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Ground-level Events Measured with *Milagro*

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We report on Ground Level Events (GLE) seen simultaneously in the global neutron monitor (NM) network and the *Milagro* instrument. We pay special attention to the events of 1997 November 6 and 2005 January 20, registered by *Milagro*, Climax and other NMs. *Milagro* is a ground-level TeV gamma-ray telescope detecting gamma rays through the Çerenkov light emitted by secondary electrons in water. It registers solar protons through secondary muons and electrons. It sits in the Jemez mountains in New Mexico, USA at an elevation 2630 m, 385 km south of the Climax NM. However, because of its method of detecting solar protons, it has a greater atmospheric cutoff. *Milagro* also has several data channels (scalers) in which to measure the intensity of the event. By combining data from Climax and several *Milagro* data channels one can study the behavior of the high end spectrum of many GLEs, including the spectrum cutoff, onset and rise time. If the proton energy is great enough an extensive air shower is produced and the response of the instrument is recorded on an event-by-event basis, providing an incident direction.

1. Introduction

By measuring the spectrum and intensity behavior of well connected ground-level events (GLE) while the event is anisotropic reveals considerable information about the progenitor shock that accelerates the protons and ions. Thus, bypassing as much as possible interplanetary transport effects allows one to examine the event at low altitudes in the early and peak acceleration stages.

The spectrum of the protons accelerated and released by the shock is determined by several factors. These factors include the strength of the shock, its speed, the diffusion coefficient up- and downstream of the shock and its radius when it releases the protons into interplanetary space. These factors manifest themselves in a characteristic spectral shape, i.e., a steepening, at the highest energies.

The proton spectrum is also linked to the duration of the GLE. At lower MeV energies, the protons and ions detected at earth can be intense for time scales of days, whereas GLEs, i.e., GeV energies, may only be enhanced for hours or even minutes. Recent modeling of GeV shock acceleration replicates the transient nature of the GLE[1, 2]. The phenomenon results from (1) the requirements of setting up the shock close to the Sun, (2) maintaining sufficient shock strength to accelerate particles to high energies, (3) maintaining a sufficient level of upstream turbulence to retain the particles for acceleration and (4) a dissipation of the same upstream turbulence that releases the GeV particles to be detected at earth, if well connected. Thus, a careful study of the evolution of the intensity, spectrum and pitch-angle distribution is necessary to properly investigate the nature of the accelerating shock and the conditions in the inner heliosphere that facilitates the process.

The basics technique we and others have used to attack the problem is to employ a pair or pairs of ground-level stations that have similar geomagnetic cutoff rigidities, similar asymptotic directions, yet have different yield functions to provide two independent integral measures of the cosmic-ray intensity[3]. The differential count rate between the two stations yields a spectral shape in the intervening rigidity range. This complements the analysis conducted with the world-wide network of NMs, where count rates differences must be attributed not only to the spectrum but also the sometimes narrow pitch-angle distribution of the protons.

The instruments used in this study are three neutron monitors—Mount Washington (MW) and Durham (D) in New Hampshire (NH), USA; and Climax in Colorado, USA. We also used the *Milagro* ground-level TeV gamma-ray telescope located at Fenton Hill, New Mexico, USA. The first pair, MW and D, differ primarily in their atmospheric overburden, whereas for the second pair, Climax is an IGY NM while *Milagro* can be used as a ground-level muon telescope at a different overburden and different cutoff. The instrument parameters are listed in the Table.

Table 1. Station Characteristics

Station	Instrument Type	Vertical Cutoff (GV)	Depth (g-cm^{-2})	Trajectory Difference
Mount Washington	IGY (12)	1.68	828	10.6°
Durham	NM64 (12)	1.88	1013	
Climax	IGY (12)	2.96	658	23.2°
Milagro	muon	3.90	734	

The *Milagro* instrument[4, 5] detects muons generated by solar and galactic protons with two layers of photomultipliers submerged in a 8-m deep water pond. The Çerenkov light from the relativistic muon illuminates one or several PMTs triggering them if the light intensity is sufficient. The basic data channel for recording the effect of solar protons is the High Threshold (HT) scaler, in which only a single PMT need trigger in a sub-μs resolving time. Other scaler data are available, including those of external particle detectors and higher levels of PMT multiplicity. These were not used in this analysis for reasons explained below.

2. Discussion

As an example of the technique the 1997 November 6 event was studied by Lockwood et al.[3] using MW and D data and Falcone et al.[6] using a *Milagro* prototype instrument, *Milagrito*, that was functionally similar to *Milagro*, but outfitted with fewer PMTs, fewer data readout channels and no auxiliary outrigger detectors. Lockwood et al. derived a rigidity spectrum power-law index of –6.2 from the ratio of the count rates in the MW and D NMs. Falcone et al. assumed an rigidity power-law index of –5.5 from 1 to 5 GV as reported by Lovell et al.[7] With this power law spectrum, they concluded from the *Milagrito* data that the rigidity spectrum must steepen from –5.5 to approximately –9 or abruptly cutoff in the range of 5-6 GV, in either case softening significantly at higher energies. They computed the *Milagrito* response to several proton spectra and all required a significant spectral break, indicative of the maximum accelerating energy of the parent shock. Furthermore, on the basis of the onset time of the increase at *Milagro* and the reported CME speed, Falcone et al. estimated that the shock accelerated the particles, abruptly releasing them 4-5 solar radii above the solar surface, consistent with release distances of several solar radii for other GLEs reported by Kahler[8].

Other GLEs were detected by the network of the four instruments listed above, including the 2000 July 14 and 2001 April 15 events. The difference in the *Milagro* and Climax responses varied dramatically, in agreement with the spectral shapes reported by Lockwood et al.[3] The results of those analyses will be reported elsewhere.

For the remainder of this paper we discuss the recent intense event of 2005 January 20. The increases and decays of the intensity-time profiles the NH NMs were similar except primarily for the magnitude of the increase. The relative increase at MW was expectedly greater than that detected by the D NM. Using the relationship reported by Lockwood et al.[3] for these two stations, the measured increase ratio of 1.6

suggests a proton (ion) spectrum of $p^{-6.2}$, softer than the energy spectrum of $E^{-2.2}$ reported by Labrador[9] at lower energies (c.a. 100 MeV), indicating the spectrum is breaking at higher energies.

The Climax and *Milagro* intensity curves are shown in Fig. 1 with the MW curve superposed for reference. It shows that Climax and *Milagro* have relatively more intense prompt increases with more rapid declines. In fact, within the time resolution of Climax (1 min) and Milagro (10 s) the intensity curves behave the same indicating that both instruments are sampling the same part of the pitch angle distribution (probably close to the axis), especially when compared to the relatively weaker prompt response of MW. Some differences between Climax and *Milagro* emerge in the tail of the decay, c.a., 0705 UT with *Milagro* exhibiting a clearer secondary peak at that time. For the time being we devote our attention to the prompt increase that is putatively caused by directly accelerated solar-flare particles rather than an interplanetary shock.

Extrapolating the linear part of the *Milagro* increase to zero counts we estimate an onset time of 0651.2 UT at *Milagro*. Gopalswamy et al.[10] using LASCO and EIT images fitted an kinematic equation to the CME images. We further assume a pitch angle distribution width of 20˚ and solar wind speed of 560 km-s^{-1} that was present before the onset and approximately one day later. (The intervening solar wind speed data from SOHO are not available but the magnetic field direction is consistent with a steady wind of this speed.) The resulting length of the Parker spiral is 1.1 AU. The last uncontaminated LASCO frame at 0654 UT shows the CME with a speed of 3242 km-s^{-1}[10]. The net result is that the computed release time of the 5 GV protons is 0653 UT, approximately the time of the last uncontaminated LASCO image. This number has a likely uncertainty of ±2 minutes, but it places the release point at 4.2 solar radii or lower. The greatest uncertainties arise from the kinematic behavior of the CME and the width of the pitch angle distribution.

The other interesting feature of this event is the short rise and fall times, 110 and 70 s, respectively. Drawing upon the analysis of Lockwood et al.[11] we examine the consequences of such short characteristic times. In particular, we assume that the shock accelerating process follows the sequence described by Lee[1] and Zank et al.[2] That is, that the piston-like CME sets up a shock at some distance from the Sun where the magnetic field weakens, after which it accelerates particles based on the compression ratio and the upstream diffusion coefficient that is necessary to retain the protons. At some point, the upstream diffusion coefficient drops (from divergence) to the point where the accelerated protons are abruptly released into interplanetary space. If the event is well connected then a GLE can be registered with an associated pitch angle distribution determined by magnetic field focusing and the details of the release process. It is the thickness of the turbulent sheath upstream of the shock and the imbedded level of turbulence that fixes the decay time of the event seen at Earth.

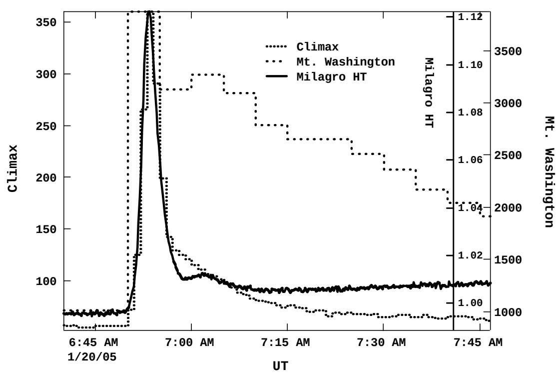

Fig. 1 Climax, Milagro and MW count rates.

Using the relationship[11] for the diffusion time away from the shock $\tau = R^2\Omega(3c^2\xi)^{-1}$, where R is the radius of the shock for the particle release, Ω is the proton gyro radius, c is the speed of light and ξ is the ratio of mean free path the to the gyro radius, we can set a lower limit to the effective mean free path of GV protons in the sheath. Using our measured and derived quantities we conclude that the mean free path to be of order 100 gyro radii (extrapolating the 1 AU IMF intensity to 4 solar radii). This rapid diffusion up- (and downstream) would be consistent with the rapid acceleration observed, while the relatively low integrated fluence (relative to the intensity) follows from the inability of the shock to retain the upstream energetic protons. The extraordinary speed of the CME is also consistent with the early shock setup time required here.

We were not able to obtain a reliable measure of the proton spectral index from the Climax and *Milagro* data to complement the D/MW power of $p^{-6.2}$. Simulations of the Milagro response to the power law measured with MW and D with the intensity of Climax resulted in anomalously high rates for higher multiplicity data channels. We tentatively interpret this failure to the fact that we modeled the response of *Milagro* using an isotropic flux of protons at the top of the atmosphere. The widely ranging response of other stations in the world-wide network of NMs indicates a very anisotropic distribution, and it is likely that the fundamental differences between the NM and the muon detector manifested themselves in divergent instrument responses. (An unrealistic pitch-angle distribution for the NH NMs would not affect the derived spectral index, but would affect the inferred intensity.) Instrument modeling of Climax and *Milagro* with explicit anisotropic fluxes is necessary to disentangle these effects.

3. Conclusions

We conclude (1) that using the four stations of MW, D, Climax and Milagro can be an effective spectroscopic tool for measuring the prompt increase associated with anisotropic GLEs. We also conclude that the GLE of 2005 January 20 was an unusual event in its intensity, brevity, placing it on the outer edges of parameter space for shock acceleration to GeV energies, but still not requiring a different process, i.e., direct solar flare acceleration.

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References

[1] M. A. Lee, Astrophys. J. (Suppl. Ser.), 158, 38 (2005).
[2] G. P. Zank *et al.*, J. Geophys. Res., 105, 25 (2000).
[3] J. A. Lockwood *et al.*, Solar Phys., 208, 113 (2002).
[4] R. Atkins *et al.*, Astrophys. J., 595, 803 (2003).
[5] A. Falcone, Astroparticle Physics, 11, 283 (1999).
[6] A. D. Falcone *et al.*, Astrophys. J., 588, 557 (2003).
[7] J. L. Lovell *et al.*, Adv. Sp. Res., (1999).
[8] S. Kahler, Astrophys. J., 428, 837 (1994).
[9] A. W. Labrador *et al.*, Spring American Geophysical Union Meeting, New Orleans, 2005.
[10] N. Gopalswamy *et al.*, 29th ICRC, Pune, India, 2005.
[11] J. A. Lockwood *et al.*, preprint, (2005).