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Survey of energetic particles observed at Voyagers 1 and 2 during 1999 - 2001

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Abstract. We summarize observations of energetic particles measured by the LECP instruments on Voyagers 1 (V1) and 2 (V2). We focus on the period 1999 to mid-2001, which includes activity maximum of solar cycle 23. During this period V1 moved from 72.6 to 81.8 AU (at 33°N lat.), and V2 moved from 56.7 to 64.6 AU (at 20°S-23°S lat.). Among the new results of interest are the following: (1) Intensities of ∼3-30 ACR H and >70 MeV GCR/ACR H showed marked decreases at both V2 and V1 during mid- to late-1999 to early 2001. (2) Passage of the Bastille Day 2000 shock by V2 in early January 2001 was accompanied by intensity increases of ∼0.5-1.5 MeV and ∼3-17 MeV H, and a decrease in >70 MeV ACR/GCR H. (3) In March 2001 there is a small intensity increase of ∼0.5-1.5 MeV H at V1 that may indicate passage of the Bastille Day shock at 80 AU. (4) Despite disturbed conditions in the outer heliosphere due to enhanced solar activity, we are still able to measure at V2 the ∼66-108 keV (∼4-7 keV/nuc) oxygen ions that comprise the low-energy portion of the super-thermal tail on the pick-up oxygen distribution.

1 Introduction

This paper is a continuation of similar reports (Krimigis et al. (1997)) on data obtained by the Low Energy Charged Particle (LECP) instruments on the Voyager spacecraft (Krimigis et al. (1977)), with emphasis on the period 1999 – mid-2001. Of particular interest is the transition from solar minimum conditions in the outer (>60 AU) heliosphere and the effects of this transition on low-energy (∼1 MeV) protons, anomalous cosmic rays (ACR), galactic cosmic rays (GCR), the transport of solar energetic particles (SEP) from the Bastille Day event of July 14, 2000, and the recently identified (Krimigis et al. (2000)) pick-up oxygen ions.

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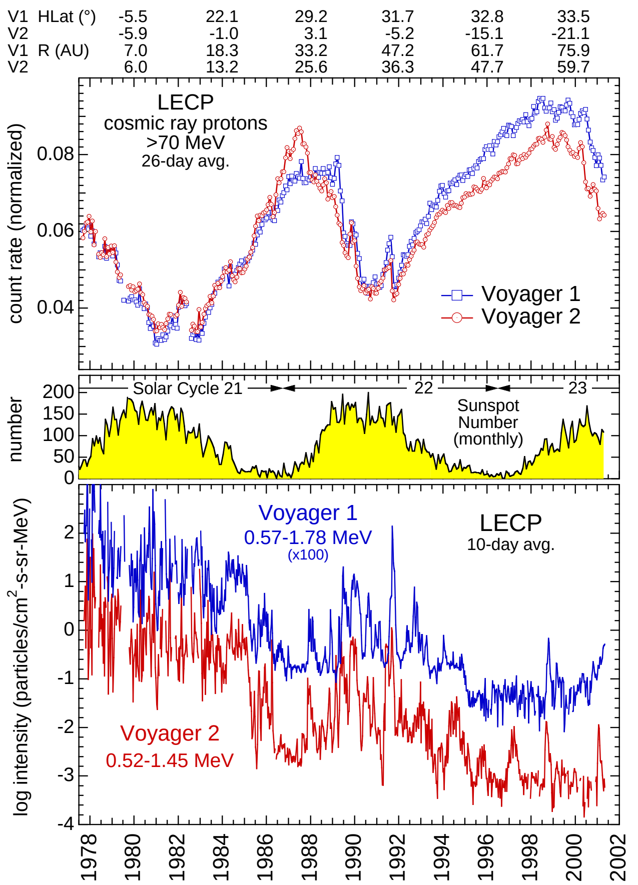

Fig. 1. Overview plot showing 23.5 years of data from the V1 and V2 LECP instruments from launch in late 1977 to mid-May 2001. Helioradius and heliographic latitude of the two spacecraft at two-year intervals are indicated along the upper axis. Top panel shows 26-day averaged count rates (normalized between the two Voyagers) of >70 MeV cosmic ray protons. Middle panel shows monthly averaged sunspot numbers. Bottom panel shows 10-day averaged intensities of protons ∼0.5-1.5 MeV, that originate mainly on the Sun and through acceleration processses solar wind.

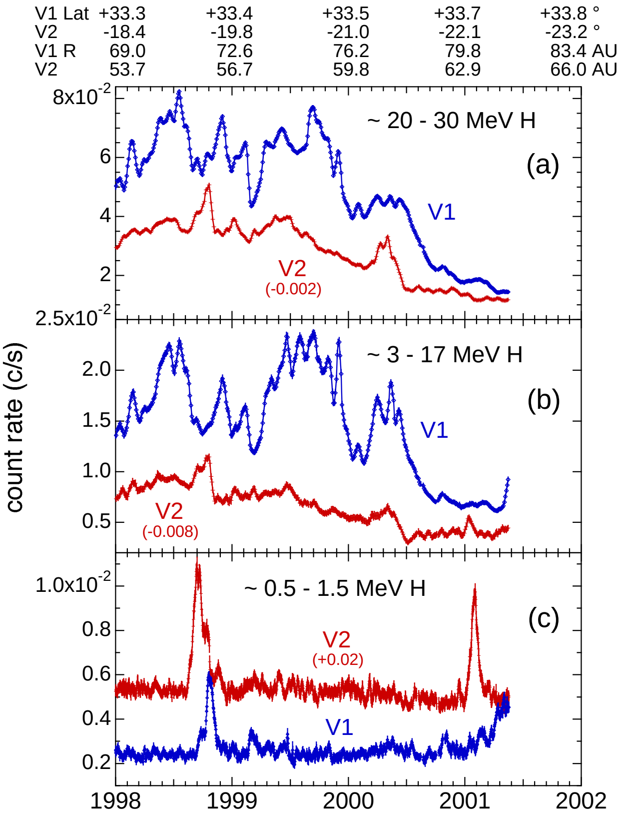

Fig. 2. Count rates from the V1 and V2 LECP instruments during 1998 to mid-May 2001. Traces display (a) ACR protons (H) ∼20-30 MeV, (b) ACR protons ∼3-17 MeV, and (c) mainly SEP/MIR-shock associated protons ∼0.5-1.5 MeV. The reason for the slow increase of ∼0.5-1.5 MeV protons at V1 from early 2001 to at least mid-May 2001 is not yet understood. All data are 5-point running means of 1-day averaged count rates.

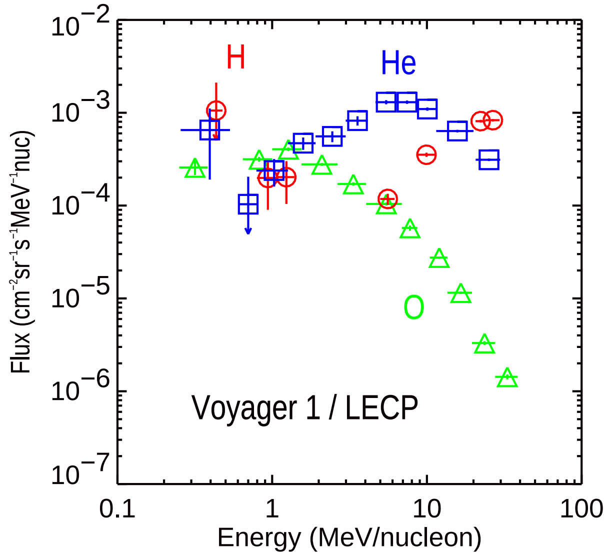

Fig. 3. Energy spectra of ACR H, He, and O at V1 during 2000. These spectra are determined by analysis of LECP pulse-height data.

2 Overview: Launch through Mid-2001

Figure 1 presents data from Voyagers 1 and 2 from launch in late 1977 to the 2001 DOY 140. The top panel shows solar cycle (mid-panel) effects on the GCR's, including onset of the new decline in intensity evident in late 1999 and continuing to date. The radial gradient (see trajectory parameters at top) between V1 and V2 is evident and growing, especially after GCR minimum in ∼1992. Of more interest is the behavior of ∼1 MeV protons (bottom panel), with intensities clearly in phase with sunspot number, but an overall decline of $\sim 10^4$ from 1 to ∼80AU, roughly as expected from an r^{-2} dependence. It is also seen that low-energy protons began a slow increase at V1 in 2000, but not at V2.

3 Evidence of Cycle 23 Onset

A more detailed view of the latest ∼3.5 year period is shown in Figure 2, with emphasis on ACR and low-energy protons. The differences between V1 and V2 in the time variations of ACR proton intensities (upper two panels) is striking, with large fluctuations at V1 being largely absent at V2. The increase at V2 beginning in July 1998 is due to a CME (coronal mass ejection) launched in April (Decker et al. (2000)) and accounts for the peaks at all three energy intervals shown, with a counterpart at V1 ∼5 weeks later. No other discrete increases evident at V1 can be readily identified at V2. Onset of a general decrease in intensities started in mid-1979 at V2 (58 AU) and late 1999 at V1 (76 AU), and, after a brief increase, recurred in early and mid-2000 at V2 and V1, respectively. The large, positive gradient between V2 and V1 largely disappeared by early 2001. Despite these time variations, the shape of the averaged spectra of ACR's for 2000, shown in Figure 3 for H, He, and O, remained unchanged from the previous year (Hill et al. (2001)). Note, however, that the spectrum shows an upturn in intensities at sub-MeV energies of H, He, and possibly O, suggesting a different source for this component.

4 Shock Propagation from 1AU

To further examine this issue, we show in Figure 4 the time evolution of intensities from late 2000 to the present at both V1 and V2. The MIR (Merged Interaction Region) and associated shock resulting from the Bastille Day (B-Day) 2000 solar activity arrived at V2 in January 2001. The shock evidently swept up and accelerated ACR protons that began to increase some two weeks before the shock's passage. The ∼0.5-1.5 MeV protons peaked about 15 days after the shock arrival, and could be an example of a weakening shock (Zank and Pauls (1997)); alternatively, the profile is consistent with the predictions of acceleration at quasi-perpendicular shocks, as seen previously in the inner heliosphere (Sarris and Krimigis (1985)). More to the point, it appears that the Bastille

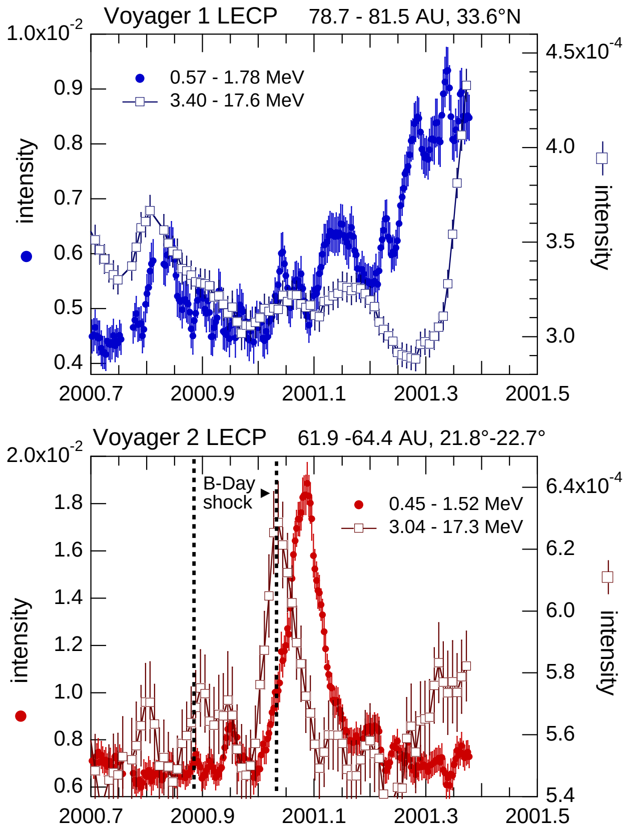

Fig. 4. Intensities of protons ∼0.5-1.5 MeV (filled circles, left ordinate axis) and ∼3-17 MeV (open squares, right ordinate axis) at V1 (top panel) and V2 (bottom panel) during the period 2000.7–2001.4. Intensities are in units of (cm^2 s sr MeV)$^{-1}$. The ∼0.5-1.5 MeV proton points are 5-point running means of 1-day averages; the ∼3-17 MeV points are 5-point running means of 3-day averages. Dashed vertical lines in the bottom panel indicate shock passage times, as discerned from the V2 Plasma Science (PLS) data, with the second shock (B-Day) being associated with the Bastille Day 2000 MIR.

Day shock has not reached V1 at ∼80 AU (upper panel), despite expectations that it should have arrived by early March 2001, if one assumes that the shock propagates as a spherical disturbance (Wang et al. (2001)). Finally, we note the gradual increase in sub-MeV intensities at V1 that began in 2001 and continues to date. It is not clear at this time what the origin of this particle population is.

5 Pickup Oxygen

Evidence for pick-up oxygen ions at both V1 and V2 (Krimigis et al. (2000)) highlighted the presence of yet another particle population that plays a significant role in the dynamics of the outer heliosphere and the termination shock (TS). Figure 4 shows evolution of this component since 1992 at V2 and the detailed correlation between solar wind velocity enhancements and intensity peaks of pick-up oxygen ions. Intensities in 2000 of ∼0.03 (cm^2 sec sr keV)$^{-1}$ are a factor of

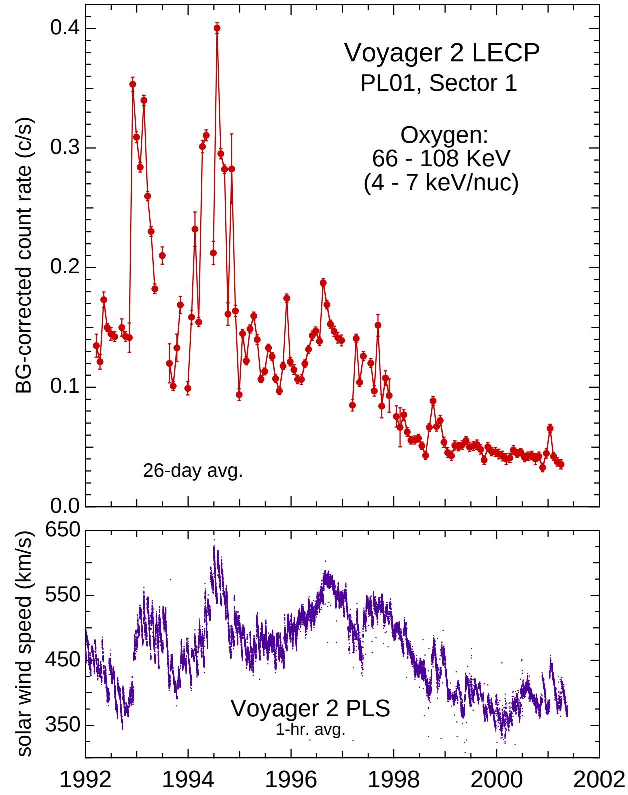

Fig. 5. Top panel: V2 LECP observations during 1992–2002.4. Shown are 26-day averaged count rates of pick-up oxygen ions in the energy range 66-108 keV (4-7 keV/nuc). These data are measured by the sunward looking Sector 1 of the LECP instrument, and have been corrected for background (BG) due to penetrating cosmic rays. Bottom panel: Hourly-averaged solar wind speed at V2 measured by the PLS instrument.

3 lower than 1997, but still well above background even at solar wind velocities of ∼400 km s^{-1}.

6 Discussion

The findings presented above serve to highlight the limited understanding of processes operating in the outer solar system. In general, it is expected that as V1 and V2 move to larger distances the presence of the TS should begin to manifest itself through intensity increases of GCR's, ACR's, and the sub-MeV population that serves as a seed population for ACR acceleration at the TS. Of these three populations, GCR's are most consistent with theory, in that a radial gradient continues to be present (cf. Figure 1). The ACR proton population exhibits substantial (>70%) fluctuations (cf. Figure 2) near solar maximum that are apparently uncorrelated between V1 and V2. This may be due to the large (>75AU) separation between the two spacecraft, but does not fit easily within the predictions of existing models. Further, the gradient disappears in late 2000 for ∼20-30 MeV H, an observation that is not readily understood using current models.

Finally, lower energy protons (and possibly He and O, cf.

Figure 3) do not seem to be part of the ACR population, based on both spectral and time-intensity behavior. Firstly, there is the overall expectation that ACR spectra should "unroll" to power laws as the spacecraft approach the TS (Ellison et al. (1999)). No such evidence is seen at V1, especially if the shock is at ∼84AU (e.g., Stone and Cummings (1999)) and currently moving inward (Whang and Burlaga (2000)). Secondly, the radial dependence of intensity is r^{-2} (cf. Figure 1), i.e., consistent with an inner source that comprises solar and near-Sun interplanetary populations.

If the TS was a significant source, one might have expected an increase by now, when V1 could be within ∼5AU of the shock. Perhaps the intensity increase of ∼0.5-1.5 H that started in 2001 at V1 (Figure 2, Panel (c)) may be an early indication of the approaching TS; again, however, one would expect similar increases in the ∼3-17 and ∼20-30 MeV ACR H (Figure 2, Panels (b) and (c)), which are not observed. In addition, the complications of the Bastille Day shock arrival at V1 make the optimistic scenario that the ∼0.5-1.5 H profiles at V1 indicate proximity to the TS rather unlikely. Hopefully, additional data over the next few months will provide an answer to this question.

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