33rd International Cosmic Ray Conference, Rio de Janeiro 2013
The Astroparticle Physics Conference

ICRC 2013

The Solar Modulation of Electrons in the Heliosphere

R.R. Nndanganeni, M.S. Potgieter

Centre for Space Research, North-West University, Potchefstroom, South Africa

rammenu@webmail.co.za

Abstract: The propagation and modulation of electrons in the heliosphere play an important role in improving our understanding and assessment of the modulation process. A full three dimensional numerical model is used to study the modulation of galactic electrons, from Earth into the inner heliosheath over an energy range from 10 MeV to 50 GeV. The modeling is compared with observations of 6-120 MeV electrons from Voyager 1 and observations from the PAMELA mission. Based on the comparison with Voyager 1 observations a new local interstellar electron spectrum (LIS) is calculated. Utilizing this new input spectrum, the modulated spectra at different positions are computed. Studying the radial profile of 12 MeV electrons in the heliosphere enables us to compute the differential intensity of galactic electrons at this energy at Earth. The model can also reproduce the extraordinary increase of electrons in the inner heliosheath. We conclude that the highest differential intensity that galactic electrons can have at Earth at 12 MeV is: 2.5×10^{-1} electrons $\mathrm{m^{-2}s^{-1}sr^{-1}MeV^{-1}}$.

Keywords: Cosmic rays, galactic electrons, heliosphere, heliopause, solar modulation

1 Introduction

The Voyager 1 spacecraft is now about 29 AU beyond the heliospheric termination shock (TS) and might have already crossed the outer boundary of the heliosphere which is normally assumed to be the heliopause. Based on the recent position of the Voyager 1 spacecraft this boundary is set to be at 122 AU in the modulation model. This implies that Voyager 1 could by now already measure the heliopause spectrum for these low energy electrons (6 MeV-120 MeV).

Low energy galactic electrons have become an interesting topic to study since the two Voyager spacecraft crossed the heliospheric TS and moved into the inner heliosheath.

The global features of these low energy electrons as observed by Voyager 1 were predicted by [1,2,7] using comprehensive numerical models. We also illustrate how extraordinary large the modulation of galactic electrons below 100 MeV is in the outer heliosphere. Our contribution follows on the report by [3] on the numerical modeling of galactic electron spectra from Earth to the latest available measurements of Voyager 1 [4].

We use PAMELA electron data observed at Earth during the recent solar minimum period [5]. Determining what the galactic electron intensity is at Earth, is still a challenge since over the first $\sim$20 AU from the Sun the differential intensity of electrons is dominated by Jovian electrons.

From a modeling point of view and utilizing the observed 6-14 MeV radial intensity profile from Voyager 1, we find it to be 2.5×10^{-1} electrons $\mathrm{m^{-2}s^{-1}sr^{-1}MeV^{-1}}$ which is significantly lower than the Jovian electron intensity at Earth. Two alternative radial profiles are also shown.

2 Numerical Model

A full three-dimensional (3D) numerical model is used to compute electron spectra at selected positions in the heliosphere, including the heliosheath. This model is based on the numerical solution of Parkers transport equation [6]:

$$\frac{\partial f}{\partial t} = -(\mathbf{V}+\langle\mathbf{v}_D\rangle)\cdot\nabla f+\nabla\cdot(\mathbf{K}_s\cdot\nabla f) + \frac{1}{3}(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln P}+Q,$$

by utilizing the Alternating Direction Implicit (ADI) scheme and modeling approach as reported by [2,3,7]. Here, $f(\mathbf{r},P,t)$ is the cosmic ray distribution function, t is time, P is rigidity, $\mathbf{r}$ is the position in 3D, with r,θ,ϕ the radial, polar and azimuthal coordinates in a heliocentric spherical coordinate system. Here $\mathbf{V}$ is the solar wind velocity, $\mathbf{v}_d$ is the pitch angle averaged guiding center drift velocity and $\mathbf{K}_s$ is the diffusion tensor. We assume $\frac{\partial f}{\partial t}=0$ which means the contribution of short-term modulation effects [8] is neglected with the focus instead on the global spatial and spectral trends. Terms on the right hand side respectively represent convection, gradient and curvature drifts, diffusion, and adiabatic energy changes, with Q the Jovian electron source function as given by [1,9].

In order to obtain compatibility with the Voyager 1 electron observations from Earth up to the heliopause (HP), a phenomenological approach is followed but influenced by basic diffusion and turbulence theory [10,12,13]. This approach leads us to specify the spatial dependence of the diffusion coefficients differently over the first 80 AU (basically up to the TS region) than in the outer heliosphere. At the same time we specify the rigidity dependence differently above and below 0.4 GV [e.g.,10,11,12]. All the modulation parameters (including the solar wind speed and solar magnetic field) as required to reproduce the Voyager 1 and PAMELA observations are given and motivated by [3].

3 Results and Discussion

In modeling the low electrons (6-120 MeV) the challenge has always been to determine the spectral shape of this low energy galactic spectrum. One of the frustrations is that there are no electron observations at Earth that give pure galactic electrons below 100 MeV. The energy range up to about 500 MeV is a crucial part of the predicted electron

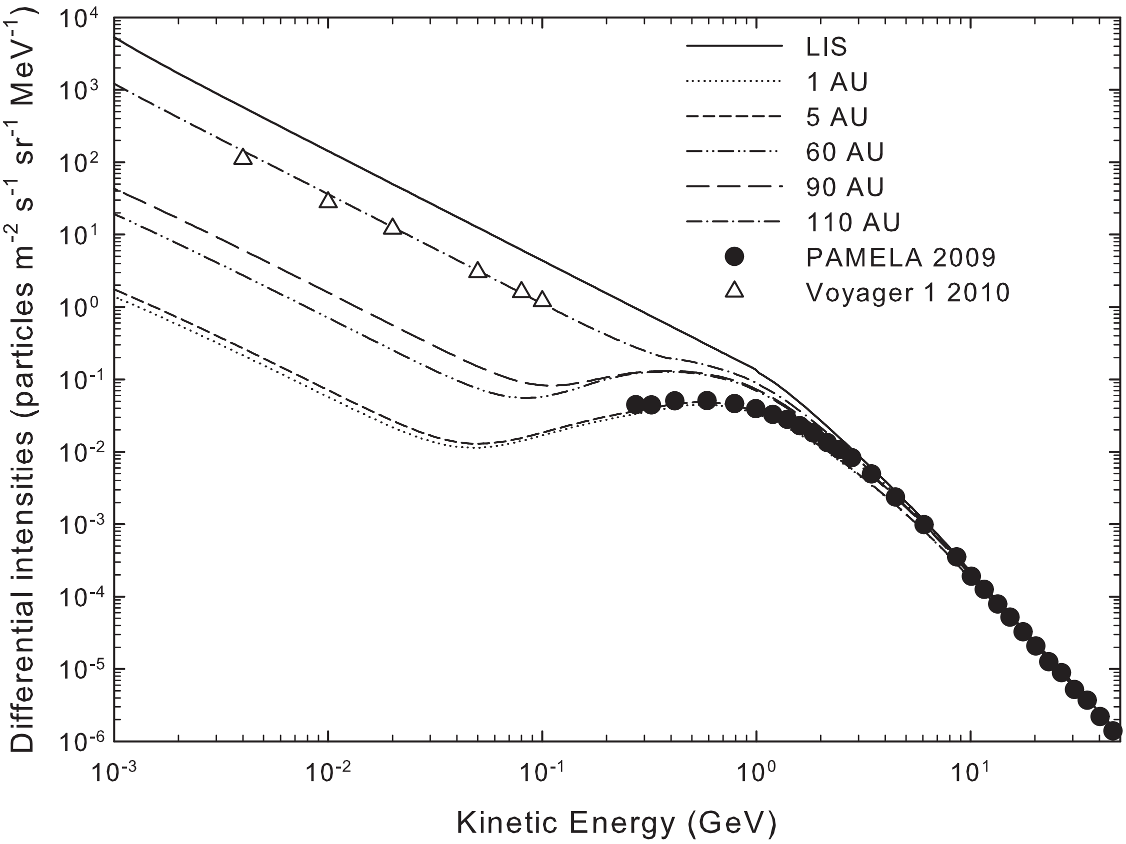

Fig. 1: Computed electron spectra as a function of kinetic energy from the inner to the outer heliosphere. Spectra are shown at 1 AU (Earth), 5 AU, 60 AU, 90 AU and 110 AU (with $\theta = 60°$). The spectra are compared with observations from Voyager 1 obtained toward the end of 2010 and PAMELA (2009 yearly average) at Earth. The LIS is specified at 122 AU.

spectrum where drifts are starting to play an increasing important role (e.g. [10]).

The situation significantly changed from 2010 when Voyager 1 had returned a spectrum for 6-120 MeV electrons. This gives a good indication of what the LIS may look like. Utilizing this observation at low energies and the 2009 electron spectrum from the PAMELA space detector at higher energies, a LIS consisting of two power laws was constructed [3,11] and used in the solar modulation of low energy electrons. The results are shown in figure 1.

This figure shows the modulation of galactic electron from the inner heliosphere to the outer heliosphere, with the spectra computed at 1 AU (Earth) and along the Voyager 1 trajectory at 5 AU, 60 AU, 90 AU and 110 AU. These spectra show how modulation is changing from the inner heliosphere to the outer heliosphere. As shown, there could be relatively little modulation in the middle of the heliosphere but it is significant in the outer heliosphere [4,7]. The 60 AU and the 90 AU spectra are almost the same above a few GeV but deviate from each other at 200 MeV, but remaining relatively close confirming the small gradients in the intensities as discussed by [7]. In this modelled case, there is modulation between 60 AU and Earth but not nearly as much as between 90 AU and 122 AU where the modulation boundary is specified. Shown with the computed spectra are observations from the PAMELA mission at Earth [14], whereas the outer heliosphere observations are from Voyager 1 obtained towards the end of 2010 (Webber, private communication, see also [15]).

It is evident from the figure that the model gives good compatibility with the observations both at Earth and in the outer heliosphere. However, in order to accomplish such a result, the LIS must have a simple power law and the diffusion coefficient must be rigidity independent at these low energies as predicted by turbulence theory; see also [3]. The consequence of this is that below 50 MeV the computed spectra maintain the shape of the LIS throughout the heliosphere. This is in sharp contrast to galactic protons which exhibit a totally different spectral shape at Earth than the proton LIS. The reason is that protons undergo significant adiabatic energy losses so that by the time they reach Earth a typical E^1 spectral slope is obtained. Also, the diffusion coefficients for protons have a different rigidity dependence than electrons below $\sim$1 GeV. Compare [16] to [10] for an illustration of the difference between proton and electron modulation.

Next, we predict the intensity that galactic electrons can have at Earth at energies below 50 MeV. It is a common knowledge that at these energies, within the first $\sim$20 AU from the Sun, Jovian electrons dominate the observed spectra. It is only beyond $r > 40$ AU that galactic electrons may start to dominate [2,9].

Shown in figure 2 are predictions of the galactic elec-

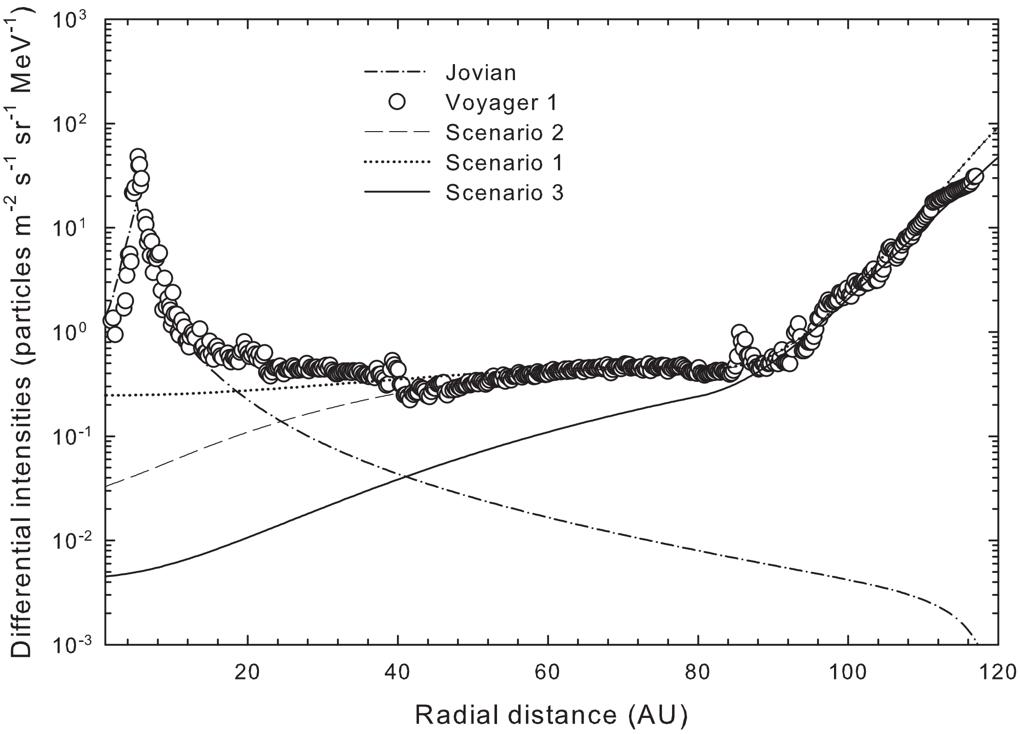

Fig. 2: Computed radial dependence of 12 MeV galactic electrons shown for three scenarios, together with Voyager 1 observations (Webber, private communication) between 6-14 MeV of galactic and Jovian electrons since its launch in 1977. This radial profile is dominated by Jovian electrons up to 20 AU, depending on which scenario is picked, whereas galactic electrons dominate clearly from $r > 80$ AU. The intensity increases in the heliosheath is spectacularly large. According to this figure, the highest possible differential intensity for 12 MeV galactic electrons at Earth is 2.5×10^{-1} $m^{-2}s^{-1}sr^{-1}MeV^{-1}$ which may typically occur during solar minimum modulation conditions.

tron intensity at Earth at these low energies using the observed radial intensity profile of 6-14 MeV electrons [Webber, private communication] as a guideline when constructing three scenarios as shown here. The observations in the middle heliosphere, between 20 AU and 80 AU are still disputable, because the intensity level is close to the threshold energy of the detector which was designed to handle high Jovian electron intensities. It is also known that protons interacting with the spacecraft frame produce secondary electrons which may increase the count rate of electrons so that it maybe incorrect to interpret the reported intensity from 20 AU to 80 AU as galactic electrons.

Using the model, we study the three different scenarios and predict the differential intensity that galactic electrons can have at Earth at this low energies. The predicted flat radial intensity in this figure (dotted line) is a possible scenario, giving the maximum intensity that galactic electrons can have at Earth. The conclusion is therefore made that this predicted differential intensity of 2.5×10^{-1} electrons $m^{-2}s^{-1}sr^{-1}MeV^{-1}$ at 12 MeV is the highest possible intensity for galactic electrons at Earth.

Two other scenarios were also considered as shown in figure 2, together with how the Jovian electron differential intensity decreases away from Jupiter, towards the outer heliosphere. Both scenarios, assuming a stronger radial dependence for the diffusion coefficients, give a much stronger radial intensity gradient toward the inner heliosphere. The second scenario (dashed line) represents at Earth what can be interpreted as probably the lowest galactic electron intensity at 12 MeV: 3×10^{-2} electrons $m^{-2}s^{-1}sr^{-1}MeV^{-1}$, if the observations between 20 AU and 80 AU were considered to be true galactic electrons. However, if observations between 20 AU and 80 AU were regarded as mainly caused by background particles then the intensity value that galactic electrons can have at Earth comes down to: 4×10^{-3} electrons $m^{-2}s^{-1}sr^{-1}MeV^{-1}$.

4 Conclusions

A new LIS is determined for galactic electrons. [See also complimentary reports on this topic at this conference]. When this LIS is used as a heliopause spectrum, the Voyager 1 observations (6-120 MeV) and PAMELA observations (200 MeV to 70 GeV) could be reproduced with our model. See [3,11] for an elaborate report on what diffusion coefficients and what other modulation parameters had to be used to accomplish this feature.

We illustrate that our model can reproduce the remarkably large modulation of galactic electrons below 100 MeV in the inner heliosheath.

The galactic electron intensity below 50 MeV is not known at Earth because of the dominance of the Jovian source electrons at these energies. Studying the radial profile from Voyager 1 of these low energy electrons in the heliosphere, based on the LIS presented here, we predict the differential intensity that galactic electrons may have at Earth. We concluded that the highest differential intensity that galactic electrons can have at 12 MeV at Earth is: 2.5×10^{-1} electrons $\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{MeV}^{-1}$.

Acknowledgment: The authors thank Bill Webber for providing them with Voyager 1 electron spectra. The partial financial support of the South African National Research Foundation (NRF) is acknowledged.

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