Milagro and Climax Measurements of the 2005 January 20 GLE Particle Spectrum

TREVOR MORGAN[1] FOR THE MILAGRO COLLABORATION AND CLIFFORD LOPATE[1]
[1]*University of New Hampshire*
contact: tmorgan@unh.edu

Abstract: *Milagro* is a ground-based TeV γ-ray telescope in the Jemez Mountains near Los Alamos NM. Designed to image TeV γ-ray sources, it is also sensitive to energetic solar particles above the local geomagnetic cutoff. It sits relatively close to the Climax neutron monitor in Colorado. Because of their geomagnetic proximity, these two instruments can be jointly used to construct a time-dependent spectrum for GLE events unaffected by particle anisotropies. Modeling of the performance of both instruments to both isotropic and anisotropic particle distributions is underway and will be used to constrain the 2005 January 20 spectrum during the brief event onset as well as the abrupt decay. The multiple data channels in the *Milagro* instrument are also sensitive to large anisotropies. We present ongoing results of the spectrum and anisotropy of the 2005 January 20 GLE.

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 basic 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 worldwide 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.

We have expanded on this concept with the *Milagro* instrument, described below. *Milagro* possesses several data channels with different energy thresholds.

The Milagro Instrument

The instruments used in this study are the neutron monitor in Climax in Colorado, USA and the *Milagro* ground-level TeV γ-ray telescope located at Fenton Hill, New Mexico, USA. Climax is an IGY NM while *Milagro* can be used as a ground-level muon telescope at a different overburden and different cutoff. Climax has a cutoff of 2.96 GV while *Milagro* has a cutoff of 3.90 GV. Climax has an atmospheric overburden of 659 g-cm^{-2}, while *Milagro* has an overburden of 734 g-cm^{-2}. The two stations differ in their asymptotic directions by ~23˚.

Figure 1: Aerial view of *Milagro*.

The *Milagro* instrument[4, 5] detects muons generated by solar and galactic protons with two layers of photomultipliers submerged in an 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 ranging up to 40 PMTs hit.

Milagro GLE Simulation

The data from the *Milagro* scaler channels during the time of the event do not conform to an isotropic distribution. Intensity curves from the worldwide network of NMs support the conclusion of an anisotropic particle distribution, as a result simulations were launched using CORSIKA and GEANT for zenith protons.

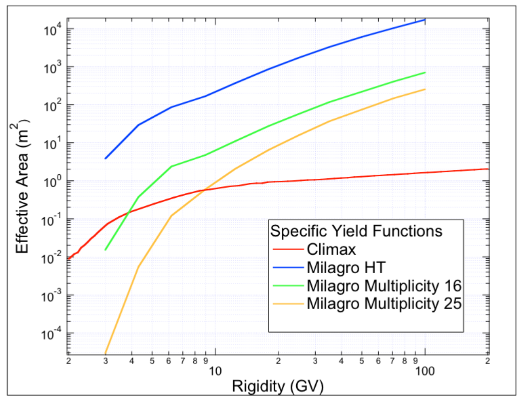

Figure 2: Specific Yield Functions for Climax, *Milagro* High Threshold, and *Milagro* 25PMT.

Analysis of the proton spectrum above the geomagnetic cutoff can be obtained from the high-multiplicity *Milagro* channels that respond to higher rigidities. As seen in Figure 2 the Multiplicity-25 yield function is decreasing faster than the HT as one approaches the geomagnetic cutoff from above. Peaks in data rates for these higher multiplicity scalers, *e.g.*, 16- and 25-PMT, during a GLE can provide the intensity and spectral shape of the particle spectrum at higher rigidities than those of just the High Threshold and Climax. An absence of the increase for a given channel during a GLE also provides information, for it indicates an upper limit or threshold rigidity to the proton spectrum.

Therefore, the *Milagro* scaler channels will be used independently or in conjunction with the nearby Climax neutron monitor to determine the intensity and spectral shape over a wide rigidity range, as well as provide an upper limit when the signal fades into the background.

GLE Measurements

The Climax and Milagro intensity curves are shown in Figure 3. It shows that Climax and *Milagro* have intense prompt increases with rapid declines. In fact, within the time resolution of Climax (1 min) and Milagro (16 s) the intensity curves behave the same indicating that both instruments are sampling the same part of the pitch angle distribution (close to the axis). Some differences between Climax and Milagro emerge in the tail of the decay (not shown), *ca.*, 0705 UT with Milagro exhibiting a clearer secondary peak at that time.

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*.[6] using LASCO and EIT images fitted a kinematic equation to the CME images. We further assume a pitch angle distribution width of 20˚, as well as a 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, consistent with release distances for other GLEs reported by Kahler[7]. The greatest uncertainties arise from the kinematic behavior of the CME and the width of the pitch angle distribution.

Using the relationship reported by Lockwood *et al.*[3] for the Durham, NH and Mt.Washington, NH NMs, the measured increase ratio of 1.6 suggests a proton (ion) rigidity spectrum of $p^{-6.2}$, softer than the energy spectrum of $E^{-2.2}$ reported by Labrador[9] at lower energies (*ca.* 100 MeV), indicating that the spectrum is breaking at higher energies.

Preliminary results using the specific yield functions from Climax and the *Milagro* HT channel give a particle spectrum of $p^{-8.4 \pm 0.5}$ from 4-6 GV. Similar softening of proton spectra during a GLE was also observed during the 1997 November 6 GLE with the *Milagro* prototype instrument, *Milagrito*. Falcone *et al*.[9] concluded that the rigidity spectral index softened from –5.5 (Lovell *et al*.[10]) to –9 or abruptly cutoff in the range of 5-6GV. Data rate increases for the 2005 January 20 GLE are seen in *Milagro* scaler channels up to a multiplicity of 25, suggesting that the upper limit to the rigidity spectrum is past 6 GV. The results from these data channels will be reported during our presentation.

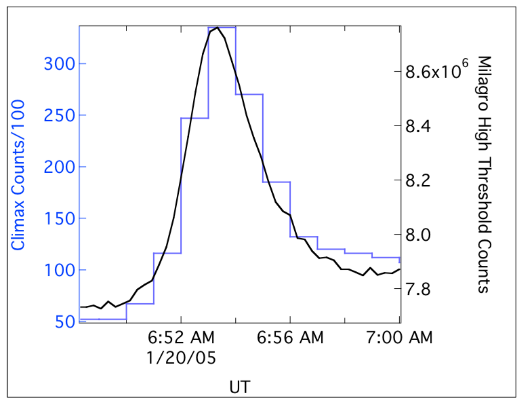

Figure 3: Intensities for Climax and *Milagro* High Threshold during the 2005 January 20 GLE.

Results and Discussion

The *Milagro* ground-level TeV γ-ray telescope detects muons form Solar and Galactic cosmic rays and can be used as a tool to study solar flares. The 2005 January 20 GLE registered data rate increases in all scaler channels up to the 25PMT channel. From the specific yield functions of Climax and *Milagro* HT a softening of the proton spectrum from $p^{-6.2}$ to $p^{-8.4 \pm 0.5}$ in the rigidity range of 4-6 GV is consistent with the data. This result qualitatively agrees with that of Falcone *et al*.[9] for the 1997 November 6 GLE.

Where a signal is present, the higher multiplicity channels from *Milagro* will be used to calculate the intensity, spectral index (or upper limit) of the rigidity spectrum during the 2005 January 20 GLE above 6 GV. This analysis will provide valuable information about the progenitor shock that accelerates the protons and ions. The data from these channels as well as the results from the zenith simulations will be complete in the near future.

The 2005 January 20 GLE 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.

Acknowledgements

This work has been supported by the National Science Foundation (under grants PHY-0075326, PHY-0096256, PHY-0097315, PHY-0206656, PHY-0245143, PHY-0245234, PHY-0302000, and ATM-0002744, ATM-0411651) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics. We thank Drs. R. Lin and R. Mewaldt for providing copies of their oral presentations at the 2005 Spring AGU meeting. We also thank Drs. N. Gopalswamy and C. Faruggia for unpublished CME and solar wind data, respectively.

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] N. Gopalswamy *et al.*, 29th ICRC, Pune, India, 2005
[7] S. Kahler, Astrophys. J., 428, 837 (1994)
[8] A. W. Labrador *et al.*, 29th ICRC, Pune, India, 2005
[9] A. D. Falcone *et al.*, Astrophys. J., 588, 557 (2003)
[10] J. L. Lovell *et al.*, Adv. Sp. Res., (1999)