Sustained Energetic Particle Intensity Enhancements at Voyager 1 Beginning in 2002

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Abstract

A possible explanation for the large low-energy enhancement of outer heliospheric ion and electron intensities observed at Voyager 1 (V1) during 2002/213 to 2003/035 is an encounter with the solar wind termination shock (TS) [4]. We study the energy spectra of H, He, C, & O ions around this time period and, using the anomalous cosmic ray (ACR) species scaling [2], find the enhancement to be consistent with an ACR population.

1. Introduction

A spacecraft encounter with the TS—the probable source of ACRs, where the solar wind drops to subsonic speeds—has long been anticipated. Recently, Krimigis et al. [4] presented evidence that this may have happened for the first time in 2002, with V1 crossing the TS and entering the heliosheath region during one or more intervals during the 2002/194 to 2003/044 period of interest (POI). This is based largely on solar wind speed determinations using Compton-Getting analysis of Low Energy Charged Particle (LECP) instrument measurements.

Here we explore the composition, species scaling, and evolution of the energy spectra from LECP before, during, and after the POI. In Figure 1 we display V1 & Voyager 2 (V2) ion intensities from 1987 to 2003. The distinct composi-

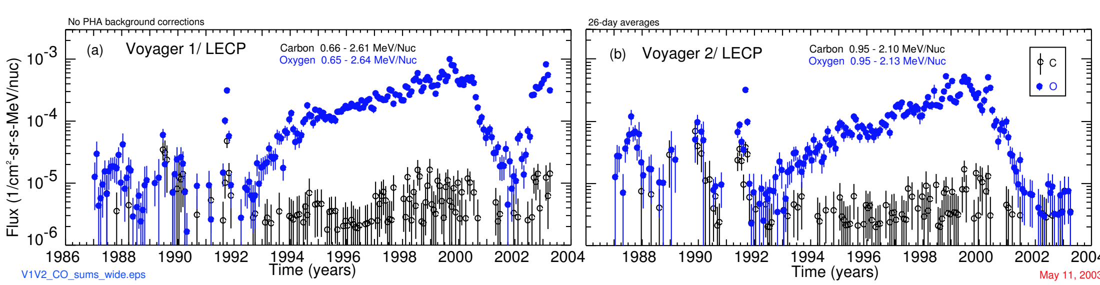

Fig. 1. Voyager 1 and Voyager 2 ∼0.7–2.7 MeV/nuc C and O intensities vs. time.

Table 1. ACR Scale Factors.

(V1 1999)	He/O	H/O
ϵ (energy)	4.6	27
α (flux)	3.3	2.9

Table 2. Possible TS Abundances.

(0.5 MeV/nuc)	j_H/j_{He}	j_{He}/j_O
LECP Data	5	20
TS curve	4.1	13.3
Model [1]	4.17	9.71

tional characteristics of ACRs are apparent during the 1992 to 2000 period, during which the ~ 1 MeV/nuc O ion intensities are enhanced by up to a factor of $\sim$50 over C. In 1991, there was a large interplanetary (IP) event during which the O & C ion intensities increased significantly, peaking during a period of about 2 months, with an O/C intensity ratio of about ~ 6. The POI is immediately seen to be unique in several ways, including the long (~ 6 month) duration, the large contrast between the 1- to 2-orders of magnitude increase at V1 with no associated increase at V2, the lack of an ACR Forbush decrease in late 2002 (Figure 2) as compared with the 1991 Forbush decrease (not shown) that is characteristic of IP events, and the large divergence of O & C intensities, quite similar to the O/C intensity ratio seen during the ACR dominated period.

2. ACR Species Scaling

The ACR "species scaling" organizes transport and modulation features in energy and is well-established as a hallmark of ACR populations [2]. It assumes common power-law indices for ACR source spectra of different species at the TS and that the diffusion coefficient be proportional to particle velocity and a power-law in rigidity. We can compare the relative composition of the modulated and unmodulated ACR spectra if the TS source spectrum of the ith ACR species has the form $j_i(E) = j_{oi}E^\gamma f(E/E_i)$, where j_{oi} is a normalizing flux, E is energy/nuc, and E_i is a characteristic energy. For an exponentially decaying f, this is essentially the form expressed by Steenberg & Moraal [5]. The modulated spectra have the form $j'_i(E) = g(E/E_{pi})j_i(E)$, for g such that j'_i peaks at an energy E_{pi}. If the ratios E_{pi}/E_i are the same for all ACR species and $\epsilon \equiv E_{p2}/E_{p1}$ represents the species scaling for two ACR species, then the intensity ratio at the spectral peaks of two ACR species becomes $\alpha \equiv j'_2(E_{p2})/j'_1(E_{p1}) = (j_{o2}/j_{o1})\epsilon^\gamma$. If, as with the Steenberg & Moraal [5] form, the TS spectra approach the power-law form $j_i(E) \approx j_{oi}E^\gamma$ when $E = Eo \ll E_i$ is satisfied, then we find that the intensity ratio at energies offset by the species scaling ϵ is $j_2(E_o)/j_1(E_o/\epsilon) = (j_{o2}/j_{o1})\epsilon^\gamma$. Thus, the following holds (ϵ and α are listed in Table 1 for H, He, & O):

$$\alpha \equiv j'_2(E_{p2})/j'_1(E_{p1}) = j_2(E_o)/j_1(E_o/\epsilon) \quad (1)$$

This indicates that the ratio of the intensities of two modulated ACR spectra at the spectral peaks is equal to the ratio of the intensities of the power-law portions

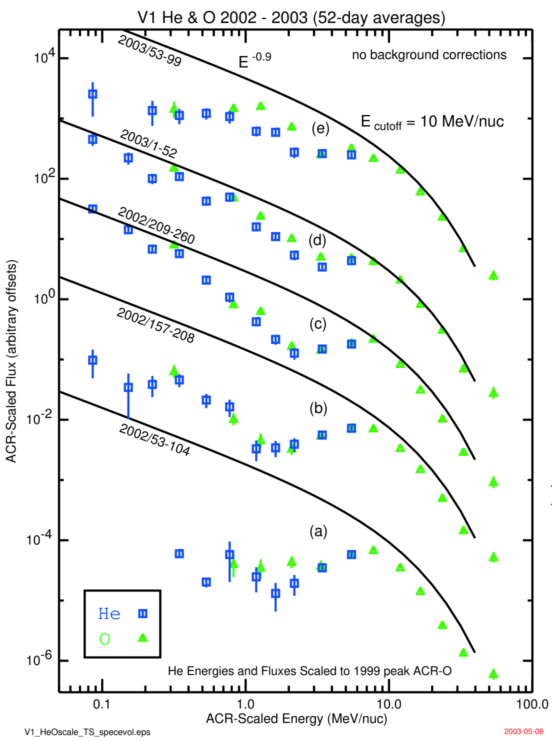

Fig. 2. V1 52-day He & O spectra (arbitrary vertical offsets). Scaling is described in the Figure 3 caption.

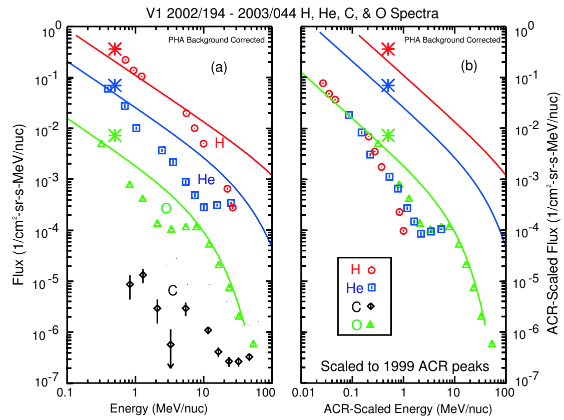

Fig. 3. V1 H, He, C, & O spectra averaged over 2002/194–2003/044. The He and H spectra are scaled in energy and flux (cf., Table 1) according to the species scaling method, based on the 1999 ACR peaks (see text). Unlike Figures 1 and 2, the intensities shown here have been background corrected using pulse height analysis. The star symbols are TS fluxes from a strong shock transport model [1].

of the unmodulated spectra, when the species scaling ϵ is employed to offset the energies at which the intensities are measured. The ratio α is not an abundance ratio. The abundance ratio of the two unmodulated ACR spectra at the energy E_o can be determined as follows: $j_2(E_o)/j_1(E_o) = \alpha\epsilon^{-\gamma}$.

3. Energy Spectra

Another view of Eq. 1 and Table 1 is that ideally any two ACR spectra that are scaled to one another by factors of ϵ in energy and α in intensity will be brought into agreement. To test whether the low-energy POI enhancement is comprised of ACRs, we scaled both H & He to O in Figures 2 & 3b, using the Table 1 values, taken from the 1999 ACR peaks observed at V1 [3]. Agreement between the scaled spectra indicates consistency with ACR composition, while disagreement indicates either that the species scaling assumptions outlined above are invalid, or that the measured population includes a significant proportion of non-ACR ions. With the possible exception of the highest-energies H shown in Figure 3, the agreement between the ACR-scaled H, He, and O is good for both the 52-day averages (Figure 2) and the POI average (Figure 3) suggesting that the enhancement is composed of ACR particles.

In Figure 2, representative 52-day He and O spectra are shown before (a, b), during (c, d), and after (e) the POI. The TS curve was selected to match the most unfolded spectrum (d) and should be used to inter-compare the intensities between each period. This curve represents a strong shock with a compression ratio of ~ 4. This same curve was scaled blindly by the 1999 values in Table 1, and is applied in Figure 3. Before (b) and after (e) the POI, the spectra in Figure 2 indicate a lower energy modulated ACR population, as evidenced by the He & O agreement, and the flattening below (b) ~ 0.3 MeV/nuc (scaled) and (e) ~ 1.5 MeV/nuc (scaled). This is as if ACRs accelerated at very local regions of the TS were modulated as they propagated towards V1 before the spacecraft entered and after it reemerged from the downstream region. Table 2 indicates the H/He and He/O abundance ratios at 0.5 MeV/nuc (Figure 3) from (1) a power law fit to the LECP data, (2) intensities at the H, He, and O TS curve, and (3) the numerical modeling of ACRs and the TS spectra, under the strong shock assumption [1].

The similarity of the ACR-scaled TS curves to the H, He, & O data is apparent (Figure 3a) but the lack of the expected monotonically decreasing unfolded TS spectra [5] should be addressed. There appear to be two components—a power-law component at lower energies and a peaked spectrum at higher energies, observable at ~ 7 MeV/nuc for O and indicated at the highest He energies shown. This can be understood as the result of particles propagating from both local and more distant regions of the TS if the shock-accelerated particle intensities vary spatially, as is likely. In this interpretation, the entire proton spectrum shown is locally accelerated at the TS as are the He & O spectra below 10 MeV/nuc & 2 MeV/nuc, respectively. But above those energies the local He and O components are masked by an ACR component accelerated elsewhere. The higher energy ACRs, due to larger gyroradii, longer acceleration time, and less impeded heliospheric transport, could originate from remote regions of the TS where the ion intensities are higher. The spectral peaks result, then, from rigidity-dependent modulation because of transport from the remote acceleration sites to V1.

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