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Differences in the spectra of anomalous cosmic ray helium nuclei in two solar magnetic polarity cycles

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

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[1] We compare the spectra of anomalous He nuclei measured in the heliosphere by the IMP, Voyager, and Pioneer spacecraft at heliospheric distances ranging from 1 to over 80 AU in the time period from 1977 to 2003. Striking differences in the energy spectra of these nuclei are found between positive and negative solar magnetic polarity cycles. These differences are such that the spectra observed in negative polarity cycles appear to be greatly deficient in particles with energies of less than ~15 MeV but have an excess intensity above >25 MeV, relative to the spectra observed in positive cycles. These spectral differences are complex and may be related to both solar modulation effects inside of the heliospheric termination shock as well as differences occurring at or near the termination shock itself. At the modulation minimum in 1998 when V2 was at a distance of 56 AU and V1 at 71 AU, a high intensity of low-energy anomalous He particles was observed with a peak in the spectrum at ~5 MeV/nuc. In late 2001 after the solar magnetic polarity had changed from positive to negative and the 11-year solar modulation had increased, the previous high intensities of the anomalous He nuclei seen in 1998 were greatly reduced at both V1 and V2, and the energy of the peak intensity had moved up to ~20–25 MeV/nuc. However, in both polarity periods the highest-energy part of this spectrum above ~30 MeV/nuc is similar with a slope of -2.8 ± 0.2. The details of these complex spectral changes are described in this paper.

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1. Introduction

[2] At energies below about 50 MeV/nuc anomalous cosmic rays (ACR) are the dominant energetic particle population in the outer heliosphere. A characteristic of this low-energy component is their predominately singly ionized charge state. This arises because the ACR are thought to be interstellar neutrals that have first become ionized in the interplanetary medium [*Fisk et al.*, 1974], and then accelerated in the outer heliosphere, probably at the solar wind termination shock [*Pesses et al.*, 1981]. Several elements have been identified in the ACR component, the largest concentrations of which are H, He and O [*Cummings and Stone*, 1995]. The intensities and spectra of these cosmic rays have been followed since the original discovery of anomalous O [*Hovestadt et al.*, 1973; *McDonald et al.*, 1974] for almost 30 years as the Pioneer and Voyager spacecraft have moved outward in the heliosphere. This study has encompassed periods of positive solar magnetic polarity up to 1980, a negative polarity period from 1980 to 1990, another positive polarity period from 1990 to 2001, with a new negative polarity period starting in 2001. During a positive polarity period the Sun's magnetic moment is such that positively charged particles drift inward from the polar regions of the heliosphere. Eleven years later when this polarity is negative these particles drift inward along the heliospheric equatorial current sheet. During this time period these spacecraft have moved outward in the heliosphere so that by the end of 2003 V2 was at ~70 AU and V1 at ~87 AU, approaching the possible location of the heliospheric termination shock (HTS) where these particles are thought to be accelerated. During the 11-year cycles of different solar magnetic polarity the spectra of these individual components have changed dramatically within the heliosphere. For example, anomalous H which was only weakly detectable at low energies in the negative magnetic period in 1987 at 24 AU at V2, [*Christian et al.*, 1988] reappeared much more strongly in the positive polarity period in 1994 [*Christian et al.*, 1995; *McDonald et al.*, 1995] and by 1999 had reached intensities ~50x those observed in 1987 at energies of 20–30 MeV [*Cummings and Stone*, 2001]. Thus the changes in the spectra and abundance of anomalous H, He and O nuclei between

[1]Department of Astronomy, New Mexico State University, Las Cruces, New Mexico, USA.
[2]Downs Laboratory, California Institute of Technology, Pasadena, California, USA.
[3]Institute for Physical Science and Technology, University of Maryland, College Park, Maryland, USA.
[4]NASA/Goddard Space Flight Center, Greenbelt, Maryland, USA.

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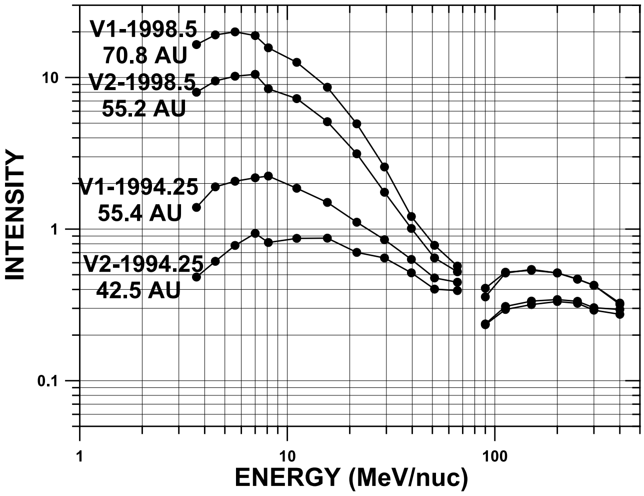

Figure 1. Spectra of He nuclei measured at V2 and V1 in 1994 and 1998 in the positive polarity cycle. Intensities are in units of particles/m^2•sr•s•MeV/nuc for Figure 1 and also Figures 2–6.

polarity cycles are large. These changes are energy-dependent as well as dependent on radial distance and solar modulation level. In this paper we shall concentrate on the spectra of anomalous He nuclei from a few MeV/nuc to ~70 MeV/nuc at various locations in the heliosphere and during different solar magnetic polarity time periods. In late 2002 the intensity of low-energy protons and helium nuclei of a few MeV/nuc, abruptly increased by large factors at V1 which was at 85 AU at that time whereas no significant changes were observed at V2 located at 69 AU [*McDonald et al.*, 2003; *Krimigis et al.*, 2003]. The spectra and intensities of anomalous He, observed at both V1 and V2 at this time in 2002, were also greatly different than those observed at these spacecraft just a few years earlier in 1998–1999 [*Stone and Cummings*, 2003]. In the intervening time the solar magnetic polarity had changed from positive in 1998–1999 to negative by 2002–2003. In an effort to study these spectral and intensity differences, we have examined the temporal and radial variations of the spectra of anomalous He nuclei observed at IMP, P10, V1 and V2 since the launch of these spacecraft in the 1970s with particular emphasis on the time period from 1998 to the present.

2. Data and Interpretation

2.1. Energy Spectra of Anomalous He Nuclei

[3] The differential energy spectra of the anomalous cosmic ray components in the heliosphere provide unique information on the acceleration process and the subsequent propagation of these particles both near the HTS and also in the heliosphere inside this shock [e.g., *Cummings et al.*, 1984]. In this study we shall make use of the energy spectra of anomalous He nuclei as indicated. This work is an extension of recent studies of these spectra and intensity variations by *McDonald et al.* [2001], *Cummings and Stone* [2001], and also by *Hill et al.* [2003] with emphasis in this paper on the different positive and negative solar magnetic polarity time periods and data after 1998.

[4] The He spectra measured at V1 and V2 in 1994 and 1998 are shown in Figure 1 [see, e.g., *Stone et al.*, 1999; *Cummings and Stone*, 2001]. The anomalous He component below ~100 MeV/nuc is easily observable since the modulated galactic component which dominates the spectrum above ~100 MeV/nuc is believed to have a spectrum which decreases with energy ~$E^{0.80}$ below 100 MeV/nuc (see below). The unfolding of the anomalous spectra at lower energies shown in Figure 1 is believed to be the result of the decreasing overall solar modulation between 1994 and 1998, as well as the increasing radial distance of the spacecraft [e.g., *Stone and Cummings*, 1999]. It is also generally argued that when these spectra are further demodulated to the location of the HTS, which is where they are believed to be accelerated, this demodulated spectrum would represent a composite accelerated spectrum "at the shock" [e.g., *Cummings et al.*, 2002].

[5] In Figure 2 we show again the He spectrum measured in 1998 at V1 at ~71 AU at a time of positive solar magnetic polarity. Also shown in Figure 2 as a dotted line is the He spectrum measured at P10 at 42 AU in 1987, also at a time of peak intensity (low solar modulation) but now at a time of negative solar magnetic polarity. Both of these spectra are also shown with a ~$E^{0.80}$ galactic He component subtracted as shown by a dashed line below ~100 MeV/nuc. The $E^{0.80}$ form for the low-energy galactic helium is derived from the shape of the galactic carbon spectrum observed below ~100 MeV/nuc by Voyager [*Webber et al.*, 2003] and also from calculations using the spherically symmetric transport equation [*Caballero-Lopez and Moraal*, 2004] which gives a spectrum of the form ~$E^{0.80}$ which fits both galactic helium and carbon nuclei at low energies.

[6] The anomalous He spectra observed in 1987 and 1998 both at times of minimum modulation are greatly different;

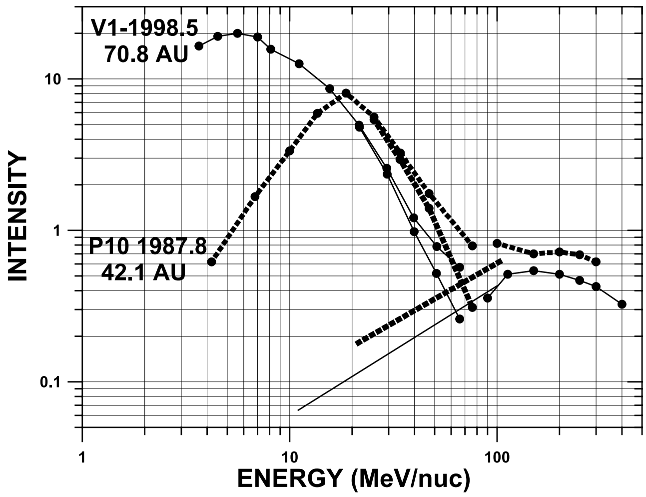

Figure 2. He spectra measured at V1 in 1998 compared with that measured by P10 in 1987 (dotted line) in a negative solar magnetic polarity period. Note the crossover of the spectra between ~15 and 20 MeV/nuc. Bottom solid and dotted lines show the estimated galactic He spectrum at low energies, based on the measured (normalized) carbon spectrum. The anomalous He spectra corrected for this galactic contribution are shown by the top solid and dotted lines for each polarity cycle, both of which correspond to a spectrum with exponent = -2.80 ± 0.20 above 25 MeV/nuc. See color version of this figure in the HTML.

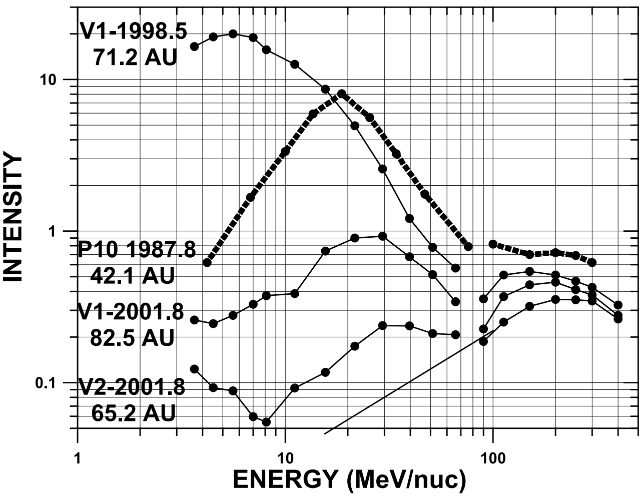

Figure 3. He spectra measured at the minimum intensity level of the 11-year modulation cycle at 2001.8 ± 0.2 at V1 and V2. Also shown is the He spectrum measured at V1 in 1998 and the He spectrum measured at P10 in 1987 (dotted line) during a similar negative solar magnetic polarity period to that at 2001.8. Solid line shows the estimated galactic He background below 100 MeV/nuc for the V2 measurement at 2001.8. See color version of this figure in the HTML.

the peak energy has changed from ~5 MeV in 1998 to ~20–25 MeV in 1987. The two anomalous He spectra actually cross over so that the 1987 spectrum is much depressed at lower energies, but is actually a factor ~2 higher at higher energies where the energy spectra for each of the two time periods, after correction for the galactic component, appear to asymptotically reach a similar constant spectral index of −2.80 ± 0.20 above ~30 MeV/nuc.

[7] Some of these spectral differences in the two polarity cycles are undoubtedly related to different modulation conditions in the outer heliosphere, (e.g., diffusion coefficients) and to the different heliocentric radii at the two times in 1987 and 1998, but the fact that the spectra actually cross over suggests the possibility that the "input" anomalous He spectra near the HTS itself in the two polarity cycles could also be different. It is therefore possible that differences seen in the two spectra at lower energies between 1987 and 1998 could be due to both differences inside of the HTS as well as intensity differences at or along the HTS in the two polarity cycles. One should recall that, in the negative cycle in 1987, these anomalous particles are believed to enter the heliosphere inside the termination shock near the heliospheric equator whereas in the positive cycle in 1998 they will enter mainly over the poles, in both cases after first drifting in opposite directions along the HTS from their region of acceleration. Thus any spectral difference "at the HTS" need not be related to the actual accelerated spectra themselves, but to other effects occurring at or along the HTS which modify the accelerated spectrum before it enters the region inside of the HTS where it is observed by V1 and V2 at heliocentric latitudes ~34° and 22° respectively in 1998. One should also note that in addition to possible latitude gradients which are expected to be small, radial gradients also play a role in the intensity and spectral differences. These gradients are expected to be small in the outer heliosphere in the positive polarity periods but may be larger in the negative period in 1987 and also in 2001 and 2002.

[8] After the high anomalous He intensities measured at V1 and V2 in 1998–1999 at a time of minimum solar modulation (as shown in Figure 1) the intensities abruptly decreased in 2000–2001 corresponding to the onset of the new solar modulation cycle and the change in magnetic polarity. This decrease amounted to a factor ~30× for 10–20 MeV/nuc anomalous He and to a decrease ~5× for 35–45 MeV/nuc anomalous He and was therefore highly energy-dependent. The He spectra measured at the minimum intensity between 2001.5 and 2002.0 at V1 at 83 AU and V2 at 66 AU are shown in Figure 3 again along with the He spectrum measured at P10 in 1987 at 42.5 AU at a time of negative solar magnetic polarity and the spectrum measured in 1998 at a time of positive polarity. The negative polarity spectra observed for anomalous He in 1987 at P10 and again in 2001 at V2 and V1 are similar but with lower intensities in 2001, and suggest now that, at 2001.75 in the outer heliosphere, the anomalous He spectrum has changed from that observed in 1998–1999 to that more appropriate of a negative solar magnetic polarity period similar to that in 1987 but at a much higher modulation level. This change is consistent with the change in magnetic polarity observed at the Earth early 2001 and then later in 2001 at V1 and V2.

[9] Between 2002.0 and 2004.0 the anomalous He intensities recover only very slightly at V2 but at V1 the anomalous He intensity increases abruptly at energies above ~10 MeV/nuc between about 2002.55 and 2003.1. The anomalous He spectrum measured at V1 during this period of increased intensity is shown in Figure 4, along with the spectrum measured at V2 at the same time, again along with the He spectrum measured at P10 in 1987. The anomalous He spectrum at V1 at 87 AU above ~10 MeV/nuc during this time period is roughly a factor ~6 higher at all energies

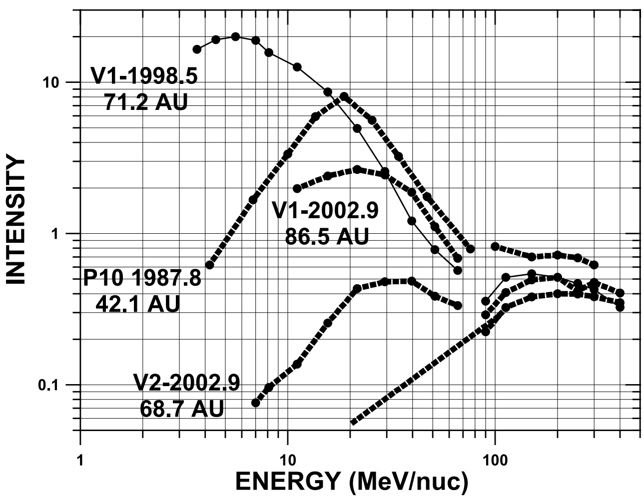

Figure 4. He spectra measured between 2002.6 and 2003.1 at V1 and V2 (dotted lines). Also shown are the P10 spectrum in 1987 (dotted line) and the V1 spectrum in 1998. Bottom dotted line shows the estimated galactic He background below 100 MeV/nuc for the V2 measurement at 2002.9. See color version of this figure in the HTML.

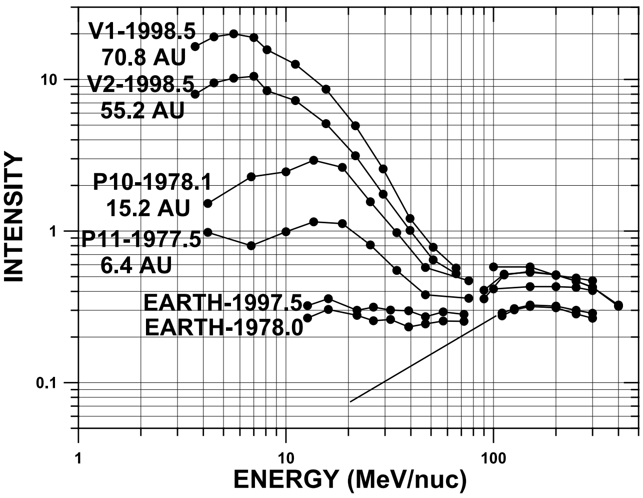

Figure 5. He spectra measured at the positive polarity cycle modulation minima in 1977–1978 and 1997–1998 at the Earth, P10, P11, and V1 and V2. Solid line shows the estimated galactic He background below 100 MeV/nuc for the spectrum at the Earth. P10, P11, and the Earth 1977–1978 data are from *Webber et al.* [1981, and references therein].

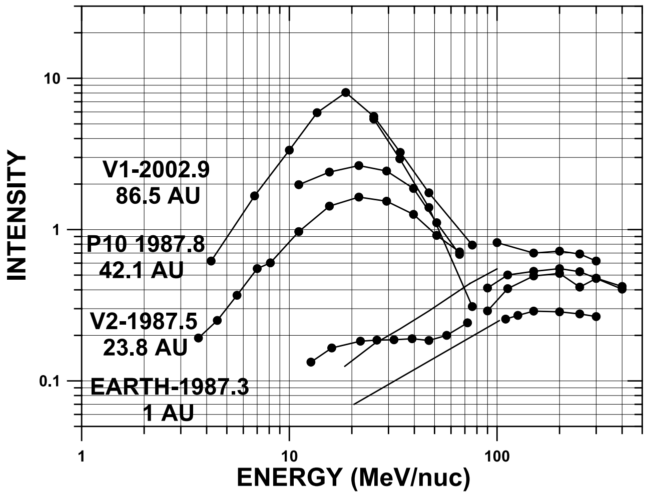

Figure 6. He spectra measured at the negative polarity modulation minimum in 1987 at the Earth, V2, and P10. Also shown is the spectrum measured at V1 at 2002.9 at 86.5 AU in a negative polarity period. Bottom solid lines shows estimated galactic He background below 100 MeV/nuc for the spectrum at the Earth and at P10 for 1987.8. Top solid line shows corrected anomalous He spectrum at P10 (see also Figure 2).

than the spectrum measured over the same time period at V2 which is now at 69 AU. It is also very similar in shape, although still with a lower intensity, to the anomalous He spectrum measured in the previous negative polarity cycle in 1987 at P10 when it was at 42 AU.

2.2. Energies of the Spectral Peaks

[10] One approach to understanding the complex differences in the anomalous He spectra in the different solar magnetic polarity cycles is to examine the changes in the energy of the peak intensities of the individual spectra. *Jokipii* [1990] has noted that for full drift effects, both along the termination shock and within the heliosphere, the peak in the positive polarity cycle could be a factor ~3 times lower in energy than in the negative cycle. In Figure 5 we show He spectra measured at several radial distances at the time of minimum modulation at 1977–1978 at the Earth, P11 and P10 and again in 1997–1998 at the Earth, V2 and V1, all of these times in positive polarity cycles. A clear radial dependence is observed for the peak energy. Spectra at times of minimum modulation at 1987 measured at the Earth, V2 and P10 in the negative polarity cycle are shown in Figure 6 along with He spectrum measured by V1 at 86.5 AU during the period from 2002.6 to 2003.1. In the negative cycle the change in peak energy with radius is less evident. From the spectra in Figures 5 and 6 we estimate the peak energies for the anomalous He spectra after correction for the $E^{0.80}$ spectrum of low-energy galactic helium. These peak energies are plotted in Figure 7 as a function of heliocentric radius for the two polarity periods. The solid and dotted lines are drawn by eye between the data points at different radii to illustrate the differences in the peak energies as a function of radius and for the different polarity cycles. In the negative cycle at the modulation minimum in 1987 the peak energy is ~20 MeV/nuc at the Earth, V2 and P10 and shows only a weak dependence on radius. The peak energy for the anomalous He spectrum measured at V1 at the time of the intensity increase from 2002.6–2003.1 lies on this same dashed line with a peak energy ~20 MeV/nuc.

[11] At the positive polarity cycle modulation minima in 1978 and 1998–1999, the peak energy is notably lower at V1 and V2 at 71 and 56 AU respectively and at all radial distances, e.g., the 1978 P10 spectrum at ~15 AU, than the peak energy in the negative polarity cycle. The radial dependence of the peak energy thus appears to be greater in this cycle as though the spectrum was unfolding as a function of radius (see also Figure 1) because of possibly a

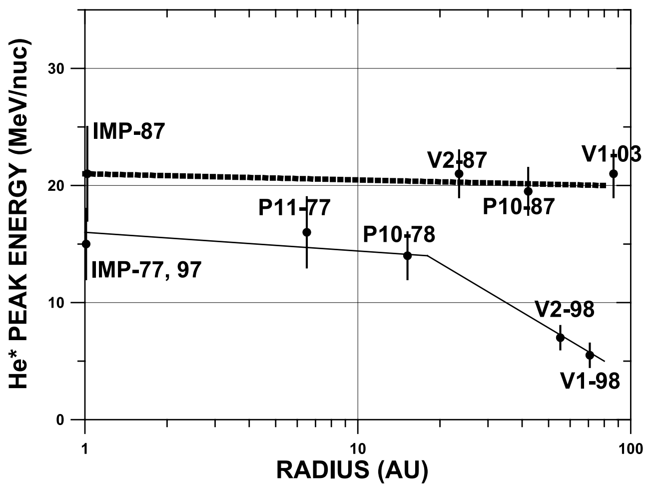

Figure 7. Peak energies for anomalous He nuclei spectra as a function of heliocentric radius. Shown are minimum modulation measurements, positive polarity cycle, 1977-1 AU, 1978-6.5 AU (P-11), 1978-15 AU (P10), 1998-56 AU (V2), and 1998-71 AU (V1). Negative cycle (dotted line) 1987-1 AU, 1987-23 AU (V2), and 1987-42 AU (P10). Also shown is the peak energy measured between 2002.6–2003.1 ≡ 03–86 AU (V1). Solid and dotted lines are for the eye.

decreasing modulation with heliospheric distance. Also in 1998 the peak energy for anomalous He as measured by V1 was ~5 MeV/nuc or about 1/4 of the peak energy of ~20 MeV/nuc measured at P10 in 1987 at a time of negative magnetic polarity. *McDonald et al.* [1992] have also examined differences in the peak energy between the negative cycle in 1987 at P10 at 42 AU and the positive cycle in 1978 at 15 AU. The respective energies of 20 and 15 MeV/nuc for the peak energy that they obtain agree with those shown in Figure 7.

3. Discussion of the Data and a Comparison With Models

[12] Most models used to describe anomalous particle temporal variations in the heliosphere assume a simple input spectrum at the location of the HTS, essentially the same in the different polarity cycles and unchanged from the accelerated spectrum itself by any effects occurring at or near the HTS. Differences in the intensities and spectra observed in the two polarity cycles within the heliosphere are then attributed to differences in modulation effects in the heliosphere inside of the HTS. These simple models can account for many of the spectral features observed, for example, the ratio of the peak energies for anomalous H (~20 MeV) and for anomalous He (~5 MeV/nuc) which is ~4 in 1998 can be explained simply by diffusion inside the HTS with a diffusion coefficient ~rigidity$^{-1.0}$ [*Moraal and Steenberg*, 1999]. *Stone and Cummings* [1999] have recognized, however, that intensity differences at the HTS in the two polarity cycles may also play an important role in understanding the temporal variations of 7–17 MeV/nuc anomalous O nuclei. The energy-dependent differences of the anomalous He spectra in the negative and positive polarity cycles indicated in the present study also suggest that the role of the HTS region itself in determining the input spectra of the anomalous components needs to be modeled in more detail. Such calculations are beyond the scope of this article whose main goal is to summarize those features that need to be explained by a more complete model.

[13] The features that such models need to explain are as follows:

[14] 1. The well defined differences in the anomalous He spectra that are observed throughout the heliosphere in the two solar magnetic polarity cycles. This includes a crossover of these spectra at ~15–20 MeV/nuc such that the intensities above this energy are roughly a factor of ~2 or more higher in negative cycles, but below this energy the intensities are much lower with a near absence of particles below ~10 MeV/nuc in the negative cycles. These differences between negative and positive cycle spectra should reflect modulation conditions inside of the HTS as well as possible spectral differences between cycles near the HTS itself.

[15] 2. The fact that the peak energy of the anomalous He spectrum in the outer heliosphere near 80 AU changes from ~5 MeV/nuc in a positive polarity cycle in 1998 to ~20–25 MeV/nuc in negative polarity cycle in 2001–2002 (but at a higher modulation level). These energy differences of the peaks between polarity cycles are also a function of heliospheric radius as can be seen in Figures 5, 6, and 7. The specific radial dependence of these peak energies should reflect modulation conditions such as a changing diffusion coefficient (modulation level) and changing drift patterns as well as the changing entry of the anomalous particles into the inner heliosphere in the two polarity cycles.

[16] With these comments in mind, we note that recent models of anomalous particle acceleration at the HTS and subsequent propagation, which specifically include an HTS embedded within a larger modulation region extending to the heliopause, do predict differences in the anomalous spectra between negative and positive solar polarity cycles. The work of both *Florinski and Jokipii* [2003] and *Potgieter and Langner* [2003] following the earlier work of Jokipii and Kota as shown by *Webber et al.* [1998] show significant differences in the anomalous He spectra in the different polarity cycles near the heliospheric equator, for example. These theoretically calculated HTS spectra are expected have a power law portion at lower energies and roll over to a very steep spectrum at high energies. The power law spectral index γ is related to the shock strength s by $\gamma = (s + 2)/(2 - 2s)$ and thus equals 2 for a value of shock strength equal 2 (for s = 3.2 the spectral index ~1.2). The anomalous spectra that are suggested by the models in the two polarity cycles are similar at lower energies, however at the higher energies a distinct bump is noted in the spectra for negative polarities, relative to that for positive polarities. This bump is in excess to the simple power law spectrum that occurs for positive polarities and results in an excess intensity in negative cycles at energies just below the rollover to a very steep spectrum. When this HTS difference is coupled with propagation calculations the resulting spectra within the heliosphere in the two polarity radial intensity profile cycles are indeed different in these models.

[17] Such a difference in the spectra of anomalous He between polarity cycles will be reflected in the measured radial intensity profiles of He at a fixed energy, for example 10–21 MeV/nuc, and is also seen in the calculated radial profiles at that fixed energy by Jokipii and Kota as shown by *Webber et al.* [1998]. The observed anomalous He intensities between 10–21 MeV/nuc as a function of radius at the minimum modulation periods in 1978, 1987 and in 1997–1998 as obtained from Figures 5 and 6 are shown in Figure 8. The differences between these radial intensity profiles at a fixed energy at the times of the positive polarity cycle minimum modulation in 1978 and again in 1997–1998 and at the negative cycle minimum modulation in 1987 are striking and are one illustration of the different anomalous He spectra in the two polarity cycles.

4. Summary and Conclusions

[18] The anomalous He spectra measured throughout the heliosphere are markedly different in the negative and positive solar magnetic polarity cycles. This point has been noted earlier in the work of *McDonald et al.* [1992, 2001] and is emphasized again in this paper. The peak energy of the anomalous He spectrum at ~80 AU measured by V1 differs by a factor of ~4 between polarity cycles, changing from ~5 MeV in a positive polarity cycle to ~20 MeV in a negative polarity cycle (Figure 7). The anomalous He spectra themselves in the two polarity cycles actually appear to cross over between ~15–20 MeV/nuc, with the intensities in the negative cycle being 2–3 times higher than those

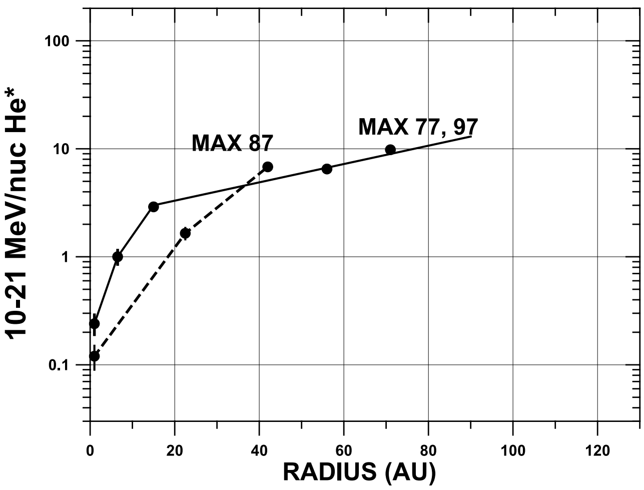

Figure 8. Radial intensity profiles of 10–21 MeV/nuc anomalous He nuclei at times of minimum modulation in 11-year cycles of positive solar magnetic polarity in 1977–1978 and 1997–1998 and the negative solar magnetic polarity cycle in 1987 (dashed line). Points at 6.5 and 15 AU are from P11 and P10 data in 1977–1978 [*Webber et al.*, 1981]. Points at 56 and 71 AU are from V2 and V1 data in 1998. Points at 23 and 42 AU are from V2 and P10 data in 1987. Errors at 1 AU are mainly due to subtraction of galactic component with an estimated uncertainty of ±20%. See color version of this figure in the HTML.

in the positive cycle above ~30 MeV/nuc. At lower energies, however, the intensities in the negative cycle are much lower under comparable circumstances than those in the positive cycle (e.g., Figures 2, 3, and 4). In spite of these complex differences at lower energies, the anomalous He spectra at energies above ~30 MeV/nuc asymptotically appear to approach a constant spectra index = −2.8 ± 0.2 in both polarity cycles. Also the radial intensity profiles of anomalous He at a fixed energy of 10–21 MeV/nuc as shown in Figure 8 show large differences between the two polarity cycles indicative of these spectral differences. The anomalous He intensities at this fixed energy of 10–21 MeV/nuc at a distance of ~90 AU as estimated from Figure 8 are much lower in the positive cycle than those extrapolated to this distance in the negative cycle.

[19] Subsequent measurements at both V1 and V2 along with improved calculations should greatly add to our understanding of the acceleration and propagation of these nuclei at or near the HTS. This process, which is probably illustrative of the acceleration of particles at similar termination shocks around other stars in the galaxy, is now accessible to direct measurement for the first time near the Sun's own termination shock.

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A. C. Cummings and E. C. Stone, Downs Laboratory, California Institute of Technology, Pasadena, CA 91125, USA.

N. Lal and B. Heikkila, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

F. B. McDonald, Institute for Physical Science and Technology, University of Maryland, College Park, MD 20742, USA.

W. R. Webber, Department of Astronomy, New Mexico State University, Las Cruces, NM 88003, USA. (bwebber@nmsu.edu)