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Relativistic Particle Injection and Interplanetary Transport during the January 20, 2005 Ground Level Enhancement

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Besides producing the largest ground level enhancement (GLE) in half a century, the relativistic solar particles detected during the event of January 20, 2005 showed some interesting temporal and directional features, including extreme anisotropy. In this paper we analyze the time evolution of cosmic ray density and anisotropy as characterized by data from the "Spaceship Earth" network of neutron monitors by using numerical solutions of the Fokker-Planck equation for particle transport. We find that a sudden change in the transport conditions during the event is needed to explain the data, and we propose that this change was caused by the solar particles themselves.

1. Introduction

The remarkable solar event of 2005 January 20 produced the highest flux of relativistic solar particles observed at many neutron monitor stations for nearly 50 years [1]. This event provides an opportunity to measure relativistic solar particle fluxes with high statistical accuracy, and in particular the recently completed Spaceship Earth network of polar neutron monitors with uniform detection characteristics [2] provides a precise determination of the directional distribution. It was particularly fortunate that a spectacular increase of $\sim 5500\%$ was observed at the South Pole station, where the Polar Bare counters, which are preferentially sensitive to particles at sub-GV rigidity, are operated along with a standard 18-NM-64 monitor, providing a special opportunity to measure the spectrum with unparalleled precision.

In addition, one might expect special physical effects in association with the extremely high flux of relativistic particles in space. Indeed, our preliminary results indicate what may be the first documented example of nonlinear transport processes of relativistic solar particles. Applying existing techniques to model the interplanetary transport of solar particles [3] and fit time profiles of particle density and weighted anisotropy [4] as determined from polar neutron monitors worldwide [5], there is a clear indication of two enhancements in particle flux at Earth, the second of which has a much lower anisotropy. The most natural explanation is that the change in transport conditions was caused by the particles themselves, which generated waves that resonantly scattered the particles injected later in the event.

2. Injection and transport modelling

First, data from 12 polar neutron monitor stations situated worldwide [5] are fit to an analytic function of the particles' pitch angle about an optimal axis of symmetry taking into account bending of particle trajectories in Earth's magnetic field. The omnidirectional intensity and weighted anisotropy (standard anisotropy multiplied by intensity) are extracted as quantities to be fit by the transport model. Two peaks, separated by an 8 minute interval, are apparent in the intensity profile, the first of which shows a much higher anisotropy than the second one.

The propagation of solar energetic particles (SEPs) from the Sun is calculated by numerically solving the Fokker-Planck equation for particle transport [3], which includes the effects of pitch angle scattering and adiabatic focusing. We compute the transport of solar protons in the energy range of detectability by neutron monitors, along an Archimedean spiral magnetic flux tube connecting the Sun and the Earth, consistent with a solar wind speed of approximately 800 $\mathrm{km\,s^{-1}}$. We then try to optimize the value of the parallel mean free path λ, assumed to be uniform along the magnetic flux tube, by least squares fitting of the intensity and weighted anisotropy while using a piecewise-linear function for the SEP injection near the Sun [4].

We find that a long scattering mean free path ($\lambda \approx 1$ AU) is necessary to explain the extreme anisotropy at the beginning of the GLE as well as the fast decay of the first intensity peak. However the slower decay of the second peak, and the more moderate anisotropy at that time, are not consistent with this same value for λ. Therefore, we find that the assumption of a uniform and constant value of the scattering mean free path leads to very poor fits. This result suggests that the amount of interplanetary scattering varied rapidly (i.e., on the order of a few minutes) during the January 20, 2005 event. Consequently, we consider the possibility that the SEPs themselves could account for this temporal variation of the properties of interplanetary space.

In the conventional treatments of SEP transport, SEPs are treated as test particles that propagate through interplanetary space without affecting its properties. This is usually correct for relativistic protons, as the kinetic energy carried by these particles is small compared to the energy contained in the magnetic fluctuations of the solar wind in the range of wave numbers that experience resonance with those SEPs. In the general case, however, the evolution of the Alfvén wave intensity should be computed consistently with the distribution of SEPs [6].

During January 20, 2005 the conditions were such that we cannot consider relativistic protons as test particles. On the one hand, the fit to neutron monitor data reveal an omnidirectional intensity of SEPs, during the maximum peak, of roughly 350% above the galactic cosmic ray background, which, as stated above, qualifies this event as the most intense since 1956 [1]. On the other hand, the modelling of the SEP intensity and anisotropy during the first minutes after event onset shows that the scattering was especially weak. These facts conspire to make the energy density carried by energetic particles to be significant compared with the energy in Alfvén waves. In fact, a rough estimation based on quasi-linear theory [7] shows that the energy density due to the kinetic energy of SEPs in the energy interval of interest was possibly almost one order of magnitude *larger* than the energy density of magnetic fluctuations in the corresponding range of wave numbers. If part of that energy is transferred from the SEPs to the medium by the excitation of Alfvén waves, then the scattering coefficient will evolve in connection with SEP passage, and the process can only be described in terms of a nonlinear transport equation.

3. Preliminary analysis using linear transport

As a first approximation to the nonlinear problem, we can suppose that during the first part of the SEP event the scattering conditions can be characterized by some uniform and constant value of the scattering mean free path, λ_1, and some power-law spectral index for interplanetary turbulence, q_1, while after the passage of the first intensity peak the scattering conditions change, leading to different values, λ_2 and q_2, again assumed to be uniform and constant for the rest of the event.

Under this approximation, we can still use solutions of the linear transport equation, linearly combining the results for two different scattering conditions, and then jointly optimizing the otherwise independent parameters

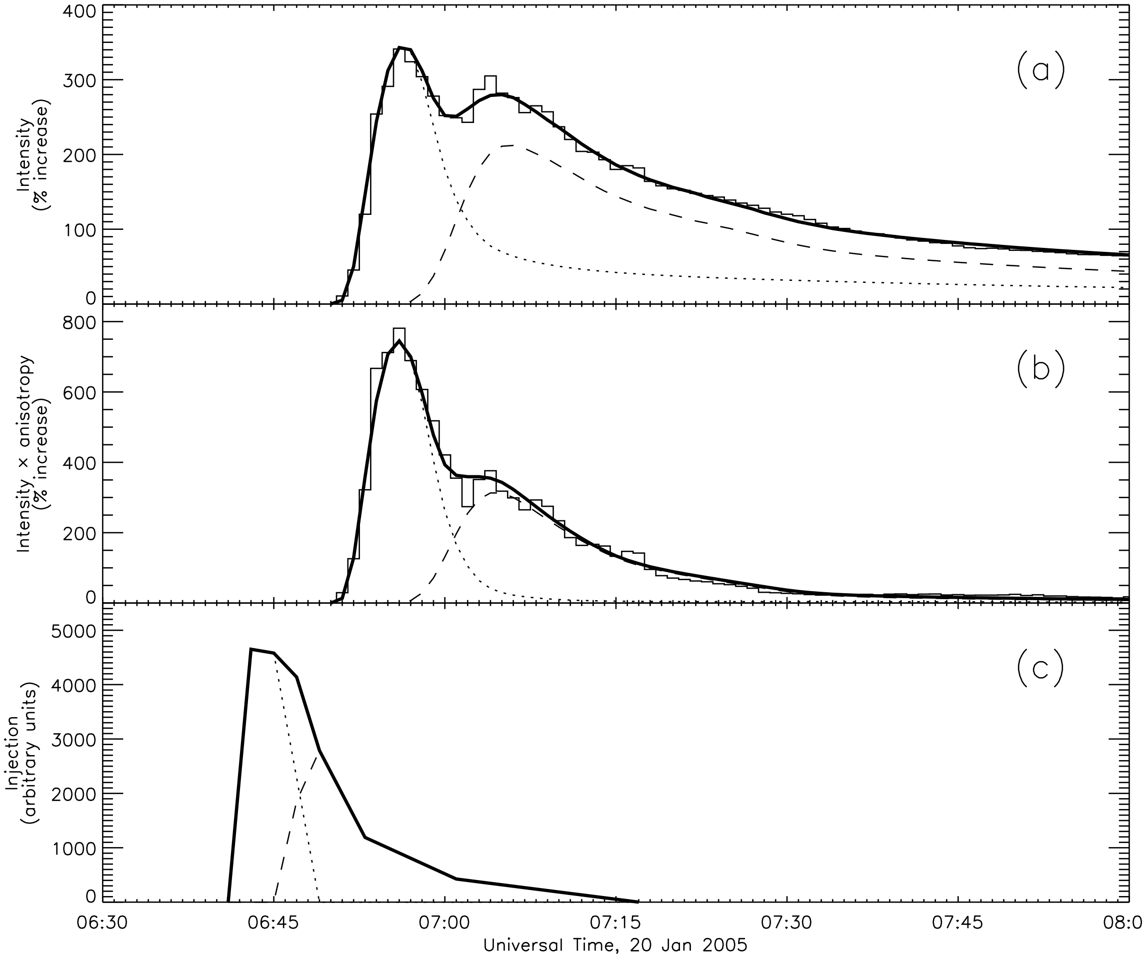

Figure 1. (a) Thin solid line: directionally averaged intensity at polar neutron monitors. Thick line: combination of two solutions to the linear transport equation, one with low scattering conditions (dotted line) and one with higher scattering conditions (dashed line), that best fits the data. (b) Same as (a), for the weighted anisotropy at polar neutron monitors. (c) Model injection function (solar time) of relativistic solar protons, optimized to fit intensity and weighted anisotropy.

λ_1, q_1, λ_2, and q_2 using two independent piecewise-linear injection functions. As before, we do this by simultaneous least squares fitting of the intensity and weighted anisotropy to the combined linear solution. The results for the best fit are shown in Figure 1.

This fitting is better than the fit with just one constant λ value by a factor of ≈ 2 in χ^2. Our analysis favors a starting value of the scattering mean free path of $\lambda_1 = 0.9 \pm 0.1$ AU, and a decrease due to wave excitation by SEP passage to $\lambda_2 = 0.6 \pm 0.1$ AU; it also favors a low value for the initial spectral index, $q_1 \approx 0.5$, but a higher final value, $q_2 \approx 1.5$. Both effects seem to be consistent with some energy being deposited by passing SEPs, although this result should also be checked by means of a self-consistent nonlinear transport model. Again, a rough estimation of the energy density carried by SEPs during the maximum peak and the energy contained in interplanetary turbulence before and after the event (using quasi-linear theory and these values of λ_1, q_1, λ_2, q_2) suggests that a considerable fraction of the SEP kinetic energy needs to be transferred to the medium to produce this effect.

Regarding timing, from this analysis we estimate the SEP injection to start at 6:41 ST ±1 minute and to peak at 6:44 ST ±2 minutes (where "ST" refers to Solar Time, or Universal Time of an event at the Sun). As can be seen in Figure 1, and contrary to our expectations, the inferred total injection function does not have two maxima; in our preliminary results for the nonlinear transport scenario the double peak in the observed intensity at Earth arises from interplanetary transport effects.

4. Summary

We have performed an analysis of the time evolution of relativistic solar proton intensity and anisotropy during the exceptionally intense GLE on 2005 January 20, as characterized by polar neutron monitor data. The data indicate two enhancements in particle flux at Earth, the second of which has a much lower anisotropy. Applying existing techniques to model the interplanetary transport of SEPs [3] and fit the time profiles of intensity and weighted anisotropy [4], we have found that the GLE is best modelled by assuming different scattering conditions at the start and later during the event, but with a smoothly varying injection time profile. We propose that the transport conditions changed rapidly during the event due to the high density of SEPs, which generated waves that resonantly scattered the particles injected later in the event. Such effects have been inferred in the vicinity of major interplanetary shock events, by means of compositional variations of accelerated particles at moderate energies [8], and we propose that in this case there is substantial generation of waves at low wave number in the interplanetary medium even ~ 1 AU ahead of the CME-driven shock. Our results seem also consistent with observations of moderate energy SEPs that show that the anisotropy of the particles streaming away from the Sun decays faster for larger events than for small ones [9].

5. Acknowledgements

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References

[1] J.W. Bieber et al., 29th ICRC, Pune (2005, this conference), paper usa-bieber-J-abs1-sh15-oral.
[2] J.W. Bieber et al., Astrophys. J., 601, L103 (2004).
[3] D. Ruffolo, Astrophys. J., 442, 861 (1995).
[4] D. Ruffolo et al., J. Geophys. Res., 103, 20591 (1998).
[5] J.W. Bieber et al., Astrophys. J., 567, 622 (2002).
[6] W.I. Axford et al., 15th ICRC, Plovdiv (1977) 11, 132.
A.R. Bell, Mon. Not. R. astr. Soc., 182, 147 (1978).
C.K. Ng et al., Astrophys. J., 591, 461 (1999).
[7] J.R. Jokipii, Rev. Geophys. Space Phys., 9, 27 (1971).
[8] A.J. Tylka et al., Geophys. Res. Lett., 26, 2141 (1999).
C.K. Ng et al., Geophys. Res. Lett., 26, 2145 (1999).
D.V. Reames and A.J. Tylka, Astrophys. J., 575, L37 (2002).
[9] D.V. Reames et al., Astrophys. J., 550, 1064 (2001).