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EVOLUTION OF ANOMALOUS COSMIC-RAY OXYGEN AND HELIUM ENERGY SPECTRA DURING THE SOLAR CYCLE 22 RECOVERY PHASE IN THE OUTER HELIOSPHERE

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ABSTRACT

We present annual 0.3–40 MeV nucleon^{-1} anomalous cosmic-ray (ACR) oxygen and helium energy spectra from the 1991–1999 cosmic-ray recovery phase of solar cycle 22. These observations were made with the Low Energy Charged Particle instruments aboard the *Voyager 1* and *Voyager 2* spacecraft while at helioradial positions ranging from 34 to 76 AU. The peak intensities of both species increased by 2 orders of magnitude during this period, while the energies of peak O and He intensity decreased from ∼9 to 1.3 MeV nucleon^{-1} and from ∼35 to 6 MeV nucleon^{-1}, respectively. Using these observations along with published O measurements from the *Solar Anomalous Magnetospheric Particle Explorer* at 1 AU, we investigate ACR transport phenomena. We make estimates related to transport parameters such as the relative change in the scattering mean free path over time, the rigidity dependence of the mean free path, and the distance between the Sun and the solar wind termination shock.

Subject headings: convection — cosmic rays — diffusion — interplanetary medium — Sun: activity

1. INTRODUCTION

Although the solar wind termination shock (TS) has yet to be directly encountered, it is generally believed that anomalous cosmic-ray (ACR) ions originate there (Fisk, Kozlovsky, & Ramaty 1974; Pesses, Jokipii, & Eichler 1981). As the heliosphere moves with respect to the local interstellar medium, ambient neutral atoms enter the heliosphere and become ionized through solar wind or UV interactions. The newly generated, singly ionized pickup ions are carried away by the solar wind to the TS, where they are accelerated (e.g., Zank et al. 2001). Some of these accelerated pickup ions, now called ACRs, remain within and move throughout the heliosphere, influenced by the solar wind and interplanetary (IP) magnetic field through transport processes such as convection, diffusion, adiabatic deceleration, and particle drift.

The *Voyager* mission has extended the study of ACRs by returning measurements from a distant region of the heliosphere where, throughout much of the solar cycle, ACRs are the dominant particle population in the ∼1–100 MeV nucleon^{-1} kinetic energy range. The energy spectra of ACRs are of great importance to the problem of cosmic-ray transport and acceleration. In this Letter, we present the annually averaged energy spectra of ACR O and He with energies in the 0.3–40 MeV nucleon^{-1} range during the 1991–1999 cosmic-ray recovery phase of solar cycle 22. Except as noted, all of the measurements presented here were made with the Low Energy Charged Particle (LECP) instruments (Krimigis et al. 1977) aboard *Voyager 1* (V1) and *Voyager 2* (V2) while the spacecraft ranged from 34 to 76 AU from the Sun (Table 1). Each LECP experiment includes a dual-aperture charged-particle telescope composed of stacked solid-state detectors, with which two-parameter dE/dx versus E measurements are made, yielding compositional and differential intensity data. The LECP measurements uniquely determine the complete outer heliospheric ACR O spectrum (i.e., including the energy of peak intensity), while the He spectra from LECP are comparable to measurements from the *Voyager* Cosmic Ray Sub-system (CRS) instruments (e.g., Stone et al. 1999). The present Letter is the first to examine the evolution of the complete outer heliospheric ACR O and He spectra over the entire solar cycle 22 recovery period, although preliminary reports were made by Hamilton et al. (1997, 1999), Hill et al. (2001), and Hill (2001).

2. OBSERVATIONS

Nine annually averaged ACR O spectra are plotted for both *Voyager* spacecraft in Figure 1, corresponding to the years 1991–1999. For clarity, data having significant non-ACR contributions, e.g., IP-accelerated ions, have been omitted, and for 1991 V2 O, a power-law fit to the IP-accelerated portion of the spectrum was subtracted (significantly affecting only 2–8 MeV nucleon^{-1} data). The remaining data points are predominantly ACR O, with the possible exception of the 0.3 MeV nucleon^{-1} V1 data points; the atypically flat spectrum below 0.6 MeV nucleon^{-1} suggests a sizable non-ACR component. This elevated low-energy oxygen intensity could be related to the observation of pickup O inferred from lower energy *Voyager* LECP data (Krimigis et al. 2000). The peak O intensity increased by 2 orders of magnitude from 1991 to 1999. From 1991 to 1994, the V1 ACR O spectral peak (Fig. 1*a*) shifted from 7.8 ± 0.9 to 1.3 ± 0.3 MeV nucleon^{-1}, while from 1991 to 1995, the ACR O spectral peak at V2 underwent a similar shift from 10 ± 2 to 1.2 ± 0.2 MeV nucleon^{-1} (Fig. 1*b*). The initial peak shift at V1 was more rapid than at V2, and for both spacecraft this was followed by a period extending to 1999 with no detectable peak energy shift. (The quoted uncertainty represents the energy band used in the intensity calculation, as indicated by the horizontal error bars on the data points in Figs. 1, 2, and 3.)

The 1992–1999 ACR He spectra are plotted for each of the two *Voyager* spacecraft in Figure 2 (the 1991 spectra are omitted because of a lack of significant ACR flux). For these spectra, data points having a significant non-ACR component have been omitted for clarity (eliminating much of the data below 2 MeV nucleon^{-1}). In 1992, the ACR He spectrum developed a peak at an energy higher than that of ACR O and above the LECP energy range. However, using the CRS instrument, Stone, Cummings, & Webber (1996) measured the He spectrum at V1 with

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TABLE 1
V1 AND V2 SPACECRAFT POSITIONS

	V1		V2	
YEAR[a]	Radius (AU)	Latitude (deg, north)	Radius (AU)	Latitude (deg, south)
1991 ……	45.4	31.5	34.9	3.4
1992 ……	49.0	31.9	37.6	6.7
1993 ……	52.7	32.3	40.5	9.5
1994 ……	56.3	32.5	43.3	11.9
1995 ……	59.9	32.8	46.2	14.1
1996 ……	63.6	33.0	49.3	16.0
1997 ……	67.2	33.2	52.3	17.7
1998 ……	70.8	33.4	55.3	19.1
1999 ……	74.5	33.5	58.4	20.5

NOTE.—Heliographic coordinates are used.

[a] Positions are for the middle of each year.

a peak at 35 ± 3 MeV nucleon^{-1} during days 105–157 of 1992. The ACR He spectra evolve similarly to O. From 1992 to 1995, the V2 ACR He spectral peak shifted from above ~25 MeV nucleon^{-1} to 6.0 ± 1.2 MeV nucleon^{-1} (Fig. 2*b*), remaining constant thereafter. At V1, a shift of the spectral peak energy from 35 ± 3 MeV nucleon^{-1} (Stone et al. 1996) to 7.4 ± 1.2 MeV nucleon^{-1} occurred from 1992 to 1994 (Fig. 2*a*), 1 yr earlier than at V2, just as with O. Then there was a slow decrease from 7.4 MeV nucleon^{-1} to 5.5 ± 0.8 MeV nucleon^{-1} over the 1994–1998 period. Also like oxygen, from 1992 to 1999 at V1 and V2, the peak ACR He intensity increased by 2 orders of magnitude. The ACR He and O spectra reached maximum intensity in 1999 and then began to decrease in response to increasing solar modulation. The spectra for 2000 and 2001 (not shown) lie below the 1997 levels.

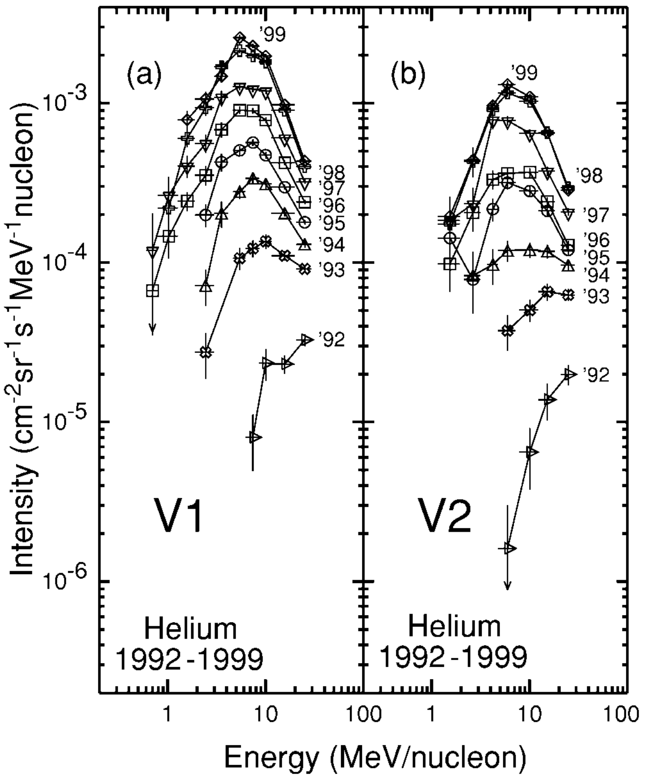

FIG. 2.—Annual energy spectra of ACR helium ions from (*a*) *Voyager 1* and (*b*) *Voyager 2* observations made during 1992–1999.

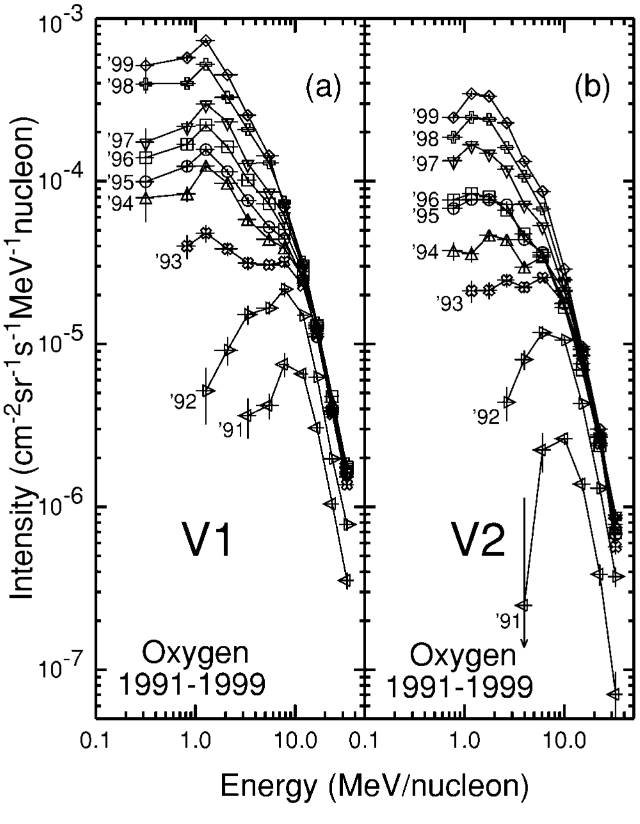

FIG. 1.—Annual energy spectra of ACR oxygen ions from (*a*) *Voyager 1* and (*b*) *Voyager 2* observations made during 1991–1999. The 0.3 MeV nucleon^{-1} intensities may contain a significant non-ACR contribution.

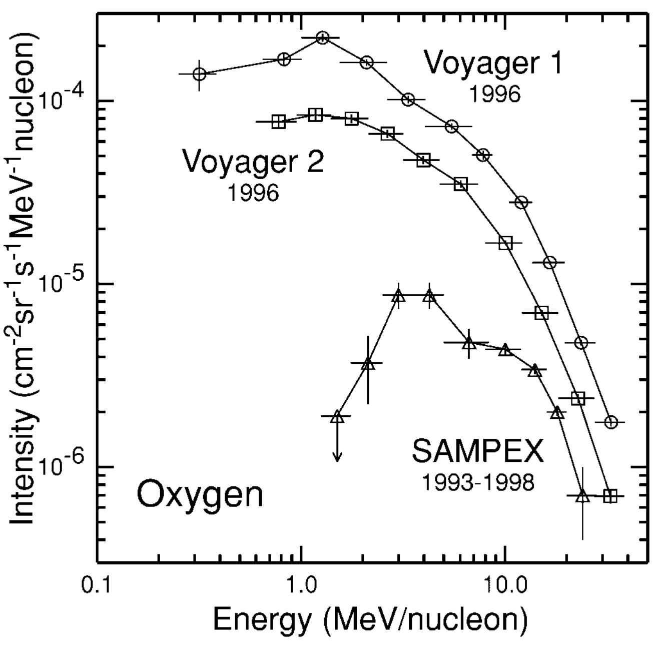

FIG. 3.—Energy spectra of ACR oxygen in the outer and inner heliosphere during the ~1996 solar minimum period. The V1 and V2 spectra (*circles and squares, respectively*) consist of annually averaged measurements from 1996 (the 0.3 MeV nucleon^{-1} V1 data point could have a significant non-ACR contribution). Below 10 MeV nucleon^{-1}, the *SAMPEX* spectrum (*triangles*) was averaged over the 1993–1998 period, while the four highest energy data points are from late 1995 (Mazur et al. 2000).

For comparison with the inner heliosphere, the 1996 ACR O spectra from V1 and V2 are displayed in Figure 3 along with an ACR O spectrum from 1 AU (Mazur et al. 2000). The 1 AU spectrum consists of 1993–1998 data from the *Solar Anomalous Magnetospheric Particle Explorer* (*SAMPEX*) in low Earth orbit. The low-energy points (below 10 MeV nucleon^{-1}) are polar cap measurements of the IP flux made with the Low-energy Ion Composition Analyzer sensor over this entire period to acquire adequate statistics, and the remaining high-energy points are from late-1995 observations made with the Heavy Ion Large Telescope (Mazur et al. 2000). Figure 3 shows the energy at the ACR oxygen spectral peak to be 1.3 ± 0.3 MeV nucleon^{-1} in the outer heliosphere as compared with a peak energy value of about 3.3 ± 0.5 MeV nucleon^{-1} at 1 AU. The V2-to-*SAMPEX* intensity ratio is ∼8 at 3 MeV nucleon^{-1} and ∼2 at 20 MeV nucleon^{-1}. These observations (at heliolatitudes from S20° to N33°) are in qualitative agreement with the large-scale transport of ACRs from the outer to the inner heliosphere, the lower rigidity ACRs being more effectively excluded from the inner heliosphere than the higher rigidity ACRs.

3. DISCUSSION

The spectral evolution of the anomalous O and He ions shown in Figures 1 and 2 exhibits an "unfolding" of the ACR spectrum as the disturbance levels in the IP magnetic field and the solar wind decrease. The turbulent IP conditions near solar maximum shorten the scattering mean free path Λ of the ACRs through the IP medium and inhibit the development of efficient curvature and gradient drift patterns. As compared with a less disturbed medium, these conditions impede lower rigidity ACRs from traveling in from the TS, causing decreased overall intensities and the spectral peak to shift to a higher energy. The reduction of disturbance levels at the *Voyager* spacecraft during the recovery period may be caused by temporal (solar cycle) variations in the properties of the IP medium itself, the motion of the spacecraft through regions of the heliosphere with spatially varying properties, or a combination of temporal and spatial variations. The more rapid shift of the spectral peak energy during the initial 1992–1994 recovery period is consistent with largely temporal variations of the IP medium coupled with the effects of the relaxation time required for the ACR distribution to come into equilibrium under the new IP conditions. The late-1994 to 1999 recovery period reveals either very slowly shifting peak energies, as for V1 He (Fig. 2*a*), or no detectable energy shift at all, as for the remaining spectra (Figs. 1 and 2*b*). This behavior is generally consistent with an increase in ACR intensity resulting from spacecraft motion through spatial intensity gradients as the *Voyager* spacecraft approach the ACR source region at the TS. The differentiation between the spatial and temporal variations of ACRs was addressed in detail by Hill (2001).

A simple scaling, put forth by Moraal & Steenberg (1999), relates the ACR peak energy E to the integral $\int V\,dr/\kappa$ from the observation position to the source for a case of spherically symmetric transport without drifts, where V is the (assumed) constant solar wind velocity, r is the heliographic radius, and κ is the diffusion coefficient from the spherically symmetric cosmic-ray transport equation (Parker 1965). With V and κ independent of radius, the relationship becomes $E = aV\Delta r/\kappa$, where a is an arbitrary constant and $\Delta r = r_s - r$ is the radial distance from an observer to the TS. Averaging the outer heliospheric values from V1 and V2, the ∼1996 ACR oxygen spectral peak at 56.5 AU (V1-V2 midpoint) and 1 AU (*SAMPEX*) of 1.3 ± 0.2 and 3.3 ± 0.5 MeV nucleon^{-1}, respectively (Fig. 3), can be used to equate the ratio $E_i/\Delta r_i$ at the two positions to get $r_s = (r_{12} - r_0 E_{12}/E_0)/(1 - E_{12}/E_0) = 93 \pm 13$ AU (the subscripts 0 and 12 indicate 1 AU and V1-V2, respectively). Our estimate is in good agreement with an average TS radius of 90 AU determined from several methods summarized by Stone (2001). Of course, the extended 1993–1998 averaging period for the *SAMPEX* spectrum together with the unchanging ACR O peak energies at V1 and V2 after 1995 mean that the data do not prevent us from making this same calculation in 1998, in which case the TS radius would be estimated to be 103 ± 14 AU.

Within the latitude range accessible to observation in the outer heliosphere, the assumptions of spherical symmetry and radially independent κ introduced above represent a reasonable approximation for the purpose of the estimates we make here. For example, of the 1–2 order of magnitude variations in ACR intensity arising from spatial or temporal transport processes, Hill (2001) showed that a numerical transport model with such assumptions can explain most of these large effects, while nonspherically symmetric arguments were only required to account for the remaining, unexplained intensity differences of about a factor of 2. Moreover, with a more sophisticated two-dimensional model, Steenberg (1998) found the best agreement between 1997 anomalous and Galactic cosmic-ray observations and his model for the case of drift-free transport with radially independent κ and V. There is theoretical justification as well for the radially independent κ that we assume. With a nonperturbative theory (NPT) for the evolution of magnetohydrodynamic turbulence in the solar wind (Zank et al. 1998 and references therein), the radial dependence of κ was found to be weak and nonmonotonic. Using a spherically symmetric modulation model, le Roux, Zank, & Ptuskin (1999) compared NPT with two other theories, found that NPT performed best, and demonstrated the roughly constant radial mean free path for modeled 28 MeV nucleon^{-1} ACR He^{+} over a large range of helioradii. Nonetheless, by making these assumptions, some significant effects could be neglected in our estimates.

Again using the Moraal & Steenberg (1999) scaling, and the fact that the product aV is constant, we can equate $E_i\kappa_i/\Delta r_i$ at two times at V1, say, to estimate the relative change in the diffusion coefficient. From 1991 to 1994, the V1 ACR oxygen peak underwent a significant shift from 7.8 ± 0.9 to 1.3 ± 0.3 MeV nucleon^{-1} as the heliosphere changed from solar maximum to minimum conditions (Fig. 1). We can determine the ratio of the diffusion coefficient in 1994 to that in 1991 as follows (referencing Table 1 and using a source radius of 90 AU): $\kappa_{94}/\kappa_{91} = (E_{91}/E_{94})(r_s - r_{94})/(r_s - r_{91}) = 4.5$. The analogous ratio for V2 is $\kappa_{95}/\kappa_{91} = 6.6$, yielding an average ratio of 5.6. Using the classical expression $\kappa = v\Lambda/3$, with particle velocity v, we can therefore estimate that the scattering mean free path near solar maximum in 1991 was about $\frac{1}{6}$ of that at the beginning of the extended solar minimum period from 1994 to 1999. By numerically modeling ACR O transport, the scattering mean free path during solar minimum has been estimated to be $\Lambda = (0.67\ \mathrm{AU})R\ \mathrm{GV}^{-1}$ by Hill (2001), where R is the ACR rigidity. For the energy range of ACR O studied here, this determination of Λ is found to agree with the mean free path that Steenberg (1998) determined to be a piecewise function of rigidity by comparing sophisticated numerical solutions with observed cosmic-ray spectra. For anomalous O with a rigidity R, the (∼1991) solar maximum scattering mean free path is therefore estimated to be $\Lambda = (0.1\ \mathrm{AU})R\ \mathrm{GV}^{-1}$. Although during this same period, Cummings & Stone (2001) found the relative change in Λ from solar maximum to solar minimum to be a factor of 10 or more (compared with our estimate of 6), their estimate of Λ at a rigidity of 1.5 GV is 0.16 ± 0.03 AU during the 1990–1991 solar maximum period, which compares well with the 0.15 AU value we estimate at the same rigidity in 1991. At higher rigidities and at solar minimum, there are significant differences between the mean free path estimates of Cummings & Stone (2001) and Hill (2001).

Cummings, Stone, & Webber (1984) previously showed that another simple scaling exists between different species of ACRs. This so-called species scaling uses the assumption that the ACRs all share the same power-law index for their source spectra and that the diffusion coefficient depends on velocity and on rigidity as a power law: $\kappa \propto vR^{\eta}$. We can equate the diffusion coefficients at energies associated with any characteristic feature of two ACR spectra, such as at the intensity peaks, to get (for particles with mass numbers A_i, peak energies E_i, and charges $q_i = z_i e$) the scaling relationship $E_2/E_1 = (A_1 z_2/A_2 z_1)^{\theta}$, where $\theta = 2\eta/(\eta + 1)$. For singly ionized particles, we obtain $\theta = \ln(E_2/E_1)/\ln(A_1/A_2)$ and $\eta = \theta/(2 - \theta)$. Late in the recovery period, we have found that ACR O and He have peak energies of 1.3 and 6.0 MeV nucleon^{-1} (Figs. 1 and 2), respectively. From Stone et al. (1999), the peak energy of ACR H in 1998 is determined to be ~35 MeV at V1. With these observations, the rigidity dependence η of the mean free path can be determined for each ACR pair, $\eta_{\mathrm{H/He}} = 1.75$, $\eta_{\mathrm{He/O}} = 1.23$, and $\eta_{\mathrm{H/O}} = 1.46$, corresponding to approximate rigidity ranges of 200–500, 400–800, and 200–800 MV, respectively. The average index value is $\eta = 1.5 \pm 0.3$, which is smaller than the value $\eta = 2$ that Cummings & Stone (1998) found using 200–700 MV H and He and larger than the $\eta = 1$ value (solely determined from 800 to 3000 MV O data) that we used above to study the change of Λ between solar cycle extrema. These values for the rigidity power-law index are in agreement with the aforementioned numerical modeling of le Roux et al. (1999), in which the use of the NPT turbulence model (Zank et al. 1998) yielded values for η of about 1.2 for rigidities from ~400 to 2000 MV and approaching $\eta = 2$ for rigidities below and above this range.

4. CONCLUSIONS

During the initial recovery period from 1991 to ~1994, the ACR O and He spectra at V1 and V2 (Figs. 1 and 2) increased in intensity by an order of magnitude, accompanied by a large shift in the energy of peak intensity (e.g., the O peak energy shifted from ~9 to 1.3 MeV nucleon^{-1}). In the 1994–1999 solar minimum period, a similarly large peak intensity increase was observed, but the peak energy became nearly constant. ACR O spectra (Fig. 3) from the outer heliospheric *Voyager* observations and the inner heliospheric *SAMPEX* measurements (Mazur et al. 2000) are consistent with the large-scale transport of ACRs from the outer to the inner heliosphere within the S20°–N33° heliolatitudinal range observed. With scaling arguments, we estimated that the scattering mean free path Λ increased by a factor of 6 from solar maximum to solar minimum, that its average rigidity dependence was $\Lambda \propto R^{1.5}$, and that the distance to the TS was from 93 ± 13 to 103 ± 14 AU during solar minimum.

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