The modulation of galactic cosmic-ray electrons in the heliosheath

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***Abstract*. Voyagers 1 and 2 have observed strongly increasing intensities of 2 to 160 MeV electrons since their crossing of the termination shock of the heliosphere, in December 2004 and September 2007 respectively. Before this time these intensities were submerged below the detector background. These increases are large compared to the concurrent increases of positive ions such as H, He, and O, and much of these increases are probably due to temporal effects as the heliosphere was resetting to solar minimum conditions from 2005 to 2008. The observations suggest that these electrons are not freshly accelerated on the termination shock, but that they rather are of galactic origin - and may be re-accelerated by that shock. Because they are relativistic, they are more sensitive to the form of the diffusion coefficient at low rigidities than ions, and it is shown that the spectra can only be understood if (a) below a certain rigidity this diffusion coefficient increases with decreasing rigidity, and (b) if the termination shock (re)-acceleration is weak.**

***Keywords*: cosmic–ray electrons, heliosheath.**

I. INTRODUCTION

In [1] we studied the modulation of galactic cosmic-ray protons and helium nuclei (H and He) throughout the heliosphere. We emphasized the modulation effects in the vicinity of the termination shock (TS) of the solar wind and in the heliosheath beyond this shock. This paper is devoted to the study of the electrons.

The Cosmic-Ray Subsystem (CRS) on Voyagers 1 and 2 measures the intensity of H in the range 1.8 to 300 MeV, He from 1.8 to 650 MeV/n, and electrons from 2.5 to 160 MeV. The high-energy telescope, HET, responds to electrons from 2.5 to 10 MeV, and the electron telescope to electrons from 6 to 160 MeV. Except for periods when there were large fluxes of electrons of Jovian or solar origin, the responses of these telescopes have been dominated by background produced by high-energy protons. However, at about the time when V1 crossed the TS, on 16 December 2004 at 94 AU, the true electron intensity started to emerge above this background. (They were first seen as the so-called TS particle events from $\sim$ 85 AU outward.) This similarly happened around the time of the TS crossing of V2, on 30 August 2007 at 84 AU. By early 2008 V1 had progressed $\sim$ 12 AU into the heliosheath beyond the shock, and it saw strongly increasing electron intensities up to then. The 6 - 14 MeV electron channel, for instance, increased at a rate of $\sim$50% per year. This was accompanied by much smaller increases in the ion intensities. Much of these increases are due to temporal effects as the heliosphere was resetting from solar maximum conditions from 2005 to early 2008, and a major task will be to separate these temporal effects from the spatial ones.

These electrons may originate from several sources. Below $\sim$ 200 MeV, GCR electrons are the source of the lower-energy diffuse gamma and X-ray emission from the galaxy, and may play a major role in ionizing and heating the interstellar medium. These lower-energy electrons are produced as knock-on electrons, as well as directly accelerated primaries and interstellar secondaries from the decay of charged pions. When combined, these processes produce what is called the electron local interstellar spectrum (LIS). This spectrum can be observed through its radio synchrotron emission as described by, e.g., [2], [3] and references therein. Within the heliosphere these electrons are strongly modulated.

The electrons may also originate from acceleration by several processes inside the heliosphere, classified as local processes, such as the TS, traveling interplanetary shocks, or stochastic acceleration in the outer regions of the heliosheath. In this case they should be called anomalous electrons, in analogy to the well-known anomalous cosmic-ray (ACR) component observed for several ion species.

In the inner heliosphere the low-energy electron spectrum is difficult to observe due to its strong modulation and the fact that the intensity at $T < 50$ MeV is submerged below the large electron intensities produced by Jupiter, e.g. [4]. In the outer heliosphere, however, the contamination from Jovian electrons is minimal.

In this paper we note that these electron spectra greatly increase the useful rigidity range available for modulation studies, and it is shown that the 2 - 160 MeV electrons observed by V1 and V2 in the heliosheath are of interstellar, rather than local origin. Their large modulation relative to that of ions, as well as their spectra, can be explained by standard modulation theory, but with two constraints. First, the TS acceleration must be weak, and, second, the diffusion mfp below rigidity $P \sim 100$ MV must increase with decreasing rigidity. Such a form was predicted by the random sweeping model of diffusion by [5].

II. OBSERVATIONS

The left panel of Figure 1 shows 14 - 26 MeV electron intensities on V1 and V2 from 2000 onwards. The TS

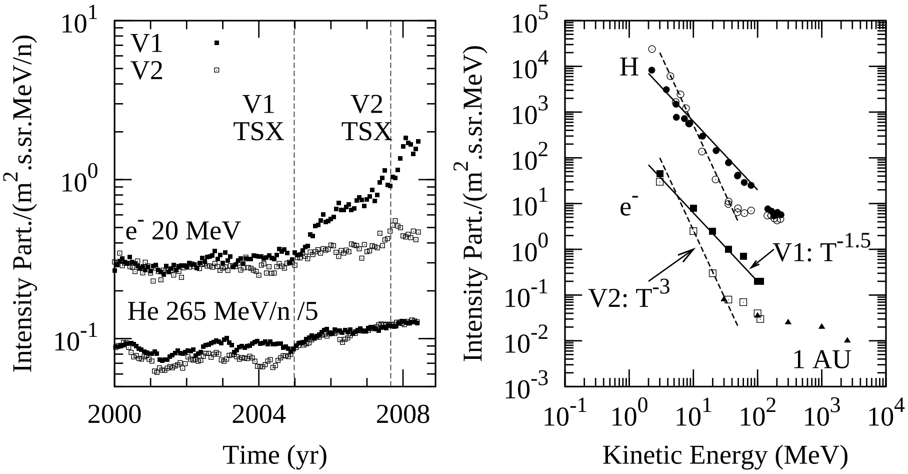

Fig. 1. Left: Intensities of 14 - 26 MeV electrons and 265 MeV/n He as observed by V1 from 2000. TS crossing are indicated. Prior to 2002 the electron channels counted only proton-induced background. Right: Electron and proton spectra observed in the heliosheath by V1 at 104 AU (closed symbols), and by V2 at 84 AU (open symbols), as well as 1 AU spectra during the solar minimum of 1987, from [6] (closed triangles). The straight lines with power law indices of -1.5 for V1, and -3 for V2 observations are drawn to guide the eye.

crossings are marked with vertical lines. As mentioned above, we believe that the intensities prior to about 2002 were dominated by background events, mainly from protons. An important hint in this regard is that the intensities in these electron channels closely track the intensity of $>$ 200 MeV GCRs over the last two solar cycles. There is no indication of different energy or charge-sign dependent modulation effects between these channels, as would be expected, for instance, during the switch-over of the state of the heliospheric magnetic field (HMF) during solar maximum conditions. For comparison, the figure also shows the 265 MeV/n He intensity. This shows the large increase of the electrons relative to these ions.

The right panel of Figure 1 shows spectra of these intensities when V1 was at $\sim$ 105 AU during the first 52 days of 2008, and V2 at $\sim$ 85 AU, almost immediately after its shock crossing, from days 240 to 340 in 2007. It also shows electron observations at 1 AU during the 1986/87 solar minimum, from [6]. These are only shown down to $\sim$ 100 MeV, because at lower energies they are increasingly dominated by Jovian electrons [4]. Notice that the V2 spectrum is significantly softer than that of V1. This is mainly due to a sharp increase of the lowest-energy V2 intensities that started immediately before its shock crossing, and lasted until well into 2008. This seems like a temporal or shock-related effect. For comparison we also show H spectra during the same time intervals. Power laws of the form $j \propto T^{-\gamma}$ are drawn by hand through these observations.

A key feature of these electron spectra is that at $\sim$ 100 MeV the modulation of the V2 intensity at 85 AU is a factor of $\sim$ 100 relative to the presumed LIS. Yet, from 85 AU down to 1 AU, the modulation is quite small. It is shown in the next section that this rather unexpected behavior can be explained with a diffusion coefficient that has the characteristic rigidity dependence of the random sweeping model of [5].

There are three indications that these electrons are not locally accelerated as the low-energy ions are. First, the 2 - 3 MeV H intensities on both Voyagers become essentially independent of time (or radial distance) immediately after the respective shock crossings. This is in stark contrast with the strong increases in the 2.5 - 5.2 and 6 - 14 MeV intensities. Since these H and electron channels have comparable values of βP, and should therefore have similar diffusion coefficients, this difference indicates that they come from different sources. [Note that momentum p, rigidity, P, kinetic energy per nucleon, T, and speed $\beta = v/c$ are related by $P = pc/q = A/Z\sqrt{T(T+2E_0)} = (A/Z)\beta(T+E_0)$, with A and Z the mass and charge numbers respectively, $E_0 = 938$ MeV the rest mass energy of a proton, while E_0 = 0.511 MeV and A = Z = 1 for electrons.] The strong increase in the V1 electron intensities with radial distance therefore favors that they are galactic cosmic rays, although the contribution of the temporal variations to this increase is unknown.

Second, the electron spectra are qualitatively different from those of locally accelerated ACR H and He. According to standard shock acceleration theory e.g. [7], a shock with compression ratio s produces a distribution function $f(p) \propto p^{3s/(1-s)}$ or energy spectrum $j(T) \propto p^{(s-2)/(1-s)}$. Since the electrons in this energy range are relativistic ($p \propto T$), while the ions are not ($p \propto T^{1/2}$), the electron spectral index should be twice as large as for the ions. However, the ACR H spectra in Figure 1 clearly have indices similar to those of electrons, namely -1.5 for V1, and -3 for V2.

Third, in the left panel of Figure 2 we compare the large increases in the electron intensities observed by V1 in the heliosheath with the smaller increases

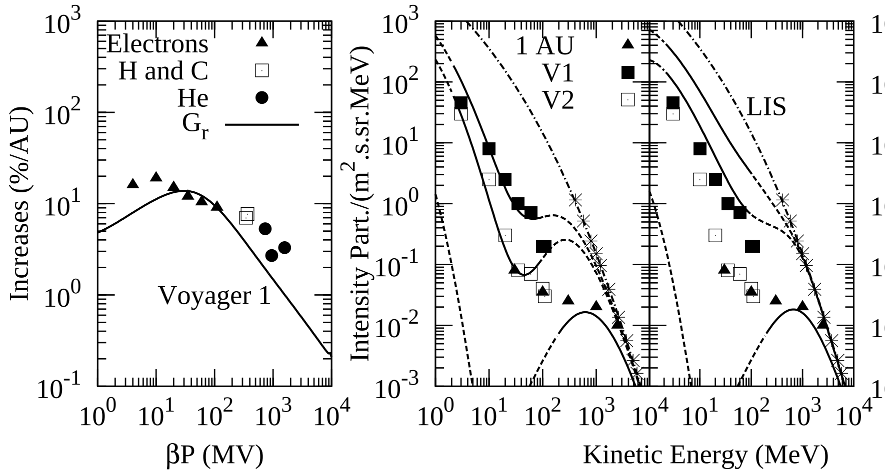

Fig. 2. Left: Increases of electron, proton, helium and carbon intensities observed by V1 in the heliosheath, as function of βP, from Jan./Feb. 2005 when the spacecraft was at 94 AU immediately past the shock, to Jan./Feb. 2008 when it was at 104 AU. Data points for C, O, as well as the outer two He points are from [8]. The curve is the calculated radial gradient, G_r, described in the text. Middle and Right: Fit to the observed spectra with the parameters described in the text. Solutions are shown in full lines in the interval where there are observations; outside this interval the solutions are continued as dashed lines. In the left and middle panels the compression ratio of the shock is $s = 1$, while in the right panel it is $s = 2.5$. LIS observations, from [9], are shown by stars.

observed in the ion intensities. This figure shows the quantity $G = 100 \times \ln(j_{08}/j_{05})/(r_{08} - r_{05})$, where '05' indicates January/February 2005, immediately after the shock crossing at $r_{05} \approx 94$ AU, while '08' indicates January/February 2008, with $r_{08} \approx 104$ AU. If the heliosphere was in a steady state, G would be a radial gradient. In reality there were significant temporal increases in the intensities during this time period, and therefore G is an unknown mixture of both. These increases are shown as function of βP because the diffusion coefficients and drift drift velocity are approximately proportional to this quantity (or a modification thereof). The figure shows a smooth ordering of these increases of the different species with βP, which suggests that they are of the same origin, and that they respond to the same modulation changes. When plotted against rigidity P alone, there is a disjunct gap between the ions and the electrons. Thus we propose that the inverse of this βP dependence indicates the rigidity dependence of the diffusion coefficients, i.e. approximately $\propto \beta P$ at high rigidities, gradually flattening off below $\beta P \approx 100$ MV. Therefore, from their spectral form, their increase with distance into the heliosheath, and the systematic ordering of these increases with those of the ions, we conclude that the 2 - 160 MeV electrons are of galactic origin. We next show that their intensities and spectra can be explained quantitatively by the same model as that for GCR nuclei, provided that the TS acceleration is weak.

III. Numerical solution of the cosmic-ray transport equation

The modulation is studied with the numerical solution of the cosmic-ray transport equation for the cosmic- ray distribution function, $f(\mathbf{r}, p, t)$,

$$\frac{\partial f}{\partial t} + \mathbf{V}\cdot\nabla f - \nabla(\mathbf{K}\cdot\nabla f) - (\frac{1}{3})(\nabla\cdot\mathbf{V})\frac{\partial f}{\partial \ln p} = Q, \quad (1)$$

where $\mathbf{V}$ is the solar wind velocity, and K the diffusion tensor with elements describing diffusion along and perpendicular to the field, as well as gradient, curvature, neutral sheet and shock drifts. The model has a shock at r_s = 90 AU, and an outer boundary at r_b = 150 AU. We let $\mathbf{V}$ and K drop a factor of s at the shock, while the HMF increases by that value. $\mathbf{V}$ increases from 400 to 800 km/s from the ecliptic plane to the poles. The solution is run for the so-called qA > 0 drift cycle (because electrons are negatively charged), with a neutral sheet tilt angle of 30°. These parameters are generally the same as in the model used by [1] to explain the modulation of GCR H and He.

The most significant difference is the rigidity dependence of the diffusion mfp. The radial dependence of the intensities is effectively determined by the radial mfp $\lambda_{rr} = \lambda_{\|}\cos^2\psi + \lambda_{\perp}\sin^2\psi$, and since ψ is large for $r >> 1$ AU, the modulation is dominated by perpendicular diffusion. Here, as in [1], we assume $\lambda_{\perp} \propto \lambda_{\|}$, and that the latitudinal mfp $\lambda_{\theta\theta} = \lambda_{\perp}$. In [1] we used the simple form $\lambda_{rr} \propto P$. Here we extend this to a double power law of the form

$$\lambda_{rr} = \lambda_0[(P^a + P_k(r)^a]^{[(\gamma_1-\gamma_2)/a]}P^{\gamma_2} \quad (2)$$

For $P >> P_k$ this has the form $\lambda_{rr} \propto P^{\gamma_1}$, while for $P << P_k$ it is $\lambda_{rr} \propto P^{\gamma_2}$. Parameter a governs transition sharpness, with sharp transitions for $a >> 1$. Figure 3 shows this function for $\gamma_1 = 1$, $\gamma_2 = -0.5$, $a = 1.5$, and $P_k(r) = 200/[r(\mathrm{AU})]^{0.3}$ MV.

The main reason for this refinement is that the electrons are sensitive to much lower rigidities than the nuclei:

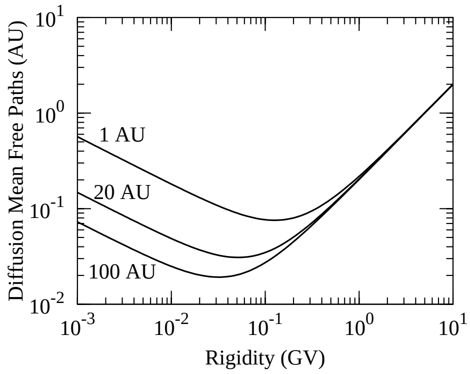

Fig. 3. The rigidity dependence of the diffusion mfp used to explain the observed electron spectra. This rigidity dependence is a function of radial distance as in (2), and the upturn below the kink is characteristic of the random sweeping model of [5].

Figure 2 (left) shows that in our study of the nuclei in [1], we were limited to the range $400 < \beta P < 2000$ MV. With the electrons added, this range is now greatly extended to $4 < \beta P < 2000$ MV.

We use the following LIS for the electrons

$$j_{\rm lis} = 0.5T^{-3.22}; T > 10 \quad {\rm GeV}$$

$$j_{\rm lis} = 0.15\left[\frac{T^{0.3}+1.5^{0.3}}{1+1.5^{0.3}}\right]^{-13.66} T^{-0.4}; T < 10 \quad {\rm GeV} \tag{3}$$

The results of the fit, with the mfp of Figure 3, are shown in Figure 2. The calculated spectra in the middle and right panels are shown in full lines for the kinetic energy interval in which observations are available. Outside this interval they are continued as dashed lines. The radial gradient calculated in the left panel is given by $G_r = 100 \times \ln(j_{r2}/j_{r1})/(r_2 - r_1)$, with r_1 = 94 AU and r_2= 104 AU, the positions of V1 in 2005 and 2008. In the left and middle panels the shock compression ratio was set at $s = 1$, while in the right-hand panel it is $s = 2.5$.

IV. Discussion and Conclusions

The spectral fit in the left and middle panels of Figure 2 demonstrate that the basic features of electron modulation in the outer heliosphere can be understood. First, the LIS for this fit is nearest to the spectrum of [2] and the 'polar approach' of [3]. Second, and more important, the diffusion mfp of Figure 3 is required to make the radial gradient between the V2 and 1 AU intensities at ~ 100 MeV as small as possible. We could only achieve this with mfps that increase with decreasing rigidity as in the random sweeping model of dynamical turbulence by [5]. Dynamical turbulence alters the scattering rate through 90° relative to static (slab) turbulence in such a way that low-energy nuclei experience enhanced scattering, while the same low-energy (but still relativistic) electrons experience less scattering. In the random-sweeping model of this dynamical turbulence, the low-energy electron mfp increases significantly with decreasing rigidity. The observations also require that the rigidity below which this mfp increases must decrease with radial distance. The reason is that there must be strong modulation (large gradients) in the outer heliosphere, with weaker modulation (smaller gradients) inside the TS. We note that [4] used a similar rigidity dependence for λ_{rr}, but with the different radial dependence.

The most important outcome of this study is that the simulations in the left and middle panels of Figure 2 were achieved with shock compression ratios $s = 1$, which means that there is no TS acceleration. The right-hand panel shows that if a reasonable value $s = 2.5$ is used, both the V1 and V2 intensities are far too high. This happens because the TS readily re-accelerates the abundantly available low-energy electrons in the (presumed) low-energy LIS, which increases strongly with decreasing kinetic energy. We could not avoid this consequence of TS acceleration with many variations of the parameters. The only way that we can see to affect a large decrease in the calculated V1 and V2 intensities below about 1 GeV, is to lower the LIS drastically from 1 GeV downwards, but in view of the observations (the stars in Figure 2) this is not possible.

Low-energy nuclei are mush less sensitive to this TS acceleration constraint because (a) adiabatic cooling is stronger, and (b) their LISs naturally flatten off due to ionization losses in the galaxy, so that there are much fewer low-energy particles available for re-acceleration at the TS.

We therefore conclude that the electrons observed in the heliosheath have opened up a very useful new window on the modulation and acceleration process in the outer heliosphere. This places new constraints on the modulation and acceleration.

V. Acknowledgments

This work was supported by NSF grant ATM 0107181, the South African National Research Foundation, and PAPIIT-UNAM grant IN108409.

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