Temporal and spectral variations of anomalous oxygen nuclei measured by Voyager 1 and Voyager 2 in the outer heliosphere

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[1] We have studied the temporal and spectral variations of anomalous oxygen nuclei at the Voyager 1 (V1) and 2 (V2) spacecraft in the outer heliosphere from 1990 to the present time in 2006 when V1 is now beyond the heliospheric termination shock. During this time period, the intensities increased from their lowest values in 1990–1991 up to a maximum in 1998–1999 and then decreased rapidly in 2000–2001 in time coincidence with the change in solar magnetic polarity from positive to negative. During the time period after 2001, significant changes in intensities and spectra are observed relative to the earlier period of positive solar magnetic polarity before 2001. It is found that the intensities of O above ~10 MeV/nuc at V1 after ~2002.0 were higher relative to the same galactic cosmic ray He intensity between 150–380 MeV/nuc than in the earlier time period. As a result, by 2006 these intensities were a factor ~3 times those measured at the intensity maximum in 1998–1999 in the previous polarity cycle. The changes observed at V2 followed a similar pattern, but the relative intensity changes of O were a factor ~2 times greater than those observed at V1. Also, above ~10 MeV/nuc, the intensity changes at V1 and V2 were nearly energy independent, and the spectra at all times before and after the solar magnetic polarity change and at all modulation levels remained $\sim E^{-3.0\pm0.2}$, possibly characteristic of a "source" spectrum. When V1 crossed the termination shock, no noticeable spectral or intensity changes were observed.

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1. Introduction

[2] The intensities and spectra of anomalous cosmic rays undergo large changes as a result of the solar 11- and 22-year modulation cycles. These changes have been observed throughout the heliosphere on Earth and at the Ulysses, Voyager, and Pioneer spacecraft. These changes are generally much larger than those for galactic cosmic rays of the same charge and rigidity. They are largest for anomalous Hydrogen (≡H*) which has the lowest rigidity, still very large for anomalous Helium (≡He*), and smallest (but still larger than those for galactic cosmic rays) for anomalous Oxygen (≡O*). For a given charge, these intensity changes also show a strong rigidity (energy) dependence as well as striking effects that depend on the 22-year solar magnetic polarity cycle [e.g., *Cummings and Stone*, 1999; *Hill et al.*, 2003; *McDonald et al.*, 2005; *Webber et al.*, 2006].

[3] On Earth, these 11-year intensity changes are so large that H* and He* disappear beneath the modulated galactic spectra at times of large solar modulation and thus cannot be followed through an entire 11–22 year modulation cycle. This has also been true in the past for O*. However, in the most recent 11-year cycle when the O intensity was at a minimum from 2001–2004, it has been possible to observe the characteristic O* spectrum with the more sensitive Advanced Composition Explorer (ACE) instruments [*Leske et al.*, 2005]. As one moves outward in the heliosphere, things get somewhat better. However, even during the period of minimum cosmic-ray intensities in 1990–1991, only O* was clearly observable at Voyager 1 (V1) and 2 (V2) at 38 AU and 33 AU, respectively; the H* and He* components were lost under the galactic particle background or background from solar/interplanetary cosmic-ray events propagating outward in the heliosphere. During the most recent intensity minimum in 2001–2004, H* completely vanished at both V1 and V2 at ~74 and 57 AU, respectively [*Webber et al.*, 2006]; He* was still present but with a greatly modified spectrum [*Webber et al.*, 2005; *McDonald et al.*, 2006]. This was also the case for

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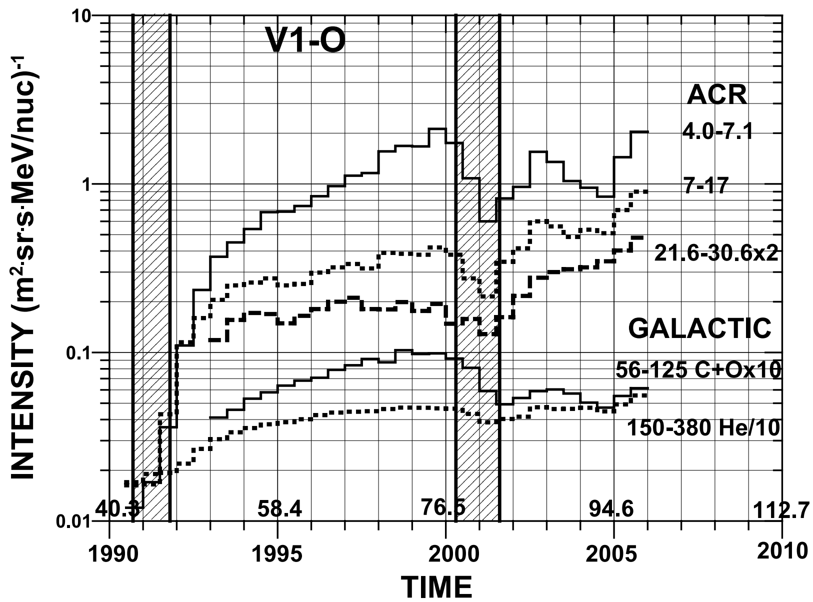

Figure 1a. Intensity versus time for various energies of ACR O and GCR at V1 from 1990 to 2006. The radial distance of V2 in AU is shown along the bottom axis. The GCR C and O spectra are summed in the 50–125 MeV/nuc energy intervals to improve statistics.

O*, which could be followed most easily because of its distinctive spectrum. In what follows, we will examine the temporal and spectral variations of the O* component at V1 and V2 from the lowest intensities in 1990–1991 to the maximum intensities in 1998–1999, to the minimum in 2001–2004, and up to the current time in 2006 when V1 is approaching 100 AU and is well beyond the heliospheric termination shock (HTS), and V2 is at ~80 AU and presumably near to but just inside the HTS.

[4] In the time period after the 2001–2004 intensity minimum, the O* intensities have increased dramatically at both V1 and V2, and the spectra have changed from those observed before 2001. However, no significant increase in O* was observed by V1 as it crossed the HTS at the end of 2004. The O* intensities at V1 have continued to steadily increase from their lowest levels in 2004 just before the HTS crossing to their highest levels today at 2006.5, when V1 is most likely ~5–10 AU beyond the nominal HTS location.

2. The Data: Temporal Changes

[5] Figures 1a and Figure 1b show the 6-month average intensities for V1 and V2, respectively, from 1990 to the current time. Three O* energy intervals are shown, 4.0–7.1, 7.1–17.1, and 21.6–30.6 MeV/nuc. In addition, the

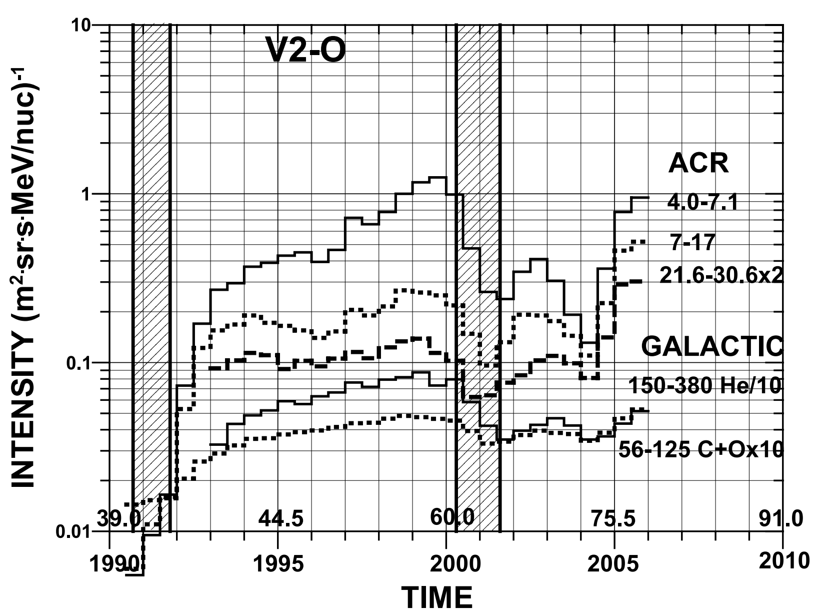

Figure 1b. Intensity versus time for various energies of ACR O and GCR at V2 from 1990 to 2006.

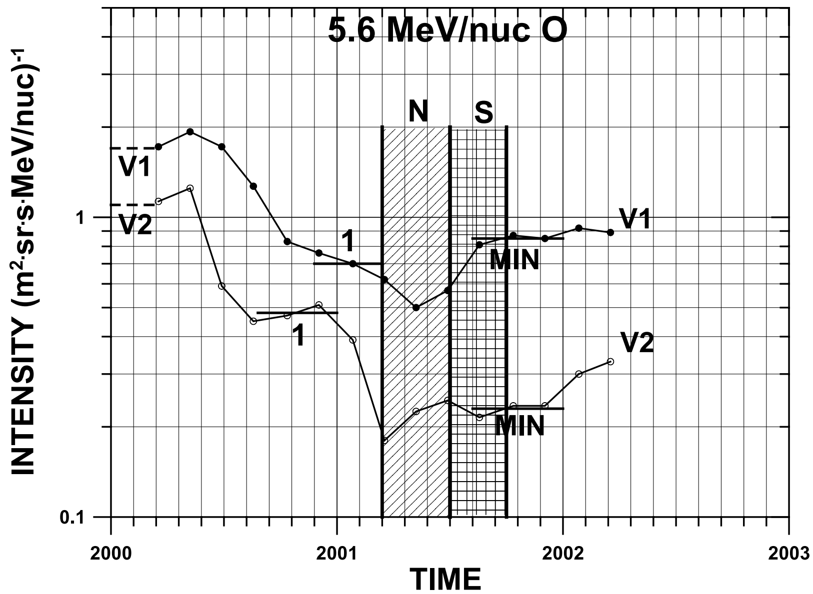

Figure 2. Intensity versus time for 4.0–7.1 MeV/nuc O nuclei between 2000 and 2002 at V1 and V2. Shown are 52-day averages. Time periods (1) and min are discussed in the text.

intensities of 56–125 MeV/nuc C + O nuclei and 150–380 MeV/nuc He nuclei are shown. The later two intervals are mainly galactic particles. The intensity increase from 1991–1992 to 1998–1999 is clearly seen in all components, both galactic and anomalous, but is much larger for the lowest energy 4.0–7.1 MeV/nuc O* nuclei. This increase is due to the recovery of the 11-year modulation cycle and to the increasing intensity with heliocentric radius, which is determined by the radial-intensity gradient. In 2000, the intensity at both V1 and V2 begins a rapid decrease which is over by the end of 2001. This decrease is shown in Figure 2 on an expanded timescale for 4.0–7.1 MeV/nuc O* nuclei using 52-day averages. The two main decreases, 1 and 2, occurring at approximately 2000.4 and 2001.1 for V2 and 2000.6 and 2001.3 for V1, coincide with much larger decreases of H* [*Webber et al.*, 2006] and He* [*Webber et al.*, 2005; *McDonald et al.*, 2006], as well as decreases of higher-energy galactic cosmic rays [*Webber and Lockwood*, 2004; *McDonald et al.*, 2005]. The time period (1) shown in Figure 2 is a period of nearly constant intensity where the spectra of O* can be obtained, likewise for the time period labeled ''min'' from about 2001.6–2002.0. This time

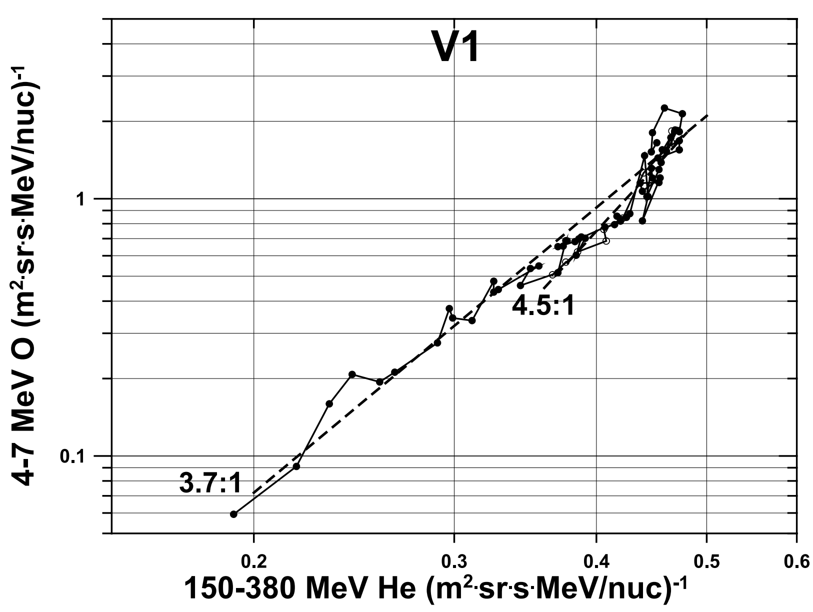

Figure 3. Regression curves of 4–7.1 MeV/nuc O nuclei versus 150–380 MeV/nuc GCR He nuclei for V1; 1992–1999 period of increasing intensity shown as solid circles, 2000–2001.5 period of decreasing intensity shown as open circles.

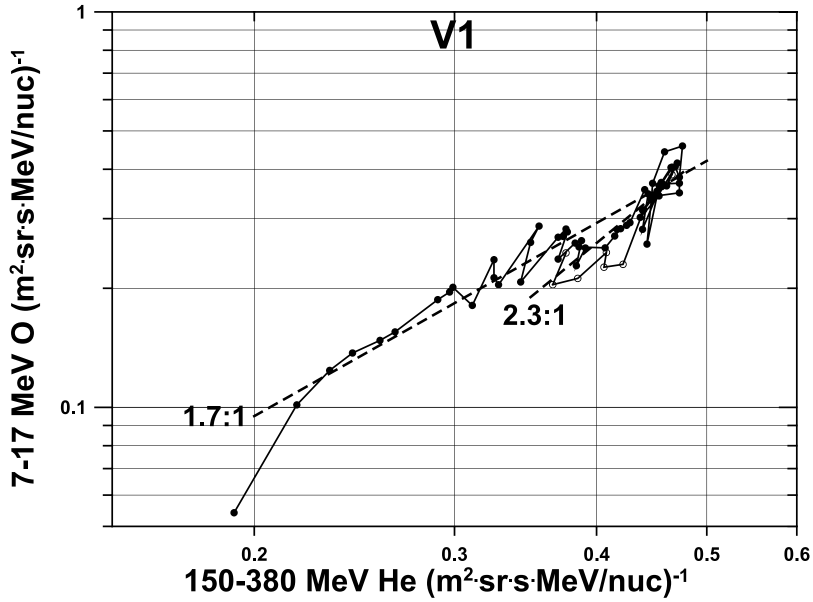

Figure 4. Same as Figure 3 but for 7–17 MeV/nuc O nuclei.

period is labeled "min" because it is the time when H* was at its minimum intensity [*Webber et al.*, 2006]. As can be seen in Figure 2, the intensity of O* had already started to recover at this time. So the intensity changes of H* and O* are no longer time coincident at that time.

[6] The time period from ~2001.5 to 2002.0 is particularly interesting. It is a time period when significant changes in the shape of the O* spectra are observed. In Figure 2, we show as a shaded region the approximate times at which the solar magnetic field changed from positive to negative in 2000–2001 in the north and south polar regions, as derived from solar magnetograph and chronograph observations and source surface extrapolations by *Wang et al.* [2002], delayed by 1.0 year because of the estimated solar wind traveltime from the Sun to the HTS [e.g., *McDonald et al.*, 2006].

[7] To examine the temporal changes in the extended time period from 1990 to the present time, we show in Figures 3–5 the regression curves at V1 comparing three energies of O* with galactic cosmic rays as represented by 150–380 MeV/nuc He nuclei. The curves for V2 are very similar and are therefore not shown. The time period of increasing intensities from 1992 to 1999 is shown as black dots connected in successive 52-day or 6-month time intervals. The open circles show the time period from 2000 to 2001.5 when the intensities were decreasing but the solar magnetic polarity remained the same. Both of the regression lines for periods of increasing and decreasing intensities have similar logarithmic slopes which are slightly larger during the decreasing intensity phase from 2000 to 2001.5. Also, the slopes of the regression lines for V2 and

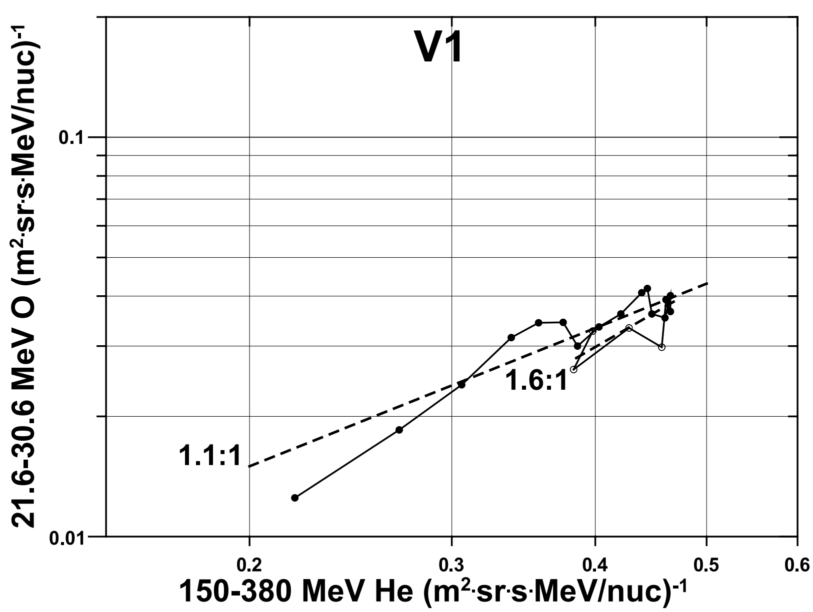

Figure 5. Same as Figure 3 but for 21.6–30.6 MeV/nuc O nuclei.

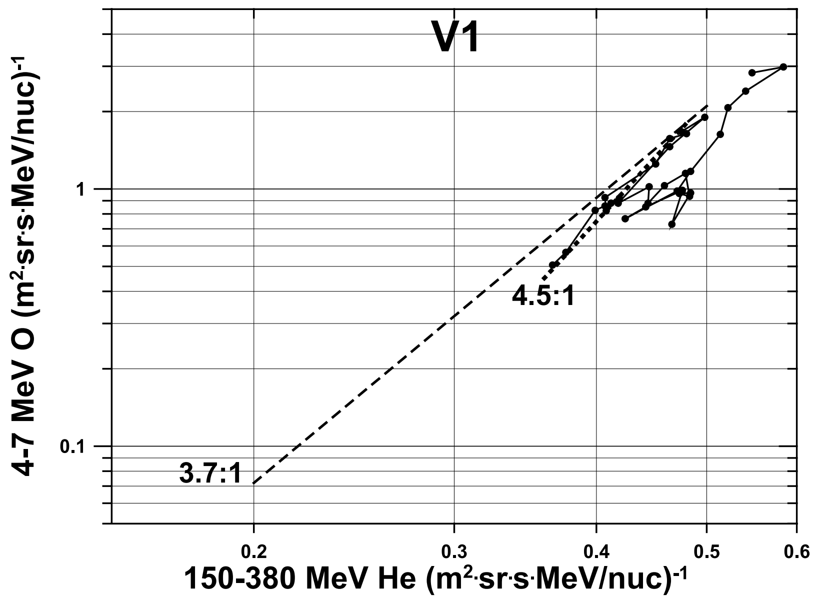

Figure 6. Regression curves of 4–7.1 MeV/nuc O nuclei versus 150–380 MeV/nuc GCR He nuclei for V1 from 2001.5 to 2006.5. Dashed line is regression curve during increasing intensity period from 1992 to 1999. Dotted line is for decreasing intensity period from 2000 to 2001.5.

V1 are nearly the same for each energy. The dashed lines are simple fits to the data and may obscure more complex temporal variations such as apparently occurred in 1995–1996. One obvious feature of these figures is that the values of the logarithmic slopes of the intensity changes are strongly dependent on energy and, for the highest energy (21.6–30.6 MeV/nuc), are almost the same as for higher-energy galactic cosmic rays.

[8] After about 2001.5, the character of the regression curves completely changes. In Figures 6–8, the regression curves of O* versus 150–380 MeV/nuc He nuclei for the same three O* energies as above are shown for V1 to the end of data at 2006.5. Again, the features of these curves for V2 are very similar and not shown. For Figure 6, showing the 4.0–7.1 MeV/nuc O* nuclei, the intensities after 2001.5 are generally well below the intensities determined from the regression lines for the earlier time period which are shown as dashed lines in this figure. This means that for a fixed higher-energy galactic intensity as represented by the 150–380 MeV nuc He, the 4.0–7.1 MeV/nuc O* intensity after 2001.5 is less than it was prior to 2001.5. For V1, this decrease below the earlier regression lines appears only after a temporary intensity increase associated with the first V1 encounter with HTS particles between 2002.6 and 2003.1 [*Krimigis et al.*, 2003; *McDonald et al.*, 2003].

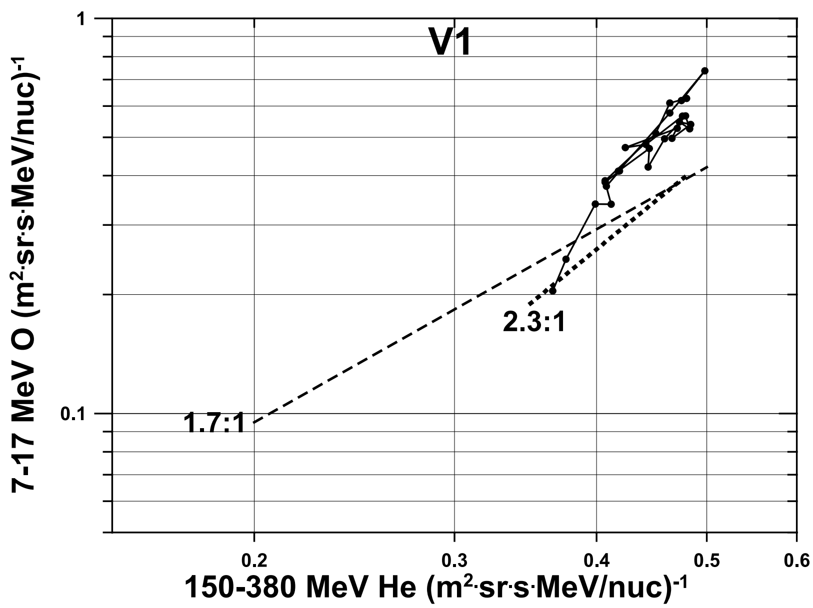

Figure 7. Same as Figure 6 but for 7–17 MeV/nuc O nuclei.

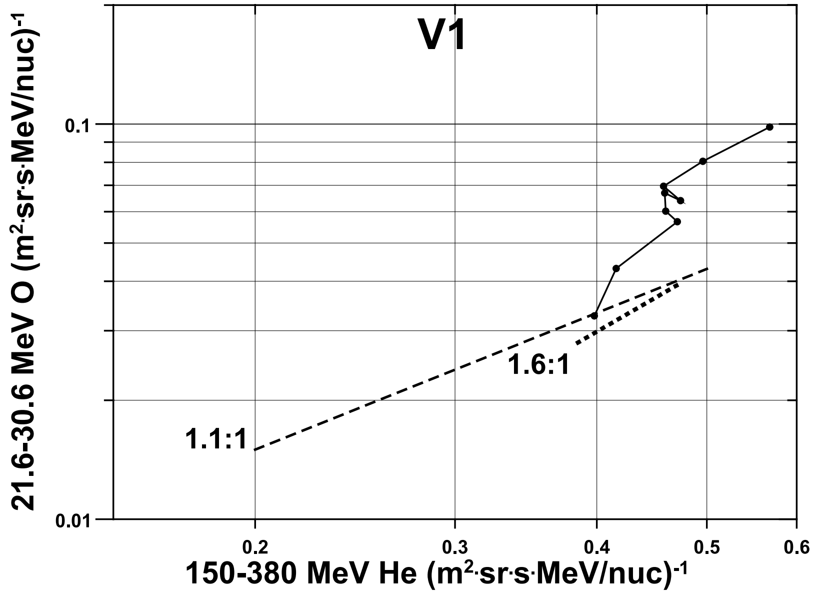

Figure 8. Same as Figure 6 but for 21.6–30.6 MeV/nuc O nuclei.

[9] For the somewhat higher energy 7.1–17.1 MeV/nuc O* nuclei shown in Figure 7, the data give a quite different picture. In this case after ~2001.5, the regression lines for V1 extend well above the regression line before ~2001.5 (for V2, this increase above the earlier regression line is delayed and occurs only after ~2004.5). In Figure 8, showing still higher energy 21.6–30.6 MeV/nuc O* nuclei, this changeover in the regression curves before and after 2001.5 is similar to the 7.1–17.1 MeV/nuc data but even more striking. The intensities at this higher O* energy for a fixed 150–380 MeV/nuc He intensity eventually become 2–3 times the intensities before 2001.5 for both V1 and V2, with most of this change taking place in 2002 at V1 (at V2, this change again occurs later, at about 2004.5). Essentially, the changes seen in Figures 6–8 define a new O* spectrum unfolding after 2001.5. This spectrum has different spectral characteristics and a 2–3 times higher intensity at the higher energies than the earlier spectra observed between ~1992 and 2001.5. These spectral characteristics and differences in intensity will be discussed in the following section.

3. The Data: Spectral Changes

[10] In Figure 9a, we show the O* spectra observed at V1 for five selected time periods. These time periods are 1999.0–2000.0, when the intensity was at its maximum in a positive solar magnetic-polarity cycle and before the intensity changes described in the previous section; between

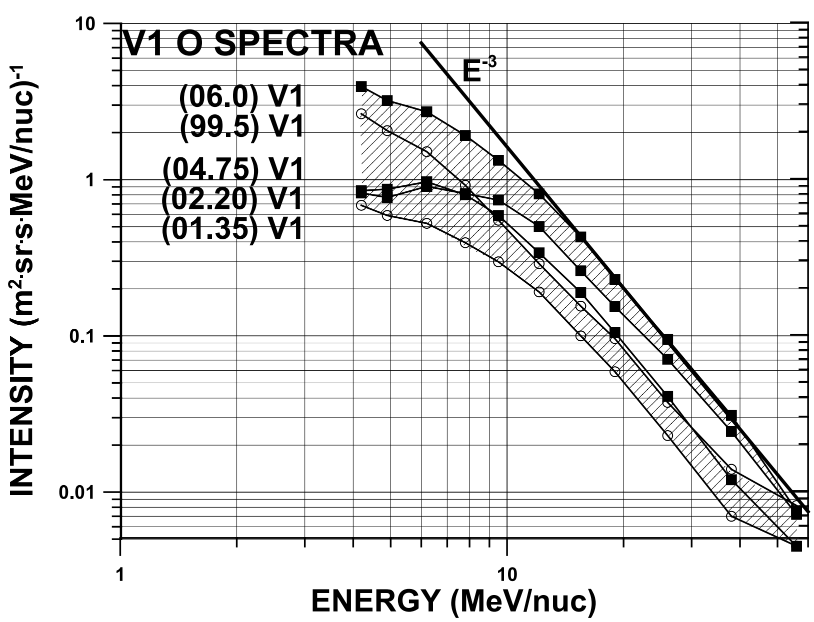

Figure 9a. O spectra measured at V1 at five times: (1) 1999.5; (2) 2001.2–2001.5; (3) 2002.0–2002.4; (4) 2004.6–2005.0; (5) 2006.5.

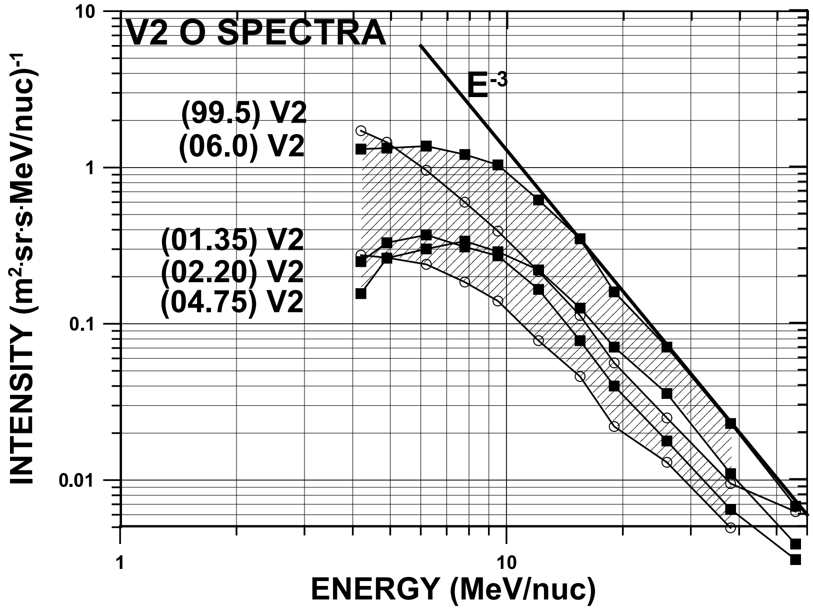

Figure 9b. Same as Figure 9a but for V2.

2001.1 and 2001.4, when the magnetic polarity was still positive but the intensity was near a minimum; at 2002.0–2002.4 and also 2004.5–2005.0 after the changeover in magnetic polarity had occurred and then after the regression curves had stabilized close to their new values for the negative solar magnetic polarity cycle but just before V1 crossed the HTS; and finally at 2006.5 when V1 was at ~100 AU and most likely 5–10 AU beyond the HTS. O* spectra for these same time intervals are shown for V2 in Figure 9b. In both cases, the spectra in the earlier positive polarity cycle before ~2001.5 are defined by open circles, and the new negative polarity cycle after ~2002.0 are defined by solid squares, with the differences between spectra in the same polarity cycle highlighted by shaded regions.

[11] In the positive polarity cycle, the fractional intensity decrease from 1999 to 2001.5 at V1, as seen in Figure 9a, is characterized by a strong energy dependence below ~10 MeV/nuc. However, above ~10 MeV/nuc, this fractional decrease is almost constant with energy corresponding to a decrease ~30% between ~10–40 MeV/nuc between the two time periods. At V2, shown in Figure 9b, the spectral changes from 1999 to 2001.5 are similar to V1, but the intensity differences between the high- and low-intensity time periods are larger. Between ~10–40 MeV/nuc, the intensity changes are again roughly constant with energy, but the decrease between the two time periods is now ~60% or about twice as large as V1.

[12] Turning now to the time period after 2002.0, we see that by about 2004.75, the intensities of O* at both V1 and V2 above ~10 MeV/nuc are now considerably larger than even those at the previous intensity maximum in 1999.5. However, at lower energies, the intensities after 2002.0 are smaller than those at 1999.5, and the spectra after 2002.0 actually reach a peak at ~6–8 MeV/nuc (no peak is seen in the positive polarity cycle data down to ~4 MeV/nuc). By 2006.5 at V1, the intensities have continued to increase above those at 2004.75 at all energies, but again, above ~10 MeV/nuc, the intensity increase is roughly constant up to ~40 MeV/nuc with an increase ~30% during this later time period. For V2, the intensity change between 2004.75 and 2006.5 is, in fact, much larger than at V1 as described above even though the absolute intensities at V2 are smaller. The intensity increase at V2 between these two time periods is also roughly constant between ~10–40 MeV/nuc with an increase ~60–80%, twice that of V1. The intensities below ~10 MeV/nuc at both locations at 2006.5 still have not evolved to a constant spectral index. Thus energy-dependent "modulation" effects exist at locations both inside and outside the HTS at these lower energies at 2006.5.

[13] Notice that the O* spectral index at V1 and V2 at times of both negative and positive polarity and also for different solar modulation levels becomes roughly constant at a value −3.0 ± 0.2 above 10–15 MeV/nuc. This point is illustrated again in Figure 10, which shows the V1 and V2 O spectra measured at the same time (2006.5). In this case, above 10–15 MeV/nuc, both V1 and V2 spectra are identical with a slope = −3.0 between ~15–40 MeV/nuc. The intensity at V1 is about 1.5 times that at V2.

[14] At energies below ~10 MeV/nuc, strong modulation effects are evident in both spectra, and these modulation effects are larger at V2 than at V1. Over time since 2004.75, these low-energy modulation effects have become less at both spacecraft as the intensities approach an $E^{-3.0}$ spectrum at the lower energies.

4. Discussion and Implications of the Data

[15] These data suggest that complex but systematic changes are occurring in the O* spectra and intensities at both V1 and V2. These intensity changes, both decreasing between 1999.5 and 2001.5 and increasing after 2002.0, are larger by a factor ~2 at V2 than at V1. Above ~10 MeV/nuc, the intensity changes have only a weak energy dependence and are, in fact, consistent with simple energy-independent intensity changes at both spacecraft for both the decreasing

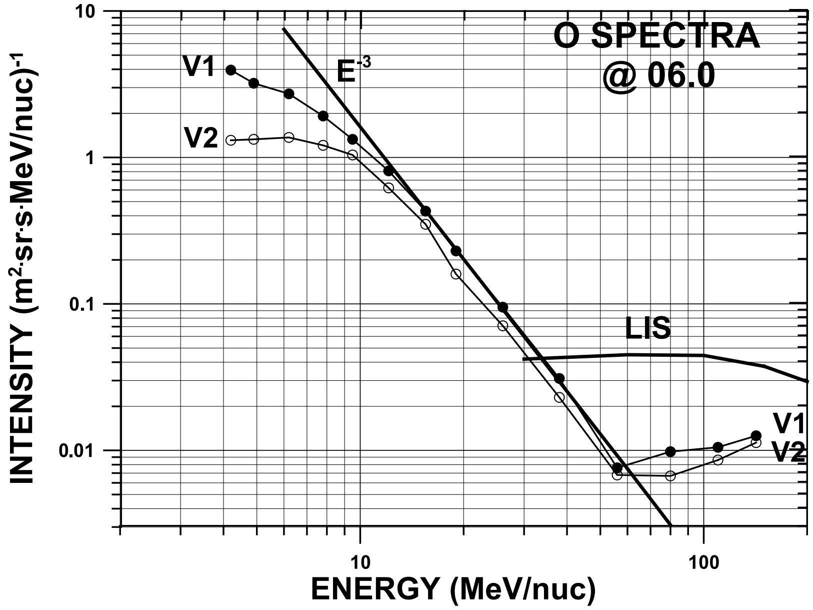

Figure 10. Overall O spectra measured at V1 and V2 at 2006.5, V1 = 100 AU, V2 = 80 AU. The estimated interstellar O spectrum ≡ Local Interstellar Spectra (LIS) from a Leaky Box model for interstellar propagation is shown [*Webber et al.*, 2003].

and increasing intensity time periods. This would be the case if the spectral intensities themselves above ~10 MeV/nuc simply moved up or down, maintaining the same spectral index. Below ~10 MeV/nuc, there are strong energy-dependent modulation effects at all times at both V1 and V2, encompassing locations both inside and outside the HTS.

[16] We therefore consider the spectral and intensity changes of O* in two energy regimes, (1) those at higher energies, above ~10 MeV/nuc, and (2) those at energies below ~10 MeV/nuc. Above ~10 MeV/nuc, where the changes are nearly energy independent, the intensity decrease between 1999.5 and 2001.5 occurs in lock-step with the decrease in galactic cosmic rays and with an amplitude that is comparable to that for 150–380 MeV/nuc galactic cosmic rays. During the period after 2002.0, there are two types of increases at energies >10 MeV/nuc. The first is a simple increase of a factor ~2–3 at both spacecraft relative to the intensities before 2001.5. The second is an increase related to the ongoing increase in galactic cosmic rays during this same time, with a relationship similar to that observed during the decreasing-intensity phase prior to 2001.5. The first type of increase essentially occurs over the short time period between 2001.3 and 2002.0 at V1 and somewhat later at V2, but at all energies it is complete by ~2004.5 at both spacecraft. The second type of increase is ongoing throughout the entire time period but is less at V1 than at V2.

[17] It should be noted that the higher energy regime above 10–15 MeV/nuc for O* corresponds to particles >40–60 MeV/nuc for He* and 160–240 MeV for H* (for equal total energies of all species). This higher energy regime is never observed for H* and only observed at the highest energies for He* because of the galactic cosmic ray (GCR) background. Thus for He* and H*, the intensity changes that are observed during this time are mostly those of the lower energy regime.

[18] The low energy regime below ~10 MeV/nuc for O* is characterized by large intensity changes and a strong energy dependence of these changes in both the decreasing intensity phase before ~2001.5 and also in the increasing intensity phase after 2002.0. These intensity changes are strongly correlated with corresponding changes of galactic cosmic rays as evidenced by the uniqueness of the regression curves between the lower energy O* nuclei and the 150–380 MeV/nuc GCR He nuclei, for example.

[19] At 2006.5 at V1 beyond the HTS and V2 just inside the HTS, the observed spectral turnover at the lowest energies is evidence for continuing modulation effects between the "source" and the spacecraft at this time.

5. The Transition Period From ~2001.3 to 2002.0 and Beyond

[20] In this time period, just as the minimum intensities were reached in 2001, there were large changes in the shape of the O* spectrum at V1 and also at V2. These changes are perhaps best illustrated in Figures 11a and 11b for V1 and V2, respectively. Figures 11a and11b are regression curves of the O* intensity just below ~10 MeV/nuc (4.0–7.1 MeV/nuc), the approximate energy at which a peak in the spectrum appeared after 2002.0, to the O* intensity just above ~10 MeV/nuc (10.6–17.1 MeV/nuc). In Figures 11a and 11b for both V1 and V2, the intensity begins to move toward a new regression line at the beginning of the transition time period at 2001.14, in such a way that the 10.6–17.1 MeV/nuc intensity increases with correspondingly little change in the 4.0–7.1 MeV/nuc intensity. This continues to the beginning of 2002. Later in 2002 and early 2003, both intensities rapidly increase and then decrease

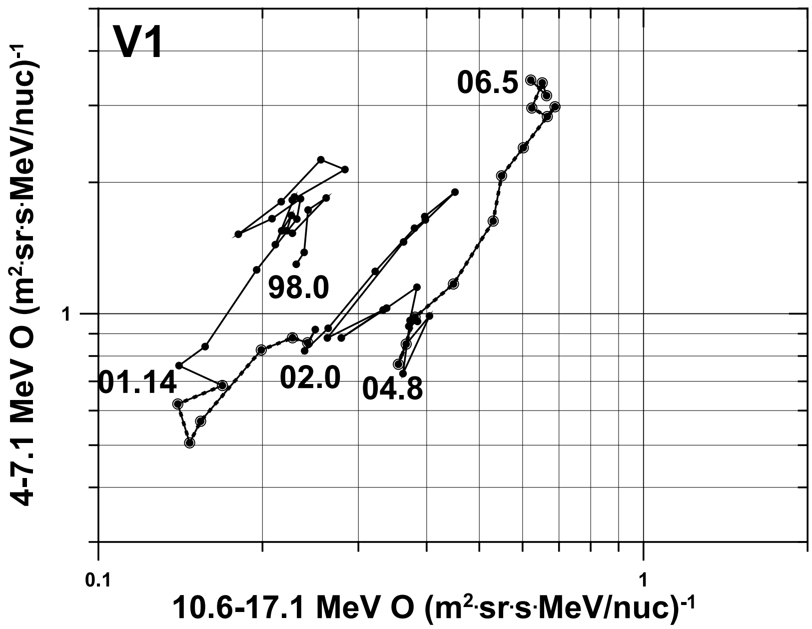

Figure 11a. Regression curve between 4–7.1 MeV/nuc O* nuclei and 10.6–17.1 MeV/nuc O* nuclei for V1 from 1998 to 2006.5.

again at V1 along a new regression line. This is exactly the time period when "termination shock particles" were first encountered at V1 at about 86 AU [*McDonald et al.*, 2003; *Krimigis et al.*, 2003]. During the remainder of 2003 and most of 2004, the intensity regression at V1 continues to slowly change, reaching a new line at about 2004.8 when V1 does encounter the HTS at 94 AU [*Stone et al.*, 2005; *Decker et al.*, 2005]. After that, the intensities at both energies continue to increase along a new regression line (shown as a beaded line).

[21] We note that similar, although not exactly identical, changes are also observed during this transition time period between ~2001.5 and 2002.0 for 10–21 MeV/nuc and 30–56 MeV/nuc He* nuclei [*McDonald et al.*, 2006]. In this case, most of the change to a new regression line between the higher and lower energy He* particles at V1 appeared to occur during the transition time period.

[22] If a similar comparison (not shown) is made between the O* intensity at 10.6–17.1 MeV/nuc versus the O* intensity at 21.6–30.6 MeV/nuc, both of which are above the intensity peak and in the high energy regime where the O* spectra are $\sim E^{-3.0}$, then the slope of the regression line is 1:1, with each of these intensities moving up along the same regression line by a factor ~2, consistent with the

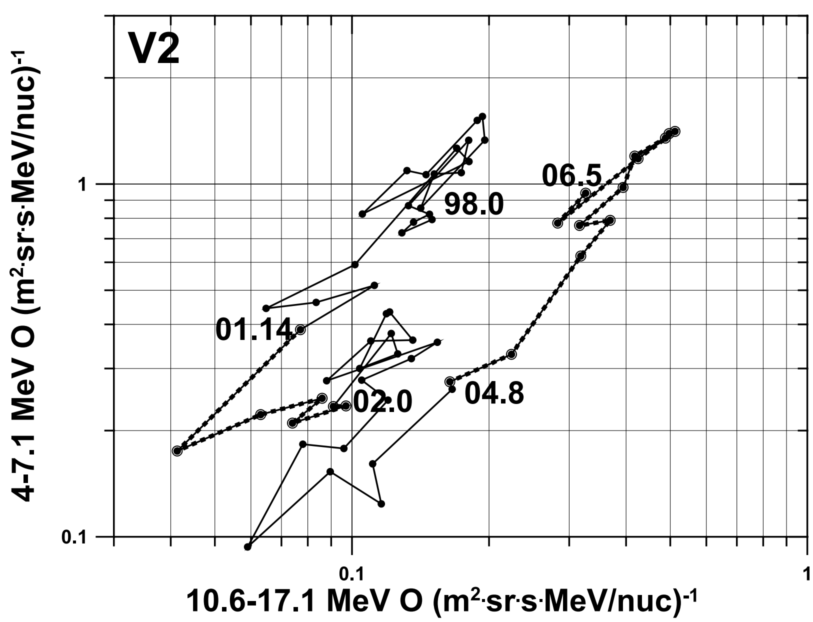

Figure 11b. Same as Figures 11a but for V2.

supposition that the spectrum in this energy range simply moves up or down without a significant change in slope.

6. Comparison of the Data With Models for the Acceleration and Modulation of Anomalous Cosmic Ray

[23] Following the initial models for the acceleration and propagation of anomalous cosmic ray (ACR) [e.g., *Pesses et al.*, 1981], the more recent models include the effects of an HTS embedded within a larger region extending to an outer boundary at the heliopause, following the initial work of *Jokipii* [1986]. In this case, the calculated shock-accelerated ACR spectra are expected to have a power-law spectrum at lower energies and roll over to a very steep spectrum at higher energies. For simple acceleration at the HTS, the power-law spectral index, γ, is related to the shock strength, s, by $\gamma = (s + 2)/(2 - 2 \bullet s)$. Thus if the spectrum of O*, which is approximately -3.0 in both polarity cycles above 10 MeV/nuc, is indeed defined by the shock strength, then $s = 1.6$.

[24] The results in this paper on O* and companion papers on He* [*McDonald et al.*, 2006] and H* [*Webber et al.*, 2006], which show that the transition between solar magnetic polarities produces complex changes in the intensities and the spectra as well as interesting temporal effects, have not been described in enough detail in the present models for us to make a detailed comparison of this new data with models. More advanced models have been developed for the acceleration of H* nuclei in opposite polarity periods [*Florinski et al.*, 2004; *Langner et al.*, 2006], as well as He* nuclei [*Langner and Potgieter*, 2004; *Caballero-Lopez et al.*, 2005]. These models generally give spectra between 5–50 MeV, with exponents in the range of -1.2 to -1.5 for the positive polarity periods corresponding to compression ratios $\sim$3, and flatter spectra in the negative polarity periods, with correspondingly higher intensities as we observe for O* [e.g., *Florinski et al.*, 2004]. However, we are not aware of any calculations of O* spectra which reproduce the observed $E^{-3.0}$ spectra or the roughly constant increase of a factor $\sim$3 in the intensity of O* nuclei between the positive and negative polarity periods that we measure. It is also possible that the true O* spectrum will reveal itself at energies below $\sim$10 MeV/nuc where the ‘‘modulation effects’’ are still large.

[25] Other nonstandard acceleration models, such as the *McComas and Schwadron* [2006] model, which considers a blunt termination shock, or that of *Gloeckler and Fisk* [2006], which considers acceleration in the turbulent medium behind the shock, may be needed to explain both the spectral exponent and the complex temporal variations that are observed.

7. Summary and Conclusions

[26] This study of the intensity and spectral changes of O* at V1 and V2 from the early 1990s to the present time in 2006 has revealed a complex series of spectral and intensity changes for these nuclei, particularly near the time of the solar magnetic polarity change. During this overall time period, V2 has moved outward from $\sim$36 AU to nearly 80 AU, just inside the HTS, and V1 has moved from $\sim$47 AU to nearly 100 AU, crossing the HTS in late 2004 at a distance of $\sim$94 AU. Also, the solar magnetic polarity has changed from positive to negative during 2000 at Earth and about 1 year later in the outer heliosphere.

[27] After a long period of slowly increasing intensities from 1992 up to a maximum in 1998–99, the O* intensities at both V1 and V2 decreased abruptly from late in 2000 to about the middle of 2001, in step with similar decreases for galactic cosmic rays. After about 2002.0, the intensities of O* at both V1 and V2 have generally increased along new regression lines relative to the earlier time period. No significant change of the O* intensities or spectrum was observed at V1 at the time of the HTS crossing; however, by 2006.5, the O* intensities above 10–15 MeV/nuc at V1 were 2–3 times higher than they were at the previous 11-year intensity maximum in 1998–99. During the time period after 2002.0, the intensity increase above 10–15 MeV/nuc at V2 was similar to that observed at V1 and, in fact, was larger by a factor of $\sim$2. At 2006.5, the absolute O* intensities at V1 were larger than those at V2 by a factor $\sim$1.5 above $\sim$10–15 MeV/nuc, and the O* spectra at both spacecraft were essentially $\sim E^{-3.0}$ up to the highest energies. These spectra showed evidence of modulation effects below 10 MeV/nuc at both spacecraft.

[28] As an aid to understanding these intensity changes, we have considered the O* spectrum in two energy regimes, a low energy regime below 10 MeV/nuc and a high energy regime above 10 MeV/nuc. In the high energy regime, the intensity changes during both the decreasing and increasing intensity periods and also at both V1 and V2 are nearly energy independent and occur in lock-step with intensity changes observed for GCR. These changes are about twice as large at V2 as compared with V1. During these intensity changes, the spectra observed at both V1 and V2 still remain $\sim E^{-3.0}$. After 2002.0, the O* intensities at both V1 and V2 approach values by late 2006 that are $\sim$3 times as large for the same GCR intensity levels as those before 2001.5 when the solar magnetic polarity was different.

[29] In the energy regime below 10 MeV/nuc, the intensity changes are considerably larger and are strongly energy dependent. These intensity changes are also strongly correlated with GCR changes. However, at 2006.5, at both V1 beyond the HTS and V2 just inside the HTS, the O* differential spectra reach a peak at $\sim$6–8 MeV, indicative of modulation effects between the ‘‘source’’ and the spacecraft at this time. This intensity peak in the O* spectrum was not seen above $\sim$4 MeV/nuc in the previous polarity cycle.

[30] When V1 crossed the HTS, there was no noticeable change in the O* spectrum or in the intensities. Instead, this time marked the beginning of a general increase of O* intensities at all energies, sustained to the present time in late 2006.

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