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Small-Scale Variations in ACR Intensities at Voyagers 1 and 2 in 1992-1998

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Abstract

We report on anomalous cosmic rays (ACR) observed by the LECP instruments on the Voyager 1 and 2 spacecraft during the period 1992-1998.5. Our focus is on short-term, small-amplitude variations in the intensities of the ACR hydrogen and helium at energies greater than about 10 MeV.

1 Introduction:

1.1 Instrumental: All data discussed herein are from the Low Energy Charged Particle (LECP) instruments on the Voyager 1 (V1) and 2 (V2) deep space probes. These instruments measure the differential intensities and anisotropies of ions ≥30 keV and electrons ≥20 keV, the differential ion composition ≥200 keV/nuc, and the integral rates of cosmic ray protons >70 MeV. We focus here on short-term (≈solar rotation), small-amplitude (≈10-30%) variations in anomalous cosmic ray (ACR) and galactic cosmic ray (GCR) ion intensities observed at V1 and V2 during 1992-1998.5, which includes the declining phase of Solar Cycle 22 (1986.8-1996.4) and the rising phase of Solar Cycle 23 (1996.4-present). During this period V1 moved in radius from 47 to 71 AU, hovering near 33°N heliographic latitude, while V2 moved from 36 to 55 AU, heading from 5°S to 19°S latitude, and the spatial separation of the spacecraft increased from 40 to 71 AU.

1.2 Overview: Figure 1 is an overview of energetic hydrogen nuclei (H) or proton intensities in four energy ranges as observed at V2 (left) and V1 (right). The top panels show integral count rates of H >70 MeV, which includes both ACR and GCR protons, but is generally dominated by the GCR component. This channel was normalized between

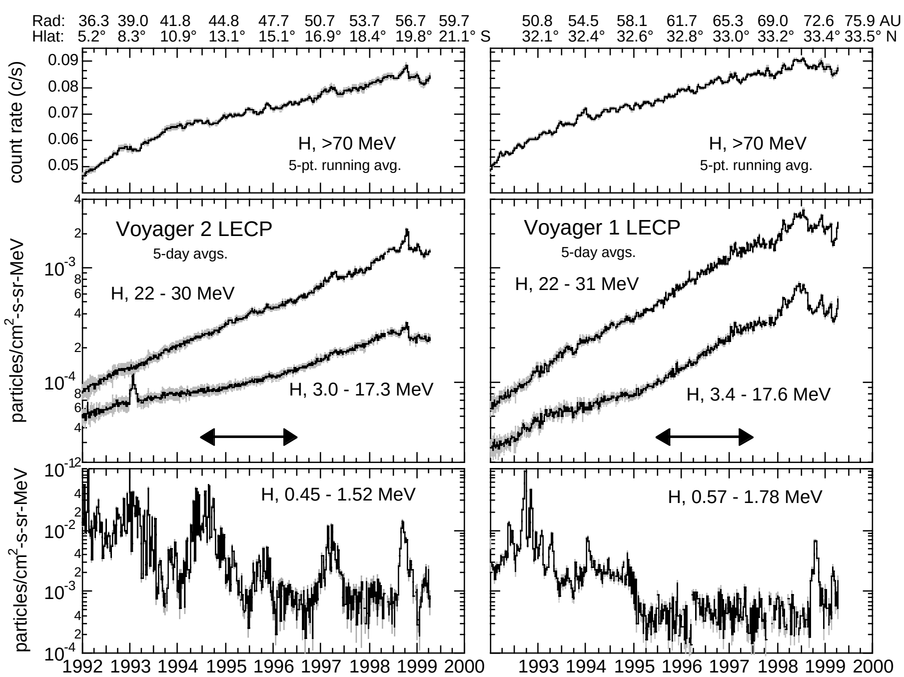

Figure 1: Overview of selected proton (H) channels from Voyager 2 (left) and Voyager 1 (right) during 1992-1999.3.

the two Voyagers soon after launch to enable comparisons of cosmic ray levels and determination of spatial gradients. The middle panels contain intensities of protons ≈20-30 MeV and ≈3-17 MeV, which are mainly ACRs. The bottom panels contain intensities of ≈0.5-1.5 MeV protons, which originate mainly at the sun (i.e., as solar energetic particles, or SEPs), or are accelerated from a lower energy source population at heliospheric shocks, or by solar wind plasma turbulence, or both. We have corrected the ≈0.5-1.5 MeV H intensities as thoroughly as possible to remove background counts due to penetrating cosmic rays.

1.3 Salient Points: We note the following points. (1) At both V1 and V2 the intensities of the GCR and ACR components recovered monotonically from 1992 (after large Forbush decreases in Sept. 1991, not shown here) to mid-1998, at which point both components undergo episodic modulation by merged interaction regions, MIRs, or their larger global relatives, GMIRs, associated with ejecta from major solar flares during Nov. 1997, Apr.-May 1998, and Aug. 1998 (Decker et al., 1999). (2) The intensity of ≈3-17 MeV ACR H remains well below that of the ≈20-30 MeV ACR H, at both V1 and V2, so the energy spectrum has a positive slope between ≈3-30 MeV. Also, the intensities of the ≈3-17 and ≈20-30 MeV ACR H and the >70 MeV GCR H are consistently larger at V1 due to the positive radial and latitudinal gradients of both components during this period (McDonald et al., 1998). (3) At V2 during 1992 to mid-1998, the ≈0.5-1.5 MeV H intensity was dominated by 'trains' of ≈26-day recurrent increases associated with CIRs, or remnants thereof (Gazis et al., 1999), but between these periods the intensity returned to low levels. At V1 during 1992-1995, intensity variations of the ≈0.5-1.5 MeV H were similar to those at V2, but during the 3.5 year period 1995 to mid-1998, the intensity remains relatively flat at a low level (analysis of SEP H arrival at V1 and V2 in mid-1998 is discussed by Decker et al, 1999). Thus, during 1992-1999.3 we see no evidence, with any statistical significance, of a rising intensity of ≈0.5-1.5 MeV ACR hydrogen.

2 ~26-Day Recurrent Variations of ACR H and He at Voyager 1:

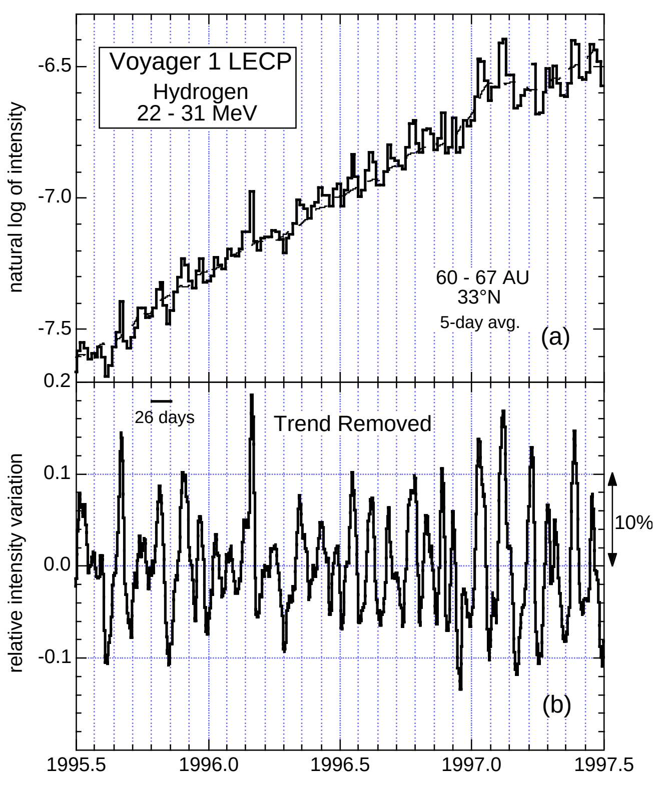

Figure 2: 22-31 MeV ACR H fluctuations at V1.

2.1 ACR Hydrogen: Barely discernable in the middle right-hand panel of Figure 1 are short-term variations superposed on the steadily rising intensity of the 3.4-17.6 and 22-31 MeV ACR protons at V1. To examine these features more closely, we have plotted in Figure 2(a) the natural log of the 22-31 MeV intensity (units of particles/cm^2-s-sr-MeV) for the two-year period 1995.5-1997.5, during which the intensity rises exponentially with an e-folding time (in the spacecraft frame) of 1.7 year. We calculated the trend using a 13-point moving average, subtracted the natural log of the trend (dashed line in Fig. 2(a)) from that of the 5-day averaged intensity (solid line in Fig. 2(a)), and plotted the difference in the bottom panel. For small variations about the mean (trend), which is the case here, one can directly interpret changes in the ordinate of Figure 2(b) as relative intensity variations.

There are two points of interest in Figure 2(b). First, the short-term variations recur with a period ~26 days, i.e., near the solar rotation period (the dotted vertical lines are spaced at 26 days). We have performed a Fourier analysis of these data, and, as expected, the peak of the power spectrum is at ≈26 days, and the width is ≈2-3 days. The second point of interest is the amplitude of the intensity variations, which in this case, is typically about 10% of average. In summary, these data exhibit a two-year stretch of ~26-day recurrent fluctuations, of amplitude ~10%, superposed on the long-term intensity rise of 22-31 MeV ACR H, in the 60-67 AU range at 33°N latitude.

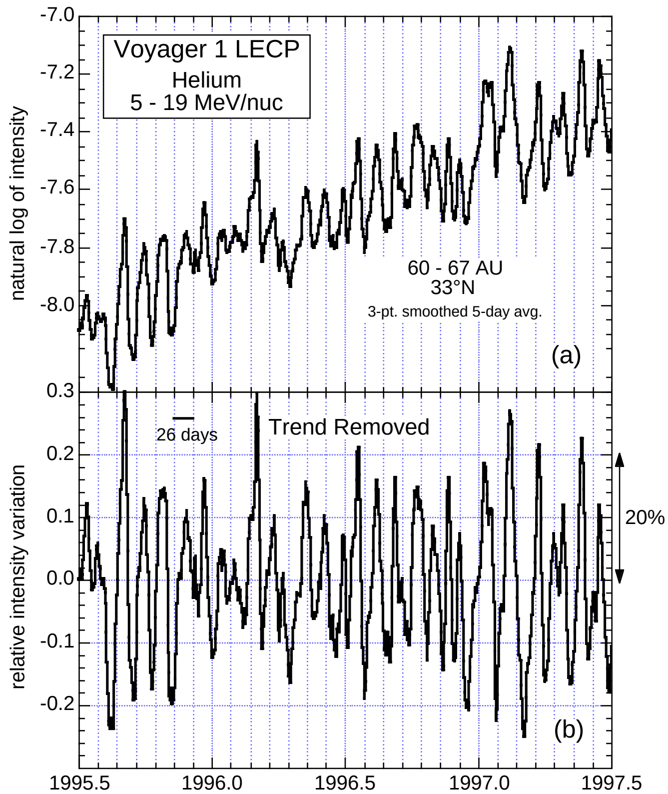

Figure 3: 5-19 MeV ACR He fluctuations at V1.

2.2 ACR Helium: Intensity fluctuations of even larger amplitude are seen in ACR helium (He) in the energy range 5-19 MeV/nuc. These data, again from V1 and during the same period as in Figure 2, are shown in Figure 3. The fluctuations in the H and He are closely correlated, as one can easily see by comparing Figures 2(a) and 3(b). However, the amplitude of relative intensity variations in the 5-19 He are ~20%, twice that of the 22-31 MeV H.

2.3 Other Energies and Ions: We have examined other ion rate channels from the V1 LECP during the 1995.5-1997.5 period. The fluctuations are also evident in the 3.4-17.6 MeV ACR H and the >70 MeV GCR H, but are of smaller amplitude compared to the 22-31 MeV H. There is also evidence of intensity fluctuations, correlated with some of those in Figures 2 and 3, in a 0.53-5.6 MeV/nuc channel that measures ions with Z≥6, which during this time period, are most likely predominantly ACR oxygen. However, the count rates are too low to permit detrending and useful comparisons with H and He data.

3 ~1/4-Year Intensity Variations at Voyager 2 during 1995:

We have examined the V2 data during the 1992-1998 period, and find no evidence of sustained periods of ~26 day recurrent fluctuations, such as those observed at V1. However, we did discover a handful of unusual intensity variations that are shown in Figure 4. The top panel contains count rates (c/s) of 5-19 MeV/nuc ACR He and the bottom panel those of 21-30 MeV ACR H, for the two-year period 1994.5-1996.5. Note the three dominant 'triangular' structures in the 5-19 MeV He data. These are also in the 21-30 MeV H rates, but of smaller amplitude. By removing the long-term exponential time trend (dashed diagonal lines), we again determine the amplitudes of these structures relative to the mean (trend). The relative count rate variation, which is also the relative intensity variation, is plotted atop the rate data as 'residual.'

The three broad intensity increases at V2 during 1995 are ~1/4-year wide, and represent variations ~20-30% in 5-19 MeV ACR He and ~5-10% in 21-30 MeV ACR H. We have examined other channels, and find that the 2nd and 3rd of these structures are also in the >70 MeV H data, but the amplitudes are only ~2-3%. As with the ~26-day recurrent variations at V1, it is the ACR He data that exhibits the largest amplitude change relative to the mean. We have examined the V2 plasma data during the periods when the triangular structures occurred, but found nothing in these data that correlated with our ACR data. Also, we have not found any similar structures in the V1 ACR H and He during the 1992-1998.5 period.

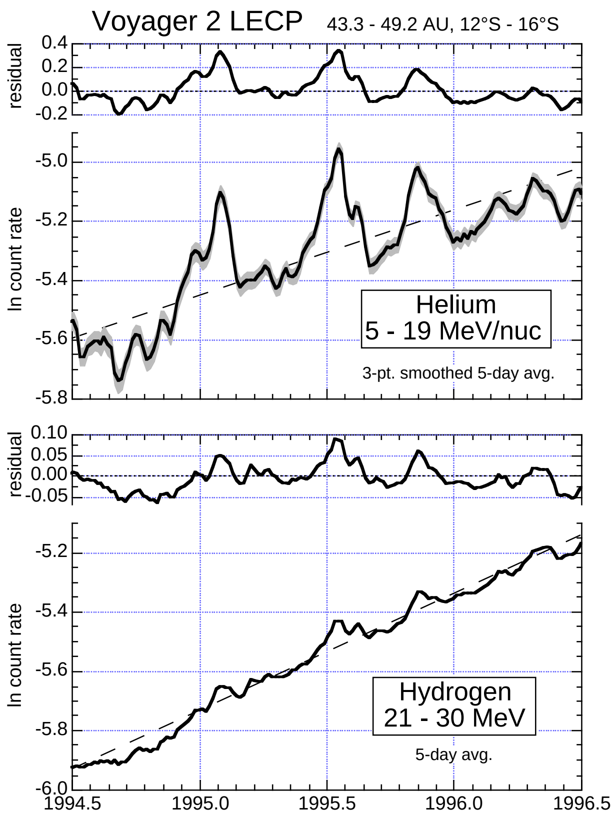

Figure 4: Unusual ~1/3-year wide variations of ACR He and H at Voyager 2 in 1995.

4 Discussion:

In addition to long-term compositional variations of ACR that one finds using long time integrations of LECP PHA data (Hamilton et al., 1999), there are also short-term variations clearly evident in rate data channels that also monitor ACR ions. We have examined, in detail, ACR observed by the LECP instruments on Voyagers 1 and 2 during 1992 to 1998.5. Our goal was to characterize short-term variations in the intensities of ACR species H and He at energies greater than about 10 MeV.

On the long term, the intensities of these species increase monotonically from 1992 to mid-1998. However, superposed on these gradual recoveries are small-scale (fraction of a year), small-amplitude (~10-20% about the mean) intensity variations. For example, there are three unusual 'triangular' intensity variations, each lasting about 1/4-year, observed during 1995 in the ACR H and He intensities at V2, but not at V1. Also, starting in mid-1995 and continuing through 1997, there are striking ~26-day recurrent intensity variations, most likely associated with the heliospheric current sheet (HCS), observed in the intensities of the anomalous H and He, and >70 MeV GCR at V1, but not at V2.

These latter results indicate that large differences in ACR and GCR modulation can occur at spacecraft with moderately different latitudes but located on opposite sides of the heliographic equator. One possible explanation for the absence (above background) at V2 of the sustained train of ~26-day recurrent variations seen at V1 is that the HCS is not only warped, as commonly characterized by its tilt angle, but is also offset, that is, the plane formed by the 'average' HCS is not coincident with the heliographic equator, but lies further south. (This is not unreasonable; indeed, Ulysses data imply that the 'surface of symmetry' for cosmic ray modulation in 1994-95 was offset about 10° south of the heliographic equator (e.g., McKibben, 1998)). This would mean that V2 sampled ACR very near the HCS, so that over a solar rotation, ACR intensity variations were 'washed-out', whereas V1, situated well above the HCS, sampled ~26-day intensity variations as the HCS rotated beneath it.

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