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Solar Energetic Particles from the April 1998 Activity: Observations from 1 to 72 AU

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Abstract

Solar energetic particles (SEPs) injected during intense activity in April-May 1998 and observed at ACE and Ulysses, have been identified in ≈0.5-1.5 MeV proton data from the LECP instrument on Voyager 2 (56 AU, 18°S) and Voyager 1 (72 AU, 33°N). A shell of ~1 MeV protons ~60 days wide reached peak intensity at V2 on 1998.7 and at V1 on 1998.8, midway between Forbush decreases observed 110 days apart at each Voyager, and evidently caused by disturbances from Nov. 1997 and April-May 1998 solar activity. We interpret these results in terms of weak-scattering propagation from 1 to 72 AU and over ~50° in latitude.

1 Solar Activity in 1997-1998:

Figure 1 shows ~1 MeV proton intensities from solar activity during 1997.7-1999.3. From top to bottom are intensities of from the EPAM instrument (Gold et al., 1999) on ACE, the HI-SCALE instrument (Lanzerotti et al., 1992) on Ulysses, the LECP instrument (Krimigis et al., 1977) on Voyager 2 (V2), and the LECP on Voyager 1 (V1). Inverted triangles along the top axis indicate approximate onset times of major flares, or a series of flares, on 1997 DOY 308 and 310 (A), 1998 DOY 110, 122, and 126 (B), and 1998 DOY 329 (C). We focus on these three periods because of the likely correspondence between these solar events and variations in energetic proton intensities observed at V1 and V2 in 1998 and 1999.

Sustained intensity increases of protons ~1 MeV from the April-May 1998 flares (B) are identifiable at 1 and 5 AU. The V1 and V2 data show that features of individual solar events are completely washed out and intensities greatly reduced at 55 and 71 AU. The SEPs at V2 and V1, which we here associate with protons injected mainly during period B, comprise a shell with peak intensity at V2 ~10^{-2}/cm^2-s-sr-MeV, reduced by a factor ~10^4 that at 1 AU, and a FWHM ~0.15 yr, or ~14 AU for a solar wind speed of 435 km/s.

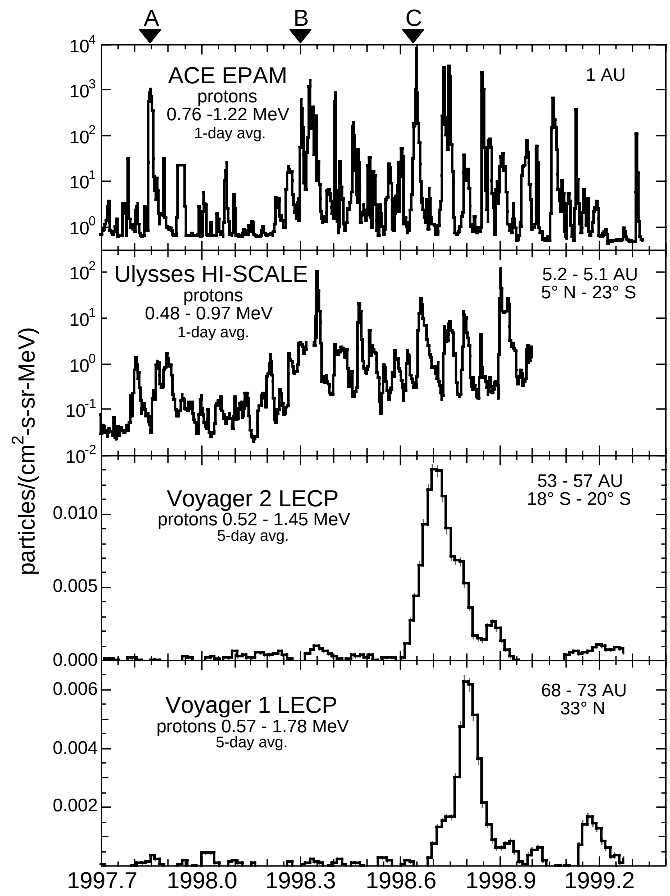

Figure 1: Intensities of ~1 MeV protons at (top to bottom) ACE (1 AU), Ulysses (5 AU), Voyager 2 (54 AU), and Voyager 1 (71 AU) associated with enhanced solar activity during 1997-98.

2 Voyager Observations:

Figures 2 and 3 show energetic proton data from V2 and V1, respectively, during the period 1997.6 to 1999.3. The top panel shows integral count rates of protons >70 MeV, which includes both anomalous cosmic ray (ACR) and galactic cosmic ray (GCR) protons, but is generally dominated by the GCR component. The middle two panels contain intensities of mainly ACR protons ≈20-30 and ≈3-17 MeV. The bottom panel contains protons ≈0.5-1.5 MeV, which originate mainly at the Sun (i.e., SEPs) or are accelerated from a lower energy source by heliospheric shocks and/or plasma turbulence.

In both Figures 2 and 3 dashed vertical lines indicate where in the proton intensities we see evidence for the passage of large-scale heliospheric disturbances, such as merged interaction regions, MIRs, or their larger *global* cousins, GMIRs. Within these disturbances the magnetic field is amplified and highly turbulent, and in combination with the strong forward shocks (which can accelerate ions and electrons), often observed at the leading edge of MIRs and GMIRs, can produce relatively large and sudden drops, or Forbush decreases (FDs), in GCR and ACR intensities.

In Figure 2, the association of the feature marked A(?) with the Nov. 1997 solar flares is tentative, but is consistent with a leveling off of >3 MeV proton intensities and a Sun to V2 transit speed ≈400 km/s (McKibben et al., 1999). Line B marks FDs in the >3 MeV proton channels, but has no obvious effect on the ≈1 MeV protons. An MIR (or GMIR) from the April-May 1998 activity (B) with speed ≈420 km/s is consistent with the cosmic ray drops at line B. The essential point to note is that the ≈1 MeV proton intensity peaks some 45 days prior to FD that marks the arrival of 'Disturbance B.'

The V1 data in Figure 3 show a one-to-one correspondence between active solar periods A, B, C, and the three FDs in the >3 MeV cosmic ray data, with the vertical lines labeled accordingly. The peak intensity of ≈1 MeV SEPs is again about 45 days before the passage of the Disturbance B. Disturbance C initiates FDs in the >3 MeV cosmic ray data, and is associated with a post-disturbance increase, due perhaps to shock acceleration, of ~1 MeV protons.

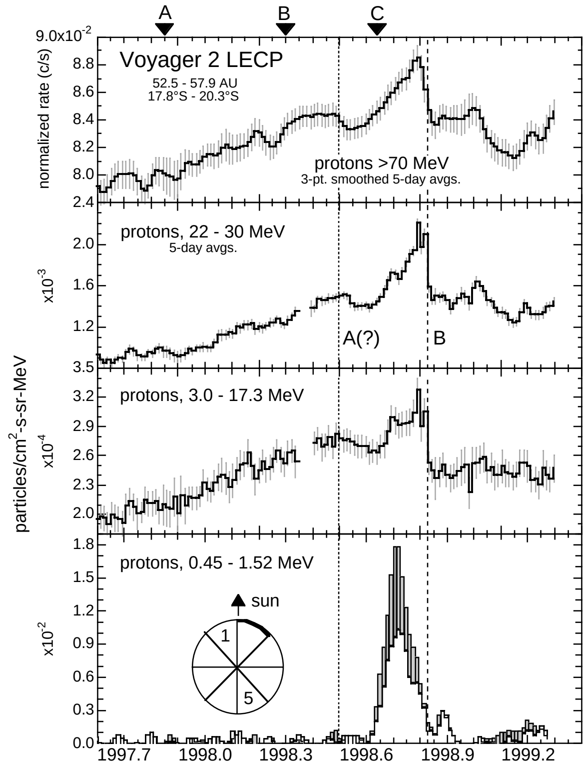

Figure 2: V2 LECP proton data (see text for details)

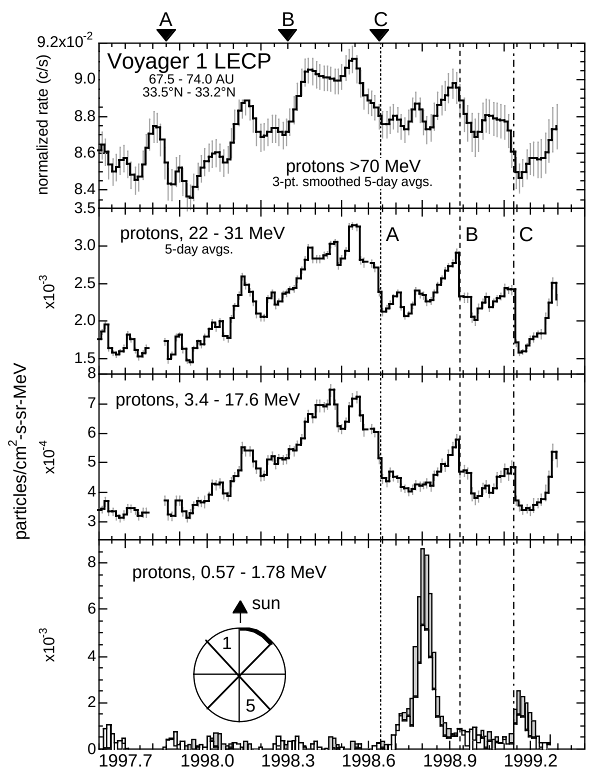

Figure 3: V1 LECP proton data (see text for details).

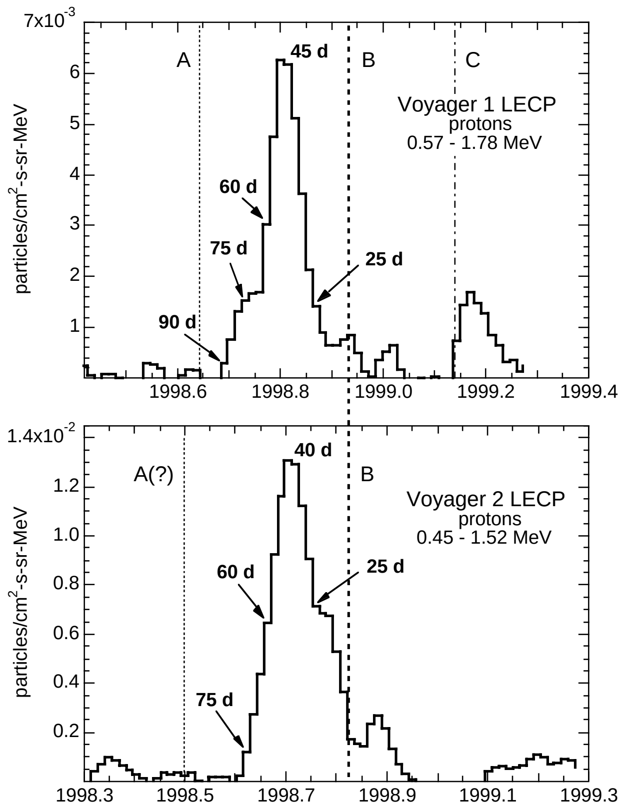

Figure 4: V1 and V2 SEP traces shifted to line up B.

3 Analysis:

3.1 Theory: We believe that the remarkably similar shapes of the ~1 MeV proton enhancements that peak at both Voyagers about 45 days before the Forbush decreases (line B in Fig. 4) are the consequence of the weak-scattering propagation and energy loss en route from the inner to the outer heliosphere. The gyro-averaged motion of the protons will be the vector sum of the guiding center velocity $\mathbf{v}_{||}$ and $\mathbf{V}_{\perp}$ (the $\mathbf{E}\times\mathbf{B}$ drift velocity in the solar wind). Then the radial component of the total velocity is $dr/dt = (\mathbf{v}_{||})_r + (\mathbf{V}_{\perp})_r$. In an archimedean spiral field beyond 3 AU, we can write to good approximation

$$dr/dt = \mu vV/\Omega r\sin\Theta + V \qquad (1)$$

where μ is the pitch cosine, V is the solar wind velocity, and Θ is the co-latitude. Since our observations are at latitudes <30°, we set $\sin\Theta=1$.

For the energy loss, we will use the relation derived by Simnett and Roelof (1999) for guiding center motion in the equatorial heliospheric magnetic field. Even in the absence of pitch-angle scattering, there is an energy loss (non-relativistically independent of mass or charge) given by

$$dv/dt \cong -(vV/2r)(1+\mu^2) \qquad (2)$$

where Ω is the sidereal rotation frequency of the Sun. The familiar expression for "adiabatic cooling" is recovered by replacing $(1+\mu^2)$ by its isotropic average of 4/3.

We could completely pose the problem by adding an additional relation giving μ as a function of r, such as the conservation of the magnetic moment $(1-\mu^2)v^2/B(r)$ = const. However, we know that there is some pitch-angle scattering, although we believe it to be weak. Even so, magnetic focussing will tend to keep an outward particle going outward. Consequently, we believe that we can obtain a good indication of the essential nature of particle propagation beyond 5 AU by holding $\mu \cong$ const. in Eqs. (1) and (2) and considering it a "typical" pitch-cosine for the particle's transit from $r=r_0$ to $r>r_0$. Since the RHS of Eq. (2) only varies by a factor of 2 for $0<\mu^2<1$, we will also consider $\mu \cong$ const. therein.

A very useful integral for our discussion is immediately obtained by substituting v in terms of dv/dt from Eq. (2) into Eq. (1) and then integrating from time t_0 (when the particles leave the disturbance at r_0 with velocity $v=v_0$) until they arrive at radius r at time t (which is before the disturbance arrives):

$$r-r_0 = -2\mu(v-v_0)/(1+\mu^2)\Omega + V(t-t_0) \qquad (3)$$

Since Eq. (2) shows that the particle is always losing energy (regardless of the sign of μ), we always have $v<v_0$ in the first term on the RHS of Eq. (3). Thus Eq. (3) implies that the radial distance δr that the particle can "run ahead" of the solar wind is given by

$$\delta r = 2\mu(v_0-v)/(1+\mu^2)\Omega < 2\mu v_0/(1+\mu^2)\Omega \qquad (4)$$

This is because the distance along each winding of the spiral eventually becomes so long that the particle moves out radially faster by field line convection ($\mathbf{V}_{\perp}$) than by running along the field ($\mathbf{v}_{||}$). Interestingly, because of the geometry of the archimedean spiral, δr is independent of the solar wind velocity V. Notice that there is a maximum δr given by the inequality in Eq. (4); it is attained when the particle has lost so much energy that $v<<v_0$.

Eq. (4) gives us the time separation at some distance r between the arrival of the particles with "typical" pitch-cosine μ as $\delta t=\delta r/V$. We do not have space here to present the complete solution of Eqs. (2) and (3) for v_0 as a function of μ, v, r, and r_0, but we summarize the results in Table 1. Protons that arrive at the Voyagers with E=0.5 MeV were launched with energy E_0 >0.5 MeV from Disturbance B when it had begun to coalesce at r_0=5 AU. For each part of the distribution that propagates with a "typical" values of the pitch cosine μ, Table 1 gives, for both V2 (56 AU) and V1 (72 AU), pairs of values for E_0 /E, the distance δr(AU) ahead of Disturbance B, and the arrival time δt(days) prior to the arrival of Disturbance B.

Table 1. Predicted arrival times (prior to Disturbance B) at V2 (56 AU) and V1 (72 AU)

"typical" μ	E_0/E	δr(AU)	δt(days)
0	25 35	0 0	0 0
0.05	13 17	6.5 7.2	22.8 25.2
0.10	9.5 12	11.0 12.5	38.5 43.8
0.15	7.8 9.8	13.5 16.5	47.3 57.8
0.20	6.7 8.3	16.0 18.5	56.0 64.8
0.30	5.5 6.8	18.7 22.5	65.5 78.8
0.40	4.8 5.9	21.0 24.5	73.5 85.8
0.50	4.4 5.3	21.5 25.7	75.3 90.0

3.2 Results and Discussion: The results in Table 1 predict that if the proton population is confined to the vicinity of the shock at r_0 in the inner heliosphere at time t_0, they will be broadly distributed over distances δr ahead of the disturbance when they arrive at radius r in the outer heliosphere at a time interval δt before the disturbance. Particles whose propagation can be characterized by small "typical" pitch cosines ($\mu \cong 0$) will arrive with the shock, while particles with $\mu \cong 0.5$ (60° "typical" pitch-angle) will arrive months before the disturbance.

Compare the values of δt in Table 1 with the intensity histories in Fig. 4. Immediately we see that the general dependence of δr (and δt) upon μ is rather similar at the two Voyagers (despite their separation of 16 AU and 51° in latitude), consistent with the very similar appearance of the events in Fig. 4. Relatively few protons arrive within the few weeks before Disturbance B. This lack of $\mu \cong 0$ protons is consistent with some degree of magnetic focussing, especially since the effect is more marked at V1. The intensity peaks at 40d at V1 and 45d at V2, in agreement with δt=38.5d and 43.8d corresponding to μ=0.10 at both Voyagers. The earliest detected intensities were 75d and 90d prior to Disturbance B, in good agreement with δt=75.3d and 90.0d corresponding to μ=0.5 at both Voyagers.

We therefore conclude that our characterization of proton propagation by a "typical" pitch-cosine gives a good semi-quantitative validation to all significant aspects of the remarkable proton events at both Voyagers preceding Disturbance B. As predicted by Eq. (4), the >0.5 MeV proton population had outrun the disturbance from 5 AU, attaining the maximum radial separation possible by field-aligned propagation (constrained by energy loss) during the ~50 AU transit to the Voyagers. Thus this interesting event confirms both the concepts of relatively scatter-free propagation (with magnetic focussing) and scatter-free energy loss (Simnett and Roelof, 1999).

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