Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 1 (SH), pages 831–834

ID 1161

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Voyager observations of energetic particles near the solar wind termination shock

E. C. STONE[1], A. C. CUMMINGS[1], F. B. MCDONALD[2], B. C. HEIKKILA[3], N. LAL[3], W. R. WEBBER[4].
[1]*California Institute of Technology, Pasadena, CA 91125, USA*
[2]*University of Maryland, College Park, MD 20742, USA*
[3]*NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[4]*New Mexico State University, Las Cruces, NM 88003, USA*
ecs@srl.caltech.edu

Abstract: Voyager 1 is observing the energy spectra of anomalous cosmic ray H, He, and O in the heliosheath. The relative abundance of H/He is 20 at 1-1.5 MeV/nuc, indicating that H pickup ions are more efficiently accelerated than was modeled from observations at higher energies. Voyager 2 began observing upstream energetic ions from the shock in late 2004 at $\sim$75 AU, about 10 AU closer to the Sun than observed by Voyager 1. Voyager 2 will be at 84.7 AU at the end of 2007 and may have crossed the termination shock.

Introduction

The composition of the anomalous cosmic rays (ACRs) reflects that of pickup ions formed by the ionization of neutral interstellar atoms flowing into the heliosphere and accelerated at the termination shock. Based on observations of higher energy ACRs at $\sim$70 AU during the last period of minimum solar modulation (1998 to mid-1999), Cummings et al. [1] used a 2D propagation model to predict a H/He ratio of 4.2 at 0.5 MeV/nuc for a strong shock and 5.2 for a weak shock. When compared with the pickup ion abundances expected at the shock, this indicated an acceleration efficiency for H that is only 0.12 (strong shock) to 0.15 (weak shock) that for He.

Voyager 1 began observing accelerated ions upstream of the shock in 2002 [2, 3]. At low energies ($\sim$1 MeV/nuc), these termination shock particles exhibited a H/He ratio of $\sim$10 [3], larger than inferred from model fits to the higher energy ACRs observed in 1998-99. However, the relationship of the upstream spectra to the spectra at the shock and to the ACRs at higher energies was not readily apparent. Voyager 1 crossed the shock in December 2004 at 94 AU [4, 5, 6] and is now well into the heliosheath where the low energy spectrum is expected to be the same as at the shock. These spectra should provide a direct measure of the relative composition of low energy ACRs accelerated at the termination shock.

Observations

Since entering the heliosheath, Voyager 1 has observed a reasonably steady intensity of $\sim$0.5 MeV H ions from the shock [6]. At somewhat higher energies (>3 MeV H), the intensity initially increased, reaching a steady level in early 2006 (Figure 1). As discussed by Cummings and Stone [7], this increase may have been the recovery of the intensity of the shock source spectrum that had been depressed by a series of merged interaction regions (MIRs) prior to 2005. The steady state nature of the Voyager 1 spectra since early 2006 suggests that they may provide a direct measure of the composition of low energy ACRs.

Spectra for H, He, C, and O observed in the first 52-day period in 2007 are typical of recent steady state spectra (Figure 2). Comparing these spectra with those observed at the recent solar minimum upstream of the shock [1] illustrates that, as expected, the modulation of the heliosheath spectra at lower energies is greatly reduced compared to that observed $\sim$20 AU upwind of the shock.

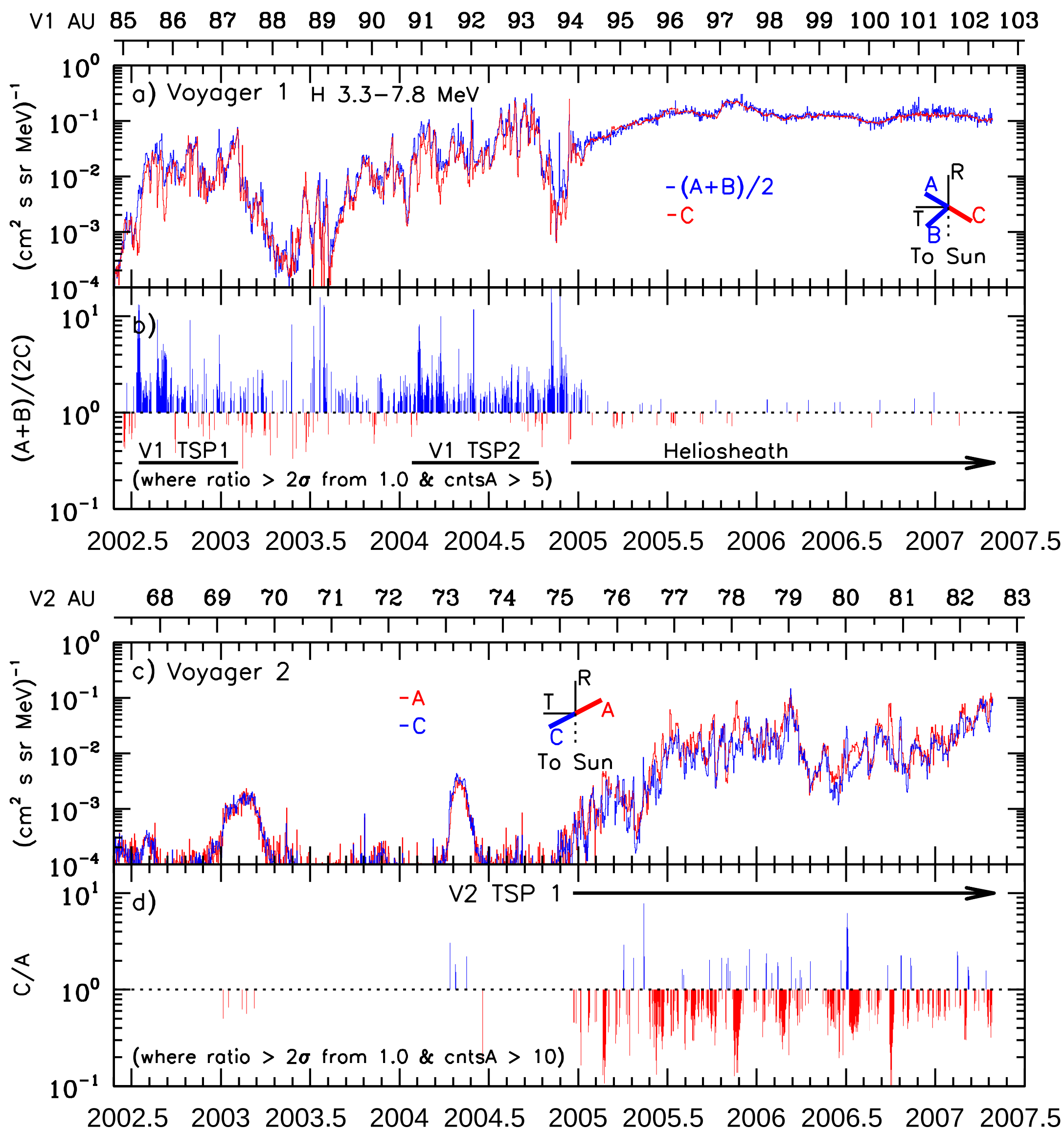

Figure 1: Intensities and streaming of energetic H ions from the termination shock observed by Voyager 1 and Voyager 2. The observing directions of the Low Energy Telescopes A, B, and C, are shown in RTN coordinates with R radially outward and T in the azimuthal direction along the spiral magnetic field toward the Sun. Voyager 1 crossed the termination shock on 2004.96. As indicated by the ratio of outward vs. inward intensities, Voyager 1 began observing ions streaming outward from the shock along the interplanetary magnetic field in mid-2002 at 85 AU. Voyager 2 began observing upstream ions beaming inward along the field in late 2004 at 75 AU, indicating that the shock is likely closer in the southern hemisphere than at Voyager 1 in the north.

Although the H and He spectra resemble power laws, close inspection (Figure 3) reveals systematic differences from a single power law. Cummings et al. [9] fit the H spectrum with four power laws,

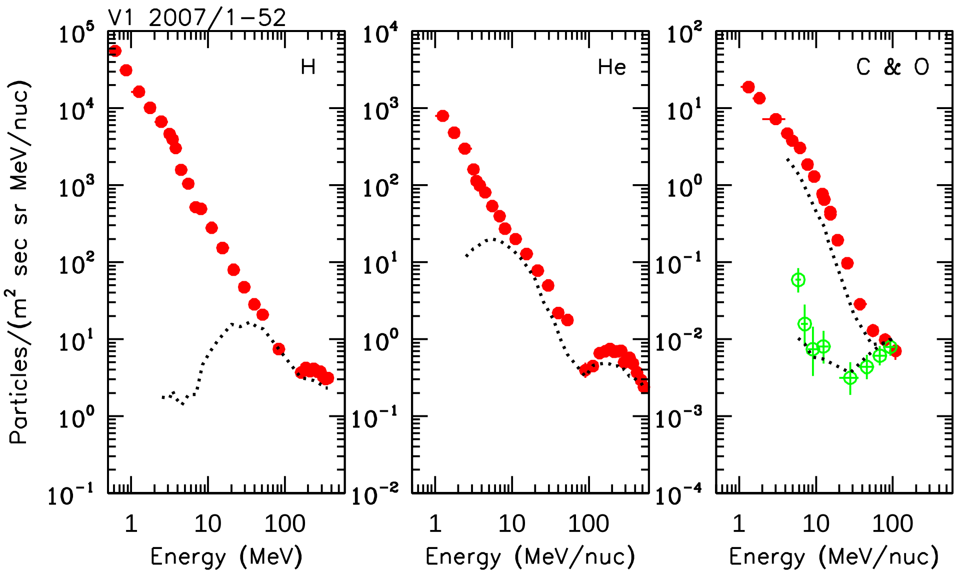

Figure 2: Energy spectra observed by Voyager 1 for days 1-52 of 2007. The dotted lines are the spectra observed at solar minimum (1998/001 to 1999/182) at ∼70 AU. Ions accelerated at the termination shock dominate below ∼100 MeV/nuc and galactic cosmic rays are apparent at higher energies. The under abundance of C is a signature that the ions accelerated at the shock originate as interstellar pickup ions [8].

finding $E^{-1.55}$ at the lowest energies, with a break at ∼0.4 MeV to $E^{-2.2}$. They suggested this was the injection source for diffusive shock acceleration that had an injection threshold energy of ∼0.9 MeV and resulted in an $E^{-1.27}$ spectrum from that energy up to a spectral break at ∼3 MeV. Although lacking data below 1 MeV/nuc, the He spectrum in Figure 3 appears to have a similar break at ∼3 MeV/nuc. The deviations from a single power law result in an H/He ratio that decreases from ∼20 at 1 MeV/nuc to ∼10 at 30 MeV/nuc. The H/He ratio at 1 to 1.5 MeV/nuc also varied from 5 to 20 as Voyager 1 approached the shock as shown in Figure 4, but has been reasonably constant in the heliosheath since early 2005.

Discussion and Conclusions

In the two stage acceleration model for ACRs proposed by Zank et al. [10], the threshold for diffusive shock acceleration for H and He were 337 and 223 keV/nuc, respectively, so they calculated the intensities of H and He at 1 MeV/nuc, just above the threshold energy. Starting with a pickup ion flux with H/He = 44, they found that with a particular choice of scattering mean free path, the two stage process resulted in a H/He ratio of ∼5.5 at 1 MeV/nuc. This indicated that the acceleration efficiency for H was 0.125 times that for He, similar to that inferred from model fits to higher energy observations [1]. However, these model fits did not anticipate the non-power law features now apparent at lower energies.

The Voyager 1 observations provide a direct measure of the H/He at 1-1.5 MeV/nuc. As shown in Figure 4, the H/He was ∼10 upstream in 2002, as reported by Krimigis et al. [3]. As Voyager 1 approached the shock, the ratio varied from 5 to 20, likely resulting from changes in the propagation conditions between Voyager 1 associated with multiple MIRs and motions of the shock relative to Voyager 1. However, since 2005/105 in the heliosheath, the rms variation of the 52-day averages has been only 10% and the average ratio has been 20.0±0.5. Assuming that 1-1.5 MeV/nuc is above the threshold for diffusive shock acceleration, this

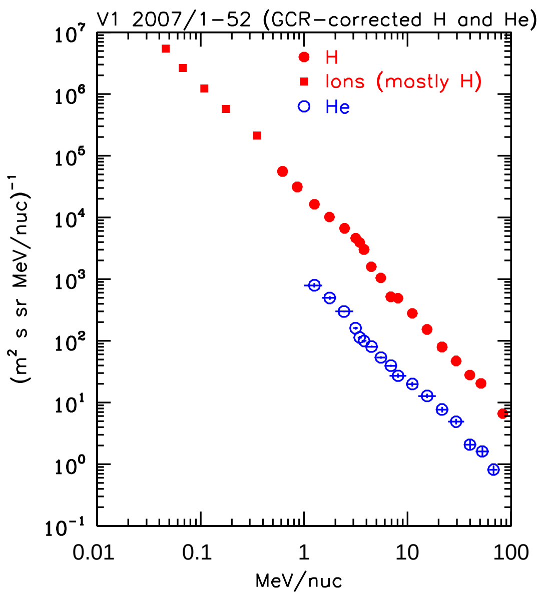

Figure 3: H and He spectra from Figure 2, with lower energy ion intensities (mostly H and <0.5 MeV) from LECP. There are breaks in the H spectrum at 0.4 and ∼3 MeV and in the He spectrum at ∼3 MeV/nuc.

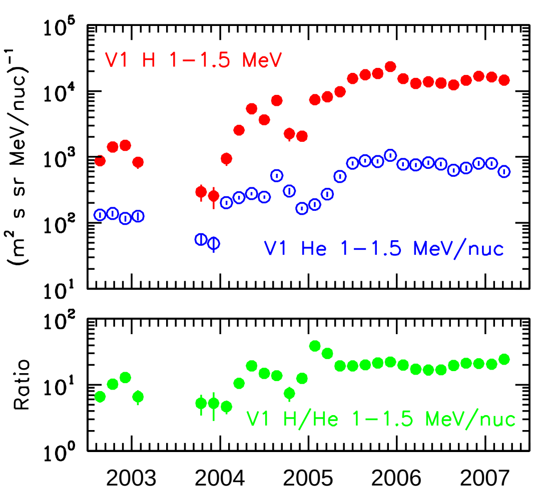

Figure 4: The H and He intensities and the H/He ratio at 1-1.5 MeV/nuc (52-day averages). The ratio was smaller and more variable upstream of the shock than in the heliosheath.

H/He ratio would indicate that the acceleration efficiency for H is ∼0.5 that of He. Further analysis and theoretical modeling are needed, however, to confirm this interpretation.

When Voyager 2 crosses the shock, it will not only determine differences in the shock location in the northern (Voyager 1) and southern (Voyager 2) hemispheres, but it will provide another measure of the spectra of low energy ions accelerated in a different region on the shock. Voyager 2 began observing upstream ions 2.5 years ago at 75 AU and will be at nearly 85 AU by the end of 2007. It is likely to have crossed the termination shock by then and add further to our understanding of shock acceleration.

Acknowledgements

We thank the Voyager Low Energy Charge Particle team for the use of their data in Figure 3. This work was supported under contract NAS7-03001.

References

[1] A. C. Cummings, et al., Astrophys. J. 578 (2002) 194–210.

[2] F. B. McDonald, E. C. Stone, A. C. Cummings, B. Heikkila, N. Lal, W. R. Webber, Enhancements of energetic particles near the heliospheric termination shock, Nature 426 (2003) 48–51.

[3] S. M. Krimigis, et al., Nature 426 (2003) 45–48.

[4] L. F. Burlaga, et al., Science 309 (2005) 2027–2029.

[5] R. B. Decker, et al., Science 309 (2005) 2020–2024.

[6] E. C. Stone, et al., Science 309 (2005) 2017–2020.

[7] E. C. Cummings, A. C. Stone, 30th International Cosmic Ray Conf., 2007.

[8] L. A. Fisk, et al., Astrophys. J. Lett. 190 (1974) L35+.

[9] A. C. Cummings, et al., Vol. 858 of American Institute of Physics Conference Series, 2006, pp. 86–91.

[10] G. P. Zank, et al., Astrophys. J. 556 (2001) 494–500.