UNUSUAL COSMIC RAY MeV ELECTRON INTENSITY CHANGES OBSERVED AT VOYAGER 1 BEYOND 107 AU IN THE HELIOSHEATH: A BOUNDARY CROSSED?

W.R Webber[1], F.B. McDonald[2], A.C. Cummings[3], E.C. Stone[3], P.R. Higbie[4], B. Heikkila[5] and N. Lal[5]

1. New Mexico State University, Department of Astronomy, Las Cruces, NM, 88003, USA
2. University of Maryland, Institute of Physical Science and Technology, College Park, MD, 20742, USA
3. California Institute of Technology, Downs Laboratory, Pasadena, CA 91125, USA
4. New Mexico State University, Physics Department, Las Cruces, NM, 88003, USA
5. NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

ABSTRACT

We believe that V1 passed a significant "boundary" in the heliosheath at 2009.7 at a distance of 111 AU from the Sun. This conclusion is based on the fact that the low energy 6-14 MeV galactic electron intensity suddenly increased by ~20% over a time period ≤ 10 days and the electron radial intensity gradient abruptly decreased from ~18%/AU to ~6%/AU at that time. For over a year prior to 2009.7 and for over a year after that time the electron intensity increased smoothly with day to day variations 2-3% consistent with statistical variations and the above measured gradients were constant during each time period. Because of the suddenness of the intensity jump, this region beyond 111 AU appears to be poorly connected to the inner region in a propagation sense. This sudden change in gradient can be explained by (1) a sudden change by a factor ~3.0 in the local diffusion coefficient that describes the electron modulation in the heliosphere; (2) a sudden change in the convective speed or direction of the solar wind plasma. A candidate for a boundary or structure of this magnitude could be a magnetic wall as described by Washimi, et al., 2010. Their calculations place this magnetic wall ~8-18 AU inside the heliopause. If this is indeed the "boundary" passed by V1 then this provides an estimate of the heliopause distance at between 119-129 AU in the V1 direction at that time. Of course Mother Nature could be fooling us again and the boundary we observe could be part of a heliopause structure itself, such as the folding back of the heliosphere current sheet structure and the changing solar wind flow patters expected near the heliopause (e.g., Pogorelov, et al., 2010; Borovikov, et al., 2011). In any case this "boundary" is not likely to be the heliopause itself since there is still a significant positive electron gradient beyond 111 AU.

Introduction

From several points of view the study of cosmic ray electrons (≤100 MeV) has historically been an enigma. From the modulation point of view these electrons with their low rigidity, high speed and relatively steep energy spectrum behave quite differently than higher energy electrons and nuclei. In particular they respond directly to the diffusion coefficient that determines their propagation or modulation. Also these electrons are the low energy tail of the galactic cosmic ray electron spectrum whose intensity can be estimated from the galactic radio-synchrotron intensity and spectrum. Comparisons of the measured electron intensities near the Earth in this low energy range with those estimated to exist in the nearby galaxy to produce the radio synchrotron emission suggest an intensity difference of a factor $\sim 10^2$-10^3 that must be accounted for by solar modulation, a much larger factor than expected for higher rigidity nuclei.

The CRS electron experiment on Voyagers 1 and 2 measure electrons in the energy range 6-120 MeV and is well suited for the study of these electrons and how the intensities measured near the Earth evolve into those estimated to exist in the LIM (Stone, et al., 1977).

This involves measuring the electron intensity at V1 and V2 as they move outward through the heliosheath to the heliopause (HP). At the HP the intensity is usually assumed to be equal to that in the LIM. So the important parameters to be determined are: 1) The electron intensity near the location of the HTS, and 2) The electron intensity at the location of the HP.

The intensity at the HTS and the HTS distance have already been determined by V1 and V2 as they move outward to their present locations of 116 and 95 AU respectively at 2011.0. The HTS distance is between 84 (V2) and 94 (V1) AU and the intensity at this location is roughly the same as measured at the Earth (McDonald, et al., 2006). So most of the increase in the electron intensity necessary to reach the estimated LIM value must occur in the heliosheath.

Indeed V1 has measured large radial intensity gradients of electrons beyond the HTS, however, these large radial gradients are not yet seen at V2 (McDonald, et al., 2006; Caballero-Lopez, et al., 2009). Until recently the electron gradient that is determined for V1 beyond the HTS has been very irregular, possibly because of transients moving outward through the heliosheath. This has made it difficult to extrapolate the electron intensity increase beyond the HTS outward to determine the intensity at the location of the HP.

After about 2008.5, when V1 was at least 12 AU beyond the HTS and at a time when the last outward major interplanetary transients from SC #23 had propagated beyond the modulation region, the electron intensity starts a smooth regular increase which continues for over a year, corresponding to ~4 AU of outward movement. At that time (2009.70) a sudden intensity increase ~20% occurs, followed by another time period of smooth regular increase, still continuing at 2011.0, but corresponding to a much smaller radial gradient. It is this later sequence of events, possibly indicating the passage of V1 through a barrier or a boundary in the outer heliosheath into a region of different propagation that we wish to discuss in this paper.

The Data

The 5-period running average of the daily intensities of 6-14 MeV electrons at V1 and V2 from the time that V1 crossed the HTS in late 2004 is shown in Figure 1. It is seen that the V1 intensity increases, more or less continuously from a low value, which has a significant background, to a value at the beginning of 2011 that is >40 times the initial intensity. The V2 intensity shows several large increases, at least one of which, starting at 2007.6, may be due to the acceleration of these electrons near to or just beyond the HTS crossing which occurred at 2007.66. The overall V2 electron intensity at 2011.0, when V2 is ~10 AU beyond where it crossed the HTS, is still ~2 times the electron intensity just before the shock crossing. It would be prudent not to use the V2 data to attempt to determine a radial gradient between V1 and V2. Conditions at -27.5° where V2 crossed the shock must be greatly different than at +34° where V1 crossed the shock.

At V1 for the first 3.5 years after the shock crossing it is difficult to determine a unique radial gradient from the V1 data itself because of the intensity oscillations or transient variations. Most of these temporal variations are time coincident with transient decreases of >70 MeV galactic cosmic rays (GCR) (Webber, et al., 2009). These GCR decreases could be caused by the largest IP shocks as they propagate beyond the HTS, through the heliosheath, ultimately reaching the HP (Webber, et al., 2007, 2009; Washimi, et al., 2010). A simple average of the 6-14 MeV electron radial gradient between 2005.5-2008.5, during a time in which the intensity increased by a factor of ~5, would lead to an average radial gradient G_r, defined as $G_r = (r_2 - r_1)^{-1} \cdot \ell n\ (J_2/J_1)$ where J_2/J_1 are the intensities at radii r_2, r_1; of ~53%/year or about 15%/AU (see also McDonald, et al., 2006).

After about 2008.5 the rate of increase in 6-14 MeV electron intensity becomes smoother and more regular. This time period is shown in expanded form in Figure 2. From 2008.5 – 2009.7 (4.3 AU in distance) this total increase of 2.20 ±0.20 corresponds to a radial gradient of 65 ±7%/year or 18.3 ±1.5%/AU. At 2009.7 (111.0 AU) the electron intensity suddenly increases by ~20% in a time period ≤10 days after which it resumes a smooth regular increase. This increase after 2009.72 is a factor of 1.34 ±0.10 over a period of 4.7 AU to 2011.0 which corresponds to a radial gradient of 22.5 ± 2%/year or 6.3 ± 0.6%/AU.

The average radial gradient after 2009.72 is thus only 0.34 that in the earlier time period from 2008.5 to 2009.7. We believe that V1 has crossed a "boundary" or "barrier" in the outer heliosheath in which the propagation conditions have changed dramatically at this time. This is discussed in more detail in the following section.

This jump in electron intensity at 2009.70 is seen in other electron channels in the energy range of 2.5-120 MeV covered by the V1 instrument, most notably the 14-26 MeV channel. Here we concentrate on the 6-14 MeV channel because of its better statistics (2-3% variations on a day to day basis).

Discussion of the Electron Radial Gradients after 2008.5 and the Sudden Intensity Change at 2009.70

Conditions in the outer heliosheath just inside the HP are not well known. However, a significant step in understanding this regime has been made recently by Pogorelev, et al., 2009; see also Washimi, et al., 2010. Pogorelov, et al., 2009, and more recently Borovikov, et al, 2011, have modeled a HCS of constant tilt as it propagates in the supersonic solar wind upstream of the HTS and then beyond the HTS into the heliosheath. These calculations show that the latitude extent of the HCS rapidly increases as the boundary between the solar wind and the interstellar medium (the HP) is approached and the solar wind flow diverts to carry the plasma down the heliotail. V1 would be expected to enter this new region of solar wind flow just prior to crossing the HP.

Using a computer intensive 3D MHD model of the heliosphere with emphasis on the heliosheath, Washimi et al., 2010, have identified at least one possible major structure in the outer heliosheath that lies between 8-18 AU inside of the HP taken to be at 142 AU in their model. This structure is called the "magnetic wall". It appears to have characteristics that could

provide a sudden jump in electron intensity and a change in radial intensity gradients inside and outside of the wall as the effective diffusion coefficient changes. The distance between the HP and the magnetic wall will indeed change with time over the 11-year solar cycle. If we assume that the observed "boundary" is the magnetic wall then according to the calculations by Washimi, et al., 2010, V1 is at that time (2009.7) between 8-18 AU inside the HP. Or in other words, the HP is at a distance of between 119-129 AU at that time.

Recent magnetic field from Voyager 1 (Burlaga and Ness, 2010), shows a large spike in the total magnetic field intensity at exactly 2009.70. This spike has a peak magnitude ~0.3 nT, 3-5 times the average value and the spike has a duration ~10 days. It is near the onset of a period when the field direction suddenly changes by 180° from 90° (negative) to 270° (positive). The duration of the 270° field lasts for over 100 days. The 90° field direction is what is expected at latitudes above the HCS. These are the most prominent features seen in the magnetic field at V1 since it crossed the HTS almost 5 years earlier

In what follows we seek a further understanding of this sequence of events using the electron data itself and other observations from the CRS experiment on V1. In Figure 3 we show the same data as in Figures 1 and 2, but now plotted vs. the V1 distance in AU, each axis on a much expanded scale. The solid circles are the electron intensities averaged in 1 AU increments. We now seek to reproduce radius-intensity profile in Figure 3 using a very simple modulation model describing the electron intensity in the heliosphere. This is a spherically symmetric model with several radial zones, the zone beyond 111 AU being well separated from the inner zones. We note that, in a simple diffusion-convection model as is commonly used to describe cosmic ray modulation of electrons and nuclei in the heliosphere, the radial gradient $G_r=CV/K_{rr}$, where G_r is the radial gradient, C is the Compton-Getting factor, V is the radial solar wind speed and K_{rr} is the radial component of the diffusion coefficient. At 2009.7 we observe that the radial gradient suddenly decreased by a factor ~3.0 as noted earlier. If this change is attributed to a change in K_{rr} then the increase in K_{rr} is a factor of 3.0.

The model we use is a spherically symmetric quasisteady state no drift transport model for cosmic rays in the heliosphere (e.g., Gleeson and Urch, 1971). This model has also been used by Jokipii, Kota and Merenyi, 1993, and the numerical model was originally provided to us by Moraal, 2003, as described in Reinecke, Moraal and McDonald, 1993. Further details of this

model as it has been applied to the recovery of cosmic ray Helium nuclei from 2004-2010, at the Earth and V1 and V2 beyond the HTS are described in Webber, et al., 2011. For spherical symmetry (and considering latitude effects to be unimportant for this application) the diffusion in each radial zone then becomes a single radial coefficient, K_{rr}. We have assumed that this coefficient is separable in the form K_{rr} (r,P)=βK_1 (P)$\cdot K_2$(r) where the rigidity part K_1(P) = K1 and the radial part K_2 (r) = K2. The rigidity dependence of K(P) is assumed to be ~P above a low rigidity P_0 and ~P^{-1} below P_0 here taken to be between 140-200 MV.

The heliosphere is considered to be a multi-zone heliosphere radially. The inner zone extends to 90 AU, the average distance of the HTS, the middle zone (the inner heliosheath) from 90-111 AU and the outer zone from 111 AU to a variable outer boundary which is taken from 120-130 AU (the HP). The outermost region is assumed to be disconnected from the inner regions. In the inner zone, K1=140 in normalized units of $4.38 \cdot 10^{20}$ $cm^{2} \cdot s^{-1}$, K2=1 and the radial solar wind speed = 1.0 in normalized units of 400 $km \cdot s^{-1}$. In the middle zone, K1H = 10.5, K2=1 and V_r = 0.333. In the outer zone, to match the observed increase in the radial gradient, G_r, K1H2 = 31.5, K2 = 1 and V is still 0.333. These values of K1 and K1H and V in the inner zones provide a good fit to the intensity vs. time changes in the 150-250 MeV/nuc Helium data between 2004-2010 at the Earth, V1 and V2 (See Webber, et al., 2010).

For the input electron spectrum we take

$$\text{Electron FLIS} = 0.000350/ (T^{3.10})/(0.20+1.15/T^{0.03}) + 1.60/(T^{1.80})$$

where T is in GeV. This is the “low” interstellar electron spectrum that gives the best fit to the lower frequency galactic radio spectrum from the work of Webber and Higbie, 2008, on electron propagation in the galaxy.

The calculated 6-14 MeV electron intensity as a function of radius in the heliosheath from 100-130 AU using the above parameters is shown as the solid line in Figure 4. Beyond ~111 AU these parameters produce a radial gradient ~6.5%/AU increasing slightly as R_B=130 AU is approached. Inward from 110 AU these parameters produce a radial gradient=18.5%/AU between 105-110 AU. This gradient decreases as the HTS at 90 AU is approached. This is because of the much larger diffusion coefficient in the inner heliosphere. These gradients are almost identical to those observed.

The difference of a factor of ~10 in K_{rr} between the inner and outer zone (K1=140, K1H=10-20) is required to explain the He data between 2004-2010 as described in Webber, et al., 2011. In effect K_{rr} is so much smaller beyond the HTS, that the inner heliosheath can indeed be described as a diffusing barrier in this simple model and at this time in the solar 11-year cycle (minimum modulation, qA-solar cycle).

It is possible to "detect" this sharp boundary using electrons because of their low rigidity, ~10 MV. As a result their radius of curvature, r_c, in the local magnetic field is small compared with the scale of the intensity jump itself which is ≤0.1 AU for a V1 transit time ≤ 10 days. For higher rigidity GCR where the values of r_c approach ~1.0 AU this intensity jump may be smeared over several AU and not as easily observable but is still seen (see Webber, et al., in preparation). This sharp boundary also requires the outermost region to be "disconnected" from the inner regions.

The fit between the data and calculations between 100 and 111 AU is striking in view of the simplicity of the model. We note that corresponding changes in the magnitude of the radial solar wind speed, V_r can produce changes in G_r, which are similar.

Also note that, since the assumed input LIS electron intensity at R_B =130 AU produces a radial intensity profile of 6-14 MeV electrons that closely matches the observed profile out to 116 AU, the calculated electron intensities at radii beyond 116 AU would be the LIS intensities if the HP were located at these distances.

Summary and Conclusions

After crossing the HTS in late 2004, the 6-14 MeV (galactic) electron intensity measured at V1 began to increase rapidly and irregularly. By about 2008.5 this intensity was at least 10 times that measured when V1 crossed the shock.

After about 2008.5 the electron intensity at V1 continued to increase rapidly but now much more smoothly so that a more accurate local radial intensity gradient could be determined. This average gradient was found to be ~18.5±1.5%/AU until about 2009.7 (111.2 AU) when the electron intensity suddenly increased by ~20% over a period ≤10 days. After that the intensity continued its smooth increase, but now corresponding to a much smaller radial gradient of 6.5 ± 0.5%/AU, which has continued to the present day (2011.0), when V1 is approaching 116 AU.

We believe that this sudden change in intensity and gradient is evidence that V1 crossed a "barrier" or a boundary at 2009.7 at which point the radial gradient decreased by a factor ~3.0. This could be explained, for example, if the diffusion coefficient increased by a factor ~3.0 within the framework of a simple diffusion convection modulation model in which the gradient is defined as $G_r=CV/K_{rr}$. If one adopts this explanation for the gradient change then a simple spherically symmetric modulation model with the diffusion coefficient changing by a factor ~3.0 at 111 AU in an outermost region not well connected with the inner conventional modulation region, accurately reproduces the observed 6-14 MeV electron intensity increase between ~105-116 AU (2008.0-2011.0) using a LIS electron spectrum input at 130 AU with an intensity = 8.56 x 10^{-3} e/cm^{2}·s·sr·MeV at 10 MeV. The change in K_{rr} required to produce the observed electron intensity changes is substantial, indicating that a major boundary has been crossed. This picture is consistent with the V2 magnetic field data which shows a large transient field increase which reaches a maximum value ~3-5 times the mean field at exactly the same time the gradient changes and also a polarity change from 90° to 270° (Burlaga and Ness, 2010).

This boundary could be the "inner part" of an extended heliopause structure itself and perhaps compatible with the recent observations of the solar wind plasma which show that the radial solar wind speed approaches zero in 2010 (Decker, et al., 2010) and also with descriptions of the extent of the HCS fold back, accompanied by a plasma flow directed towards the tail of the heliosphere just inside the HP as described by Pogorelov, et al., 2009 and Borovikov, et al., 2011. In this case V1 has entered this region of plasma flow toward the tail, a region which extends to the heliopause itself in their model.

REFERENCES

Borovikov, S.N., N.V. Pogorelov, L.F. Burlaga and J.D. Richardson, (2011), Plasma near the heliosheath: Observations and modeling, Ap.J. Lett., 728, 1-5

Burlaga, L.F. and N.F. Ness (2010), Sectors and large scale magnetic field strength fluctuations in the heliosheath near 110 AU: Voyager 1, 2009, Ap.J., 735, 1306-1316

Caballero-Lopez, R.A., H. Moraal and F.B. McDonald, (2010), The modulation of galactic cosmic ray electrons in the heliosheath, Ap.J., 725, 121-127

Decker, R.B., et al., (2010), Low-energy charged particles at Voyagers 1 and 2 10-20 AU into the heliosheath, AGU, Fall Meeting, abstract #SH23D-02

Gleeson, L.J. and I.A. Urch, (1971), Energy losses and the modulation of galactic cosmic rays, Astrophys. Space Sci., 11, 288-308

Jokipii, J.R., J. Kota and Merenyi, (1993), The gradient of galactic cosmic rays at the solar wind termination shock, Ap. J., 405, 753-786

McDonald, F.B., et al., (2006), Voyager observations of galactic and anomalous cosmic rays in the heliosheath, AIP Conf. Proc., 858, 71, eds. Heerikhuisen, Florinski, Zank and Pogorelov

Pogorelov, N.V., S.N. Borovikov, G.P. Zank and T. Ogino, (2009), Three dimensional features of the outer heliosphere due to coupling between the interstellar and interplanetary fields; The wavy heliospheric current sheet, Ap.J., 696, 1478-1490

Reinecke, J.P.L., H. Moraal and F.B. McDonald, (1993), The cosmic radiation in the heliosphere at successive solar minima: Steady state no-drift solutions of the transport equations, J. Geophys. Res., 98, (A6), 9417-9431

Stone, E.C., et al., (1977), Cosmic ray investigation for the Voyager missions: Energetic particle studies in the outer heliosphere – and beyond, Space Sci. Rev., 21, 355-376 doi: 10.1007/BF00211546

Washimi, H., G.P. Zank, Q. Hu and T. Tanaka, (2010), Realistic and time-varying outer heliospheric modeling by three-dimensional MHD simulation, Ap.J., (submitted 2010)

Webber, W.R., A.C. Cummings, F.B. McDonald, E.C. Stone, B. Heikkila and N. Lal, (2007), Passage of a large interplanetary shock from the inner heliosphere to the heliospheric termination shock and beyond: Its effects on cosmic rays at V1 and V2, Geophys. Res. Lett., 34, L20107, doi:10.1029/2007GL31339

Webber, W. R. and P. R. Higbie, (2008), Limits on the interstellar cosmic ray electron spectrum below ~1-2 GeV derived from the galactic polar radio spectrum and constrained by new Voyager 1 measurements, J. Geophys. Res., 113, A11106, doi:10.1029/2008JA013386

Webber, W.R., A.C. Cummings, F.B. McDonald, E.C. Stone, B. Heikkila and N. Lal, (2009), Transient intensity changes of cosmic rays beyond the heliospheric termination shock as observed at Voyager 1, JGR, 114, A07108, doi:10.1029/2009JA014156

Webber, W.R., F.B. McDonald, P.R. Higbie and B. Heikkila, (2011), Recovery of 150-250 MeV/nuc cosmic ray helium nuclei intensities between 2004-2010 as measured near the Earth, at Voyager 2 and also in the heliosheath (Voyager 1), Pre-print Arxiv

FIGURE CAPTIONS

Figure 1: The 5-day running averages of the 6-14 MeV electron intensities measured at V1 and V2 from 2005.0 to 2011.0. V1 crossed the HTS at 2004.96 at a distance of 94.0 AU and V2 crossed at 2007.66 at a distance of 83.7 AU.

Figure 2: The 5-day running average of the 6-14 MeV electron intensities measured at V1 from 2008.5 to 2011.0 (V1 distance = 106.7 to 115.7 AU). The sudden intensity increase of ~20% at 2009.70 (111.2 AU) and the change in radial gradients before and after this increase are clearly evident.

Figure 3: The V1 data in Figure 1 plotted as a function of the V1 distance in AU. The solid circles represent the average intensities in 1AU increments from 107 to 116 AU.

Figure 4: The calculated 6-14 MeV electron intensity between 100-130 AU using a simple spherically symmetric multi-zone modulation model. The intensity at the HP location of 130 AU is taken to be 86 particles/m2.sr.sec-MeV as obtained from a LIS spectrum. The radial diffusion coefficients are K1H= 10.5 in the middle zone from 90-111 AU and K1H2 = 31.5 in the outermost zone from 111 to 130 AU. The solid red dots are the 26d average electron intensities.