Voyager Observations of Galactic Ions and Electrons in the Heliosheath

F.B. McDonald*, **E.C. Stone**†, **A.C. Cummings**†, **W.R. Webber**‡, **B.C. Heikkila**§ **and N. Lal**§

Institute for Physical Science and Technology, University of Maryland, College Park, MD, USA
†*California Institute of Technology, Pasadena, CA, USA*
‡*Department of Physics and Astronomy, New Mexico State University, Las Cruces, New Mexico, USA*
§*NASA/Goddard Space Flight Center, Greenbelt, MD, USA*

***Abstract*. Voyager observations of galactic cosmic ray ions and electrons in the heliosheath now extend from 2004.96 to 2009.2, covering a significant part of the cycle 23 recovery from near solar maximum to solar minimum conditions. While the radial intensity gradient of 265 MeV/n GCR He in mid-2008 was 0.1 ± 0.2 %/AU, its rate of intensity increase since mid-2006 has been 7.4 %/year. The rate of increase for lower rigidity GCRs (200 MeV/n He, 260 MeV H) is even higher. 10 MeV electrons are increasing at a rate of 60% a year over the same period, strongly supporting a galactic origin for this component. For GCR ions the increase appears to be mainly temporal while for electrons the increase is both temporal and spatial. This continuing increase in cosmic ray intensity may be in part related to the reduced magnetic field strength observed in the inner heliosphere. A comparison of the changes of the GCR ions and electrons suggest that the galactic component may not enter near the nose of the heliosphere but at the flanks or in the tail region.**

***Keywords*: Galactic cosmic rays, Anomalous cosmic rays, Termination shock**

I. Introduction

The structure and dynamics of the distant heliosphere reflect the dynamic interplay between the out-flowing supersonic solar wind and the local interstellar medium (LISM). Near 100 AU where the pressure of the expanding solar wind approaches that of the LISM, the solar wind undergoes an abrupt transition through the formation of a large standing shock, the heliospheric termination shock (TS). In the heliosheath the suddenly heated and decelerated solar wind will flow around the TS forming an extended helio-tail produced by the relative motion of the solar system with respect to the LISM (cf. [1]). The heliosheath near the nose of the heliosphere is expected to be 30-50 AU thick [2]. Galactic cosmic rays will be modulated as they traverse the heliosheath and may experience modest re-acceleration crossing the TS [3], [4], [5].

The energetic particle population expected to dominate at the TS shock were anomalous cosmic rays. These predominantly singly-charged, low-velocity, high rigidity ions have their origin as interstellar neutrals, which have been ionized in IP space by charge exchange or photo-ionization that are convected out to the TS where it was assumed they would be accelerated to energies extending beyond 50 MeV/n [6], [7].

II. Observation

V1 crossed the TS on December 16, 2004 at 94 AU (34°N) entering the region of the heliosheath where it has remained over the past 4.2 years [9]. V2 made multiple crossings on August 30, 31, 2007 at 83.7 AU (27.5°S) [10] but has also remained in the heliosheath since that time.

At the TS on 2004.96 the 265 MeV/n GCR He was close to its 2001.25 solar maximum level when the radial gradient intensity corrections are applied. The 2.5-140 MeV electrons were at the detector background level and the ACR He intensities were a factor of 23 less than that expected for a weak shock (compression ratio s=2.40 and a factor of 16 less for a strong shock (s=4) and lower than had been observed by V1 over significant periods in the immediate foreshock region just after solar maximum.

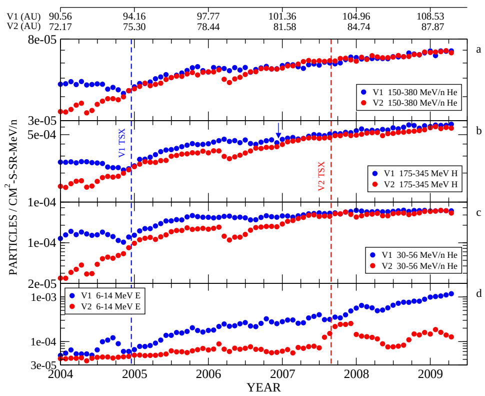

Fig. 1. Voyager GCR He and H, ACR He and 10 MeV E. This data and that of the following 5 figures are from the Voyager CRS experiment (E.C. Stone, PI)

Some 2.7 years later, when V2 crossed the termination shock, the 265 MeV GCR He had increased by 60% and the radial intensity gradient was 0.1 ± 0.2 %/AU,

TABLE I

Voyager-1	2006.14 - 2008.92	Rigidity	% Below Webber/Higbi LIS
150-380 MeV/n GCR He	7.4 %/Year	1369MV	21%
145-244 MeV/n GCR He	9.6 %/Year	1266MV	30%
180-350 MeV GCR H	15.5 %/Year	684MV	44%
30-56 MeV/n ACR He	12.6 %/Year	1150MV	

essentially its same value as at the V1 TS crossing (TSX).

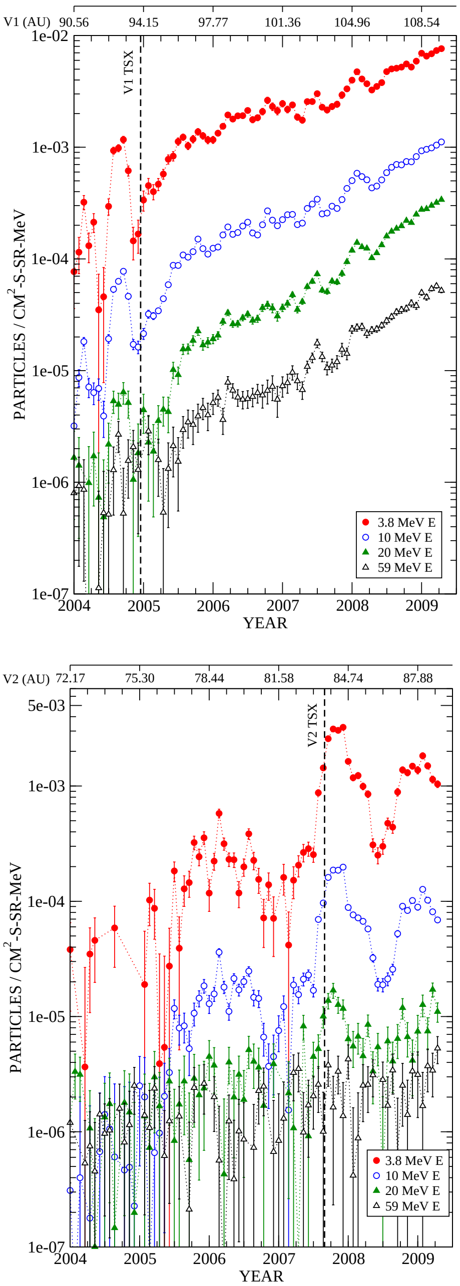

Fig. 2. Background corrected intensities for 4 V1 and V2 energy channels (26 day avg.) There are also 2 additional energy channels at 30 and 116 MeV

The time histories of 265 MeV/n He and H and 43 MeV/n ACR He (Fig. 1a,b,c) show a consistent pattern from $\sim$ 2007-2009.35 - a steady increase and a very small radial gradient. The small values of G_r (<0.3%/AU) and the much larger intensity increases (Table 1) indicate the changes are predominantly temporal and not spatial. The rate of change of 265 MeV H (R=684MV)(Table 1) is slightly double that of 265 MeV He (R=684MV).

The behavior of the 10 MeV electron component (R=10MV)(Fig. 1d) is very different from that of the higher energy and much higher rigidity cosmic ray ions. The peak extending from 2004.5-2004.86 is produced by large transients from the November 2003 large Halloween events and subsequent activity and is probably related to the interactions between the merged interaction regions and the TS. At the time of the TSX, the electron intensity is below the background level of the detector.

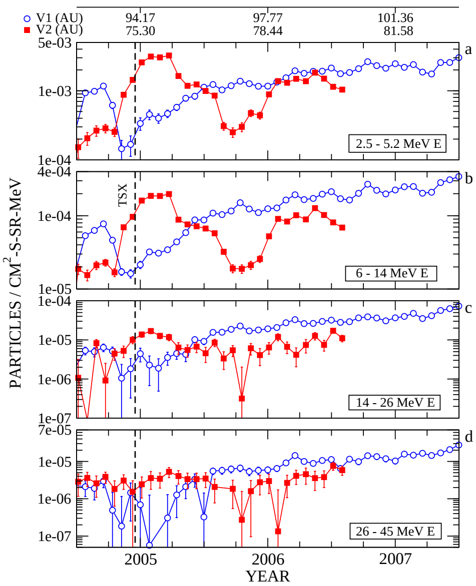

Fig. 3. Combined data of Figure 2a,b with the V2 time axis shifted so that the time of the termination crossing of the 2 spacecraft coincides.

The background corrected intensities for 4 energy intervals is shown in Fig. 2a,b in which there is a rapid rise to 2005.8, followed by a 60%/year increase. At the higher energies the rate is on the order of 80%.

At V2, there is a large increase just after the TSX

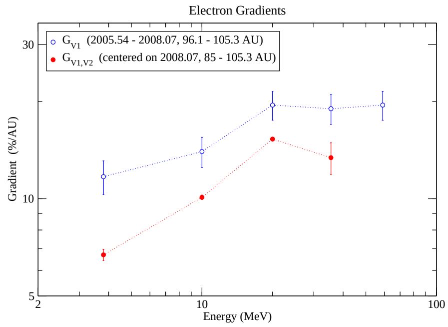

Fig. 4. Electron radial intensity gradients. The top data set are implied gradients obtained from the rate of change of the V1 electron intensity divided by the radial distance traveled over that time. The lower data points are the actual radial gradients measured at V1 and V2 between 85 and 105.3 AU.

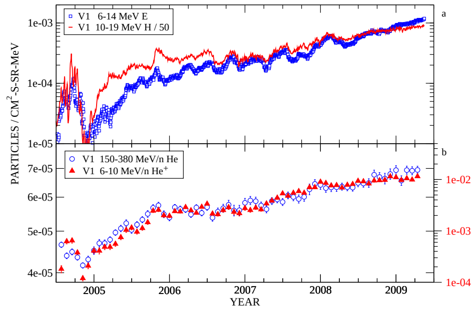

Fig. 5. Comparison of (a) 6-14 MeV E and 10-19 MeV H (5 day moving averages). Only the intensities have been normalized; the intensity scale is the same for both components. (b) 150-380 MeV/n GCR He and 6-10 MeV/n ACR He. There is a different intensity scale for the 2 components and they have different offsets.

that is limited to energies below some 30 MeV with an energy spectra steeper than that of V1. There are no strong transients at this time and the increase is interpreted as representing moderate reacceleration at the TS as had been previously proposed by Potgieter and Ferreira.

It is instructive to combine Figs. 2a,b and time-shift the V2 data -2.7 years so that the V1 and V2 TSX coincide. This plot, (Fig. 3) suggests that both temporal and spatial effects are important. In Fig. 4 the electron radial intensity gradients are shown for a period centered on 2008.07. Also shown is an implied gradient from the V1 data alone obtained by measuring the rate of increase of the 10 MeV electrons and dividing by the radial distance V1 traveled over that time. This plot suggests that at this time spatial changes appear to be somewhat larger than temporal increases. This tentative conclusion may change as the Voyagers move deeper into the heliosheath.

Previously a close correlation has been found between changes in the GCR and ACR intensity in and near the heliosheath [8]. A plot of 265 MeV/n vs 6-10 MeV/n ACR He shows this correlation is still present but with a small divergence over the last 0.3 years. A similar plot (but without changing the intensity scale) shows a similar correlation for 10 MeV E vs 14.5 MeV ACR H over a 2.6 year period (2006.15-2008.75) with a similar divergence beginning in 2008.75.

This relation between ACRs and GCRs can be further explored using cross-correlation plots (Fig. 6). For 8 MeV/n ACR He there is a clear flattening of the ACR intensity starting around 2008.5 (Fig. 6a). There is a similar tendency for ACR H (Fig. 6b) which is not as pronounced as for the higher rigidity ACR He. For 30-56 MeV/n ACR He, (Fig. 1c) the constant intensity begins earlier (2007.5). What is surprising is the strong correlation between GCR He and 10 MeV electrons.

III. Discussion

At 1 AU, the cosmic ray time history over the current solar minimum has been different from that of the previous 5 cycles. The Sun has remained unusually quiet and the interplanetary magnetic field is at its lowest level since measurements began in 1963. It is probable that these modulation conditions are also playing a role in the distant heliosphere and account for some of the ongoing GCR increases observed at the Voyagers.

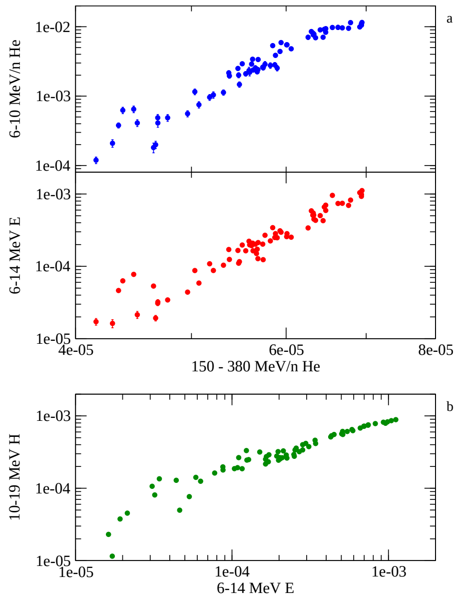

Fig. 6. Cross-correlation plots (a) 6-10 MeV/n ACR He and 6-14 MeV GCR E vs 150-380 MeV/n He. (b) 10-19 MeV ACR H vs 6-14 MeV GCR E.

Voyager 1 and 2 energetic particle experiments found that, contrary to expectations, the TS near the nose of the heliosphere was not the ACR acceleration site (Stone *et al.* [9], [10]. The close correlation between ACRs and GCRs at the Voyager locations in the heliosheath along with the very small radial intensity gradients of GCRs and higher rigidity ACRs suggest that one possible interpretation is that they have followed essentially the same path from the ACR acceleration site and the GCR entry region to the Voyagers on the front side of the heliosphere. The close temporal correlation of GCR ions and 10 MeV electrons would indicate the electrons may also have followed this same path. In this interpretation these relatively lower energy GCR ions and electrons do not reach Voyager from the nearest point on the heliopause but travel a more circuitous route. Higher energy cosmic rays would travel more direct paths. In effect this would be a new modulation process for the lower energy GCRs.

McComas and Schwadron [11] have advocated the flank region of the TS as the ACR acceleration site. Kota [12] has argued for either the flank or tail region. Further Voyager observations deeper in the heliosheath and eventually in local interstellar space should provide further insight.

REFERENCES

[1] Holzer, T. E., Annual Rev. Astron. and Astrophy. 27: 199, (1989)
[2] Gurnett, D. A., W.S. Kurth and E.C. Stone, GRL, 3030 (23), 2209, doi 10.1029/2003GLO 18501, (2003)
[3] Jokipii, J.R., Ap.J., 446: 47, (1996)
[4] Steenberg, C.D., PhD Thesis, Potchefstroom Univ., South Africa
[5] Potgieter, M.S. and S.E.S. Ferreira, JGR, 107, 10.1029/2001 JA009040, (2002)
[6] Fisk, L.A., B. Kozlovsky, and R. Ramaty, ApJ, 190, L35, (1974)
[7] Pesses, M.E, Jokipii, J.R. and Eichler, D., ApJ. 246, L85 (1981)
[8] McDonald, F.B., Webber, W.R., Stone, E.C., Cummings, A.C., Heikkila, B.C. and Lal, N., C.P. 858, Physics of the Inner Heliosheath, P79, (2006)
[9] Stone, E.C., *et al.* Science 309, 2017, (2005)
[10] Stone, E.C., *et al.* Nature 454 P71, 2008
[11] McComas, D.J. and Schwadron, N.A., GRL 33:25437, (2006)
[12] Kota, J. 30th ICRC, Vol 6, P853, (2007)