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Galactic cosmic ray H and He nuclei energy spectra measured by Voyagers 1 and 2 near the heliospheric termination shock in positive and negative solar magnetic polarity cycles

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[1] Using data from the Voyager 1 and 2 spacecraft, we have followed the intensity variations of H, He and C + O nuclei between 1998 and 2008 and determined the spectra for H and He at the time of minimum modulation in 1998, when the solar magnetic polarity was positive and again in 2008 when the solar magnetic polarity was negative. At these times these data are representative of conditions near a heliospheric termination shock assumed to be located at ~90 AU. Above ~400 MeV/nuc for He nuclei the 11-year solar modulation cycle observed at the Earth is not seen; instead there is a 22-year variation. The negative polarity cycle intensities above ~150 MeV/nuc are higher than those in the positive polarity cycle by a factor of 1.4–1.7 times for both H and He nuclei. Below ~100 MeV/nuc the C nuclei intensities are similar in the two cycles to within ±10%. These observations are compared with theoretical calculations which also show a negative to positive polarity cycle intensity difference at higher energies, most likely associated with energy changes due to drifts near the termination shock, but the comparison suggests that improved estimates of the local interstellar spectra are required.

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1. Introduction

[2] At the beginning of 2008 the Voyager 2 (V2) spacecraft is just beyond the heliospheric termination shock (HTS) and Voyager 1 (V1) is well beyond this shock [*Stone et al.*, 2008], perhaps halfway through the heliosheath to the heliopause (HP), believed to be the outermost boundary for solar modulation effects in the heliosphere. At the same time ACE data (http://www.srl.caltech.edu/ACE) now suggests that the modulation minimum at the Earth in this 11-year solar cycle was reached about 2008.0, implying that a minimum modulation in the outer heliosphere will be reached ~12–15 months later in early 2009. At the time of minimum modulation in the previous cycle in 1998–1999, V2 and V1 were at 58 and 73 AU respectively, just inside the HTS location estimated then to be between 85 and 95 AU. The small interplanetary gradients measured in 1998–1999 between V2 and V1 suggest that the intensities measured at that time at V1 or V2 were a good proxy for those near the HTS itself [*McDonald et al.*, 1999; *Webber and Lockwood*, 2004a]. So we now are in a position to use the Voyager spacecraft data at 2008.0 and in 1998–1999 to determine the spectra of cosmic ray H, He (and heavier nuclei) near the HTS at greatly reduced solar modulation levels than at the Earth and for two opposite solar magnetic polarity levels, a positive polarity in 1998–1999 and a negative polarity in 2008. This polarity difference is important for understanding the amount of residual modulation of galactic cosmic rays beyond the HTS. We will present evidence to show that the overall intensities above ~150 MeV in early 2008 near and beyond the HTS are already significantly greater than in 1998–1999 indicating a distinct polarity difference in the modulation beyond the HTS. It is within this framework that we present V1 and V2 data on the time variations and spectra of galactic H, He (and C) nuclei in 1998–1999 and again in the time period around 2008.0.

2. Data: Intensity Versus Time

[3] In Figure 1 we show 52-day average intensity time curves for GCR H, He and C + O nuclei of various energies from 56 to 540 MeV/nuc from 1998 to the present time at V1 covering the time period from the previous 11-year solar

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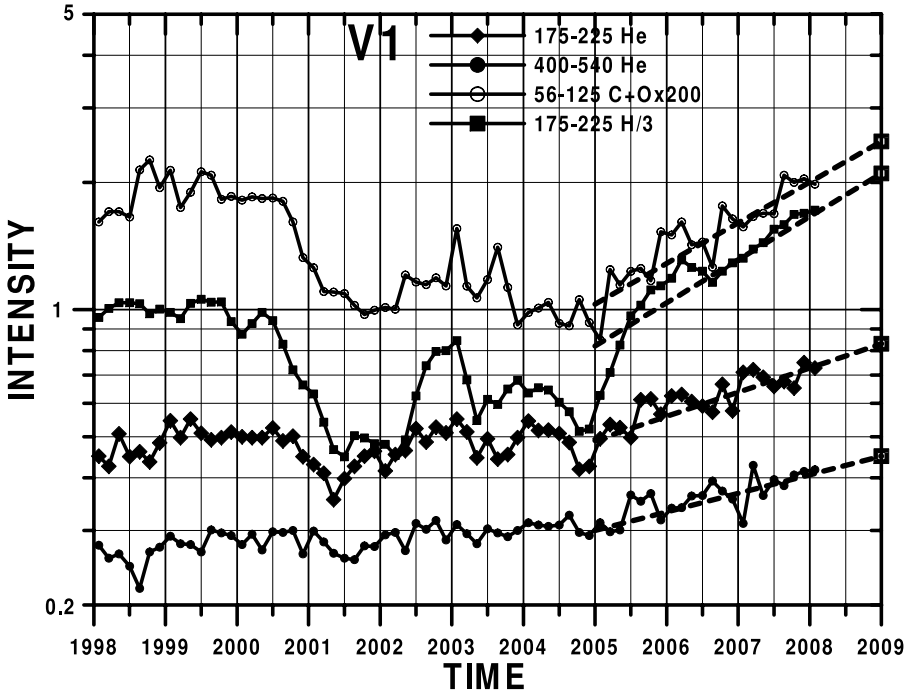

Figure 1. Intensity versus time curves of various channels from 1998 to 2008 at V1 (52 day averages). (1) 56–125 MeV/nuc (C + O) × 200; (2) 175–225 MeV H nuclei/3; (3) 175–225 MeV/nuc He nuclei; (4) 400–540 MeV/nuc He nuclei. Dashed lines illustrate increase after 2005.0.

cycle maximum (positive cycle) to the current cycle maximum (negative cycle). The lower energy C + O intensities from 56 to 125 MeV/nuc are used as a proxy for the GCR He intensities below ~100 MeV which are partially obscured by ACR particles. The H and He intensities at the higher energies used here do not contain a significant ACR background. It is seen that, at the lowest energy, for C + O, the expected 11-year solar modulation cycle is observed. The initial decrease starts in 2000, about 2 years later than at the Earth and has a maximum amplitude ~50% for V1 [see also *Webber and Lockwood*, 2004b; *McDonald et al.*, 2006]. By early 2008, the intensities have recovered to their level in 1998–1999, ±10%, at both V1 (and V2). For 175–225 MeV H nuclei (P = 0.60–0.685 GV) at V1 the 11-year decrease has a maximum amplitude ~60% and in early 2008 the intensity was ~75% greater than the 1998–1999 average. For 175–225 MeV/nuc He nuclei (P = 1.20–1.37 GV) at V1 the 11-year decrease has a maximum amplitude ~25% and in early 2008 the intensity was ~50% higher than the 1998–1999 average. For 400–540 MeV/nuc He nuclei (P = 1.91–2.28 GV) at V1 no significant (≤10%) 11-year modulation decrease is observed and the intensity by early 2008 was ~45% higher than the 1998–1999 average.

[4] Thus at V1, which is near or beyond the HTS throughout the entire time period, a (delayed) 11-year modulation cycle is observed at the lowest energies, but not at the highest energies where the modulation has the characteristics of a 22-year wave with a maximum at negative polarity. At the negative polarity maximum for energies above ~150 MeV/nuc in 2008 the intensities are significantly higher, by a factor ~1.4–1.7 for both H and He nuclei, than at the positive polarity maximum. Thus in a sense the whole energy spectrum of H and He nuclei has appeared to shift to higher energies in the negative polarity cycle producing higher intensities at higher energies above the spectral peak, but at lower energies, ~100 MeV/nuc and below, the intensities at both maxima near the HTS are about equal. This is most likely the result of oppositely directed gradient and curative drifts in the solar magnetic polarity cycles as modeled by *Jokipii et al.* [1993] and *Reinecke and Potgieter* [1994], and others.

3. Data: Energy Spectra

[5] The H and He nuclei energy spectra in 1998–1999 are almost identical at V2 and V1 located at 56 and 73 AU respectively thus implying small interplanetary radial gradients as noted earlier. For H nuclei the V1–V2 intensity difference is −4%, for He nuclei it is +7.5%, so that an extrapolation to an assumed HTS as 85–90 AU leads to differences ≤10% from the observed V1 intensities. Therefore for comparison with the spectra measured later in 2008 we use the V1 spectrum in 1999 at 73 AU for H and He nuclei (1) in Figure 2. Also shown in this figure are the spectra at 2008.0 at V2 (2) which has just crossed the HTS and also at V1 (3) which is now at ~105 AU, approximately 20 AU beyond the present shock location estimated to be ~85 AU for V1 [see *Webber et al.*, 2007]. It is apparent that the spectra at V1 and V2 in 2008, both beyond the HTS and separated by ~20 AU in radial distance, are very similar for both H and He nuclei. There-

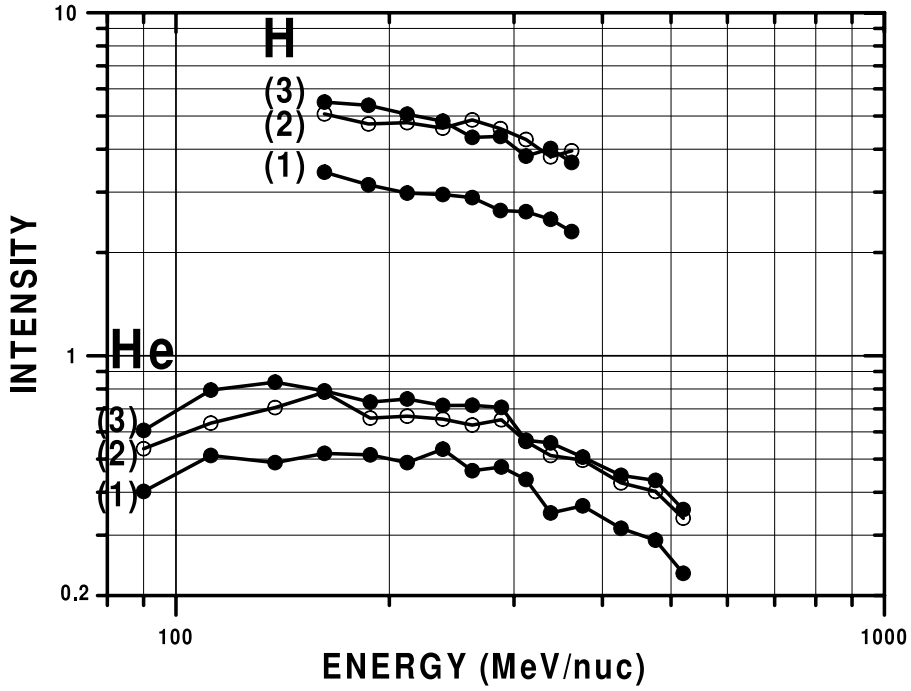

Figure 2. The H and He nuclei spectra. (1) Average for 1999 at V1 (73 AU); (2) at 2008.0 at V2 (85 AU) just after crossing the HTS; (3) at 2008.0 at V1 (105 AU) ~20 AU beyond the shock. Intensities are in particles/m^2·sr·s·MeV/nuc.

fore the gradients in the heliosheath are small over most of this energy range [see *Stone et al.*, 2008].

4. Discussion of the Data

4.1. Negative and Positive Polarity Cycle Modulation Model Calculations

[6] There are now a number of model calculations starting with assumed IS spectra for H and He nuclei and then calculating the expected intensities near the HTS in positive or negative solar magnetic polarity cycles, starting with the initial calculations of *Jokipii et al.* [1993] who used a heliosphere with an embedded heliospheric termination shock and drifts along the shock which alternate from cycle to cycle and play an important role in the intensity differences that are calculated. Conditions both inside and outside the HTS are considered in the latest models including drift in latitude along the HTS, and drift inside the HTS along with a wavy heliospheric current sheet. The most extensive of these calculations are by the South African groups who have calculated intensities near the HTS in both positive and negative polarity cycles for both H and He nuclei as well as C nuclei [e.g., *Langner and Potgieter*, 2004, 2005; *Caballero-Lopez et al.*, 2004]. We use these calculations here for comparison because they cover both H and He nuclei considered in this study. In general the calculations appear to be consistent with each other within the differences in the IS spectra used which appears to be the largest source of uncertainty. These intensity calculations for positive and negative polarity cycles near an HTS located at 90 AU for H and He nuclei are shown in Figure 3 along with the Voyager measurements in 1999 and 2008.

4.2. Comparison of Calculations With Voyager Measurements

[7] It is seen from Figure 3 that the predicted H nuclei intensities of *Langner and Potgieter* [2004] near the HTS exceed at all energies those measured by Voyager for both polarities. This is presumably because of the IS H nuclei intensities used in this calculation. What is interesting however, is the calculated negative to positive cycle intensity difference near the HTS which is ~2.0 at ~300 MeV and above, decreasing to ~1.0 at ~100 MeV, just slightly larger than the intensity ratio Voyager observes over comparable energy intervals.

[8] For He nuclei the agreement between calculations and measurements is better. For the positive cycle in 1998–1999 the model calculated intensities are ~10–30% higher than the measurements over the energy range from ~100–500 MeV/nuc. For the negative cycle at 2008.0 the calculations are above the measurements by a factor ~2.0 at the same energies. The calculated ratio of negative to positive polarity intensities near the HTS is typically ~2.0 at energies above ~100 MeV/nuc, becoming smaller at lower energies but not reaching ~1.0 until ~30 MeV/nuc. This is larger than the observed ratio above ~150 MeV/nuc which is between 1.3–1.5.

[9] It is apparent that the IS spectrum used in the *Langner and Potgieter* [2005] calculations for H nuclei is too high by a factor ~2.0 at energies from ~150–350 MeV. For the IS He spectrum, since the agreement between measurements and predictions is much closer, particularly for the positive cycle, the required modifications to the IS spectrum are smaller. The fact that the Voyager spacecraft can determine the positive to negative polarity cycle intensity ratio near the

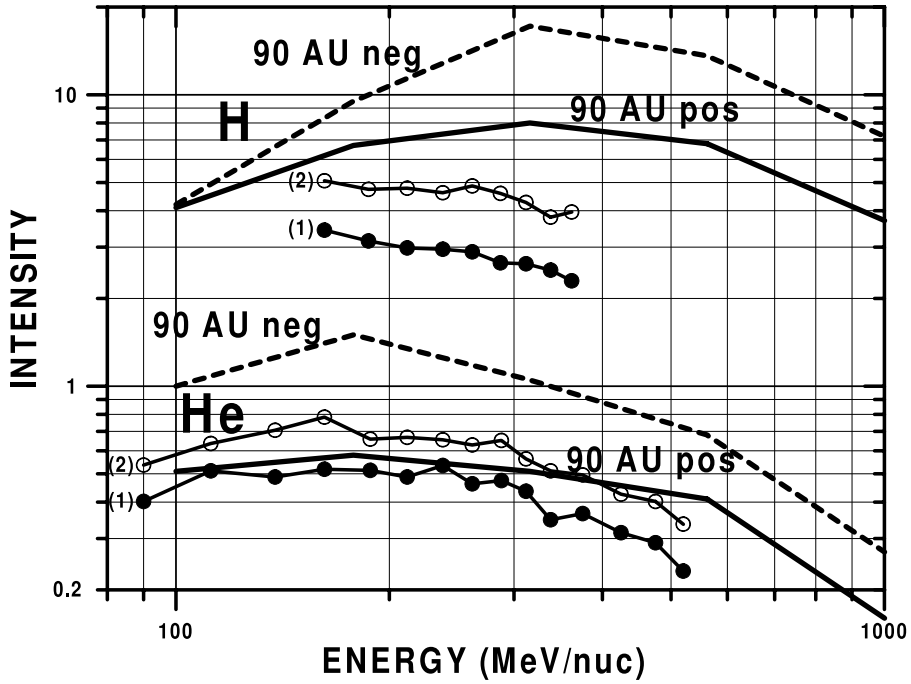

Figure 3. Calculated H nuclei spectra [*Langner and Potgieter*, 2005] and He nuclei spectra [*Langner and Potgieter*, 2004] near the HTS in positive and negative solar magnetic polarity cycles. Voyager H and He measurements near the HTS at 1999 (V1) and 2008.0 (V2) are also shown. Intensities are in particles/m^2·sr·s·MeV/nuc.

HTS plays a key role in understanding the outer heliospheric modulation and the role of drifts near the HTS and therefore to help determine the correct IS spectrum.

5. Interstellar H and He Spectra and Solar Modulation Below ~100 MeV

[10] At energies ≤100 MeV/nuc the IS H and He spectra are almost completely hidden under the high intensities of ACR H and He nuclei [*Cummings et al.*, 2006]. Since the intensities of these ACR also continue to increase in the heliosphere beyond the HTS much like those for GCR [*McDonald et al.*, 2006] it is unlikely that the low energy part of the galactic H and He spectra will be observable until V1 is well beyond the heliopause [see also *Ferreira et al.*, 2007]. We therefore must use a proxy to determine this low energy intensity. Carbon is the best proxy since it has the highest intensity and also is free of ACR above ~10–20 MeV/nuc. We have already noted from Figure 1 that the C + O intensity at ~100 MeV/nuc and below at 2008.0 at V1 and V2 is the same as the 1998–1999 average at V1 and V2 within ±10%. So no large negative to positive cycle spectral splitting is observed at these lower energies.

6. Further Unfolding of the Spectra Between 2008.0 and 2009.0

[11] The negative to positive cycle intensity ratios for H and He nuclei presented here in Figures 2 and 3 are those determined at 2008.0 just after V2 crossed the HTS. Reference to Figure 1 shows that the intensities at V1 (and V2) are still increasing toward their values at the time of the absolute minimum for this solar activity cycle. Evidence from the ACE experiment near the Earth for the same energy nuclei as those observed by Voyager indicates that this minimum (maximum intensities) was reached at about 2008.0 (http://www.srl.caltech.edu/ACE). The propagation time for solar disturbances to reach the HP is ~415 days [e.g., *Gurnett et al.*, 1993] so one should expect the maximum intensities beyond the HTS to be reached by early in 2009. The rate of increase in the various energy channels in Figure 1 since the beginning of 2005 when the 11-year intensity recovery started is between 10 and 20% per year. Between 2007.5 and 2008.0 this rate of increase is maintained. As a result the intensities for H and He nuclei shown in Figures 2 and 3 for 2008.0 should project to 10–20% higher intensities at the time of absolute modulation minimum in this current negative cycle. The boxes at 2009.0 in Figure 1 give the estimated intensities at this time based on an extrapolation of the intensity time curves from 2005.0. This additional intensity increase beyond 2008.0 needs to be included in further considerations of the negative to positive solar cycle intensity ratios discussed here.

7. Summary and Conclusions

[12] Using data from the Voyager 1 and 2 spacecraft, we have followed the intensity variations over a 11-year solar cycle and determined the energy spectra of H and He nuclei between ~100–500 MeV/nuc in the outer heliosphere at three times: (1) in 1998–1999 at ~73 AU inside the HTS at a time of minimum modulation when the interplanetary gradients were small in a positive solar magnetic polarity cycle;

(2) at 2008.0 approaching a time of minimum modulation in a negative solar magnetic polarity cycle at V2 (85 AU) just after this spacecraft crossed the HTS; and also (3) at 2008.0 at V1 (105 AU) when it is ~20 AU beyond the HTS. These differential energy spectra have peaks at ~150–200 MeV for both H and He nuclei.

[13] The ratio of intensities above ~150 MeV between the higher intensity negative and the lower intensity positive polarity cycles is between 1.5 and 1.7 for H and 1.4 and 1.7 for He. A comparison of our new data with modulation models is difficult because of the differing IS spectra used in the models, but the modulation models appear to predict larger negative to positive 11-year cycle intensity differences near the HTS than the ones we measure. This ratio is important for understanding the role of drifts near the HTS and beyond. Improved estimates of the local IS spectra are required along with additional model calculations to fit the Voyager observations and understand more fully the solar modulation beyond the HTS.

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References

Caballero-Lopez, R. A., H. Moraal, and F. B. McDonald (2004), Galactic modulation: Effects of the solar wind termination shock and the heliosheath, *J. Geophys. Res.*, *109*, A05105, doi:10.1029/2003JA010358.

Cummings, A. C., E. C. Stone, F. B. McDonald, B. C. Heikkila, N. Lal, and W. R. Webber (2006), Termination shock particles spectral features, *AIP Conf. Proc.*, *858*, 86–91, doi:10.1063/1.2359310.

Ferreira, S. E. S., M. S. Potgieter, and K. Scherer (2007), The transport and acceleration of anomalous cosmic rays in the inner heliosheath, *J. Geophys. Res.*, *112*, A11101, doi:10.1029/2007JA012477.

Gurnett, D. A., W. S. Kurth, S. C. Allendorf, and R. L. Poynter (1993), Radio emission from the heliopause triggered by an interplanetary shock, *Science*, *262*, 199–203, doi:10.1126/science.262.5131.199.

Jokipii, J. R., J. Kota, and E. Merenyi (1993), The gradient of galactic cosmic rays at the solar wind termination shock, *Astrophys. J.*, *405*, 782–786, doi:10.1086/172407.

Langner, U. W., and M. S. Potgieter (2004), Effects of the solar wind termination shock and heliosheath on the heliospheric modulation of galactic and anomalous helium, *Ann. Geophys.*, *22*, 3063–3072.

Langner, U. W., and M. S. Potgieter (2005), Modulation of galactic protons in an asymmetrical heliosphere, *Astrophys. J.*, *630*, 1114–1124, doi:10.1086/431547.

McDonald, F. B., N. Lal, and R. A. McGuire (1999), The onset of solar cycle 23 at 1 AU and 70 AU, *Proc. ICRC*, *26*, 539–542.

McDonald, F. B., W. R. Webber, E. C. Stone, A. C. Cummings, B. C. Heikkila, and N. Lal (2006), Voyager observations of galactic and anomalous cosmic rays in the heliosheath, *AIP Conf. Proc.*, *858*, 79–85, doi:10.1063/1.2359309.

Reinecke, J. P. L., and M. S. Potgieter (1994), An explanation for the difference in cosmic ray modulation at low and neutron monitor energies during consecutive solar minimum periods, *J. Geophys. Res.*, *99*, 14,761–14,767, doi:10.1029/94JA00792.

Stone, E. C., A. C. Cummings, F. B. McDonald, B. C. Heikilla, N. Lal, and W. R. Webber (2008), An asymmetric solar wind termination shock, *Nature*, *454*, 71, doi:10.1038/Nature07022.

Webber, W. R., and J. A. Lockwood (2004a), Heliocentric radial intensity profiles of Galactic cosmic rays measured by the IMP, Voyager and Pioneer spacecraft in solar 11-year modulation cycles of opposite magnetic polarity, *J. Geophys. Res.*, *109*, A11101, doi:10.1029/2004JA010642.

Webber, W. R., and J. A. Lockwood (2004b), Onset and amplitude of the 11-year solar modulation of cosmic ray intensities at the Earth and Voyagers 1 and 2 during the period from 1997 to 2003, *J. Geophys. Res.*, *109*, A09103, doi:10.1029/2004JA010492.

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 and Voyagers 1 and 2, *Geophys. Res. Lett.*, *34*, L20107, doi:10.1029/2007GL031339.

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