a long period of time.

Ptuskin et al. [9] investigated and re-examined some of the physical processes in galactic space, involving in particular the rigidity dependence of the diffusion of cosmic rays through the Galaxy. They applied three different theoretical approaches in the GALPROP code: diffusive reacceleration with damping (called the DRD model); plain diffusion (PD model) with an ad hoc break in the galactic diffusion coefficient and an approach with distributed reacceleration (DR model) and power law diffusion with no breaks. The PD and DR models give a GS with relatively high intensities at low energies, while the DRD model produces a completely different GS, with much lower intensities for $E < \sim 3$ GeV. They also presented modulated spectra at Earth obtained by using a rudimentary force-field modulation model (see the review by Quenby [23]) in comparison with observations. This modulation model is not valid for electron modulation at $E < \sim 1$ GeV because it handles adiabatic energy losses as if electrons are losing as much energy as protons, which is not the case. For a comprehensive illustration of electron modulation including particle drifts, see [21,28].

Webber and Higbie [11] followed up on the work of Ptuskin et al. [9] and used a Monte Carlo Diffusion Model for electron propagation in the Galaxy to calculate alternative electron GS below ~1 GeV. They referred to these GS as interstellar spectra. This was the first attempt to actually compute a LIS (to be compared to Voyager 1 data) instead of simply assuming the GS to be the LIS. They also emphasized that solar modulation effects should be properly handled at these lower energies in the outer heliosphere to reconcile Voyager 1 observations with those at Earth when using computed GS (see also Langner et al. [10]). The force-field model cannot be used for observations in the outer heliosphere where adiabatic energy losses are almost negligible (see e.g., Caballero-Lopez and Moraal [24]). Webber and Higbie [11] calculated several plausible LIS and found most of them lower than the GS from Langner et al. [10]. They also critically evaluated the electron spectra presented by Ptuskin et al. [9] and found them either too high or too low, depending on the energy considered. Three of their spectra, identified as IS2.2, IS2.3 and IS2.4, are basically the same down to ~500 MeV with their IS2.3 spectrum very similar to the GS by [10]. Since both groups utilized observed radio data to improve the spectral shape of these spectra at energies $E < \sim 50$ MeV, it is not so surprising that their spectral forms are more or less similar. However, they computed different differential flux values at these very low energies. Unfortunately, the spectra from [11] were presented only up to 10 GeV, and their final spectra only down to 10 MeV.

Inspection of all the LIS that Webber and Higbie [11] computed or reported on, indicates that some of them are not consistent with