Detection of the 6 November 1997 Ground Level Event by Milagrito

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Abstract. Solar Energetic Particles (SEPs) with energies exceeding 10 GeV associated with the 6 November 1997 solar flare/CME (coronal mass ejection) have been detected with Milagrito, a prototype of the Milagro Gamma Ray Observatory. While SEP acceleration beyond 1 GeV is well established, few data exist for protons or ions beyond 10 GeV. The Milagro observatory, a ground based water Cherenkov detector designed for observing very high energy gamma ray sources, can also be used to study the Sun. Milagrito, which operated for approximately one year in 1997/98, was sensitive to solar proton and neutron fluxes above ~4 GeV. Milagrito operated in a scaler mode which was primarily sensitive to muons, low energy photons, and electrons, and the detector operated in a mode sensitive to showers and high zenith angle muons. In its scaler mode, Milagrito registered a rate increase coincident with the 6 November 1997 ground level event observed by Climax and other neutron monitors. An analysis, based on preliminary effective area estimates, indicates the presence of >10 GeV particles.

INTRODUCTION

Particle acceleration beyond 1 GeV due to solar processes is well established (1), but its intensity and energy still amazes researchers. However, few data exist demonstrating acceleration of protons or ions beyond 10 GeV (2, 3). The energy upper limit of solar particle acceleration is unknown but is an important parameter, since it relates not only to the nature of the acceleration process, itself not ascertained, but also to the environment at or near the Sun where the acceleration takes place. The Milagro instrument, a water Cherenkov detector near Los Alamos, NM, is at 2650 m elevation with a geomagnetic vertical cutoff rigidity of ~4 GV. It is sensitive to hadronic cosmic rays from approximately 5 GeV to beyond 1 TeV. These primary particles are detected via Cherenkov light, produced by secondary shower particles, as they traverse a large ($80 \times 60 \times 8$ m) water-filled pond containing 723 photomultiplier tubes (228 PMTs for the prototype, Milagrito). This energy range overlaps that of neutron monitors (in the region < 10 GeV) such that Milagro complements the worldwide network of these instruments. These ground-based instruments, in turn, complement spacecraft cosmic ray measurements at lower energies. This suite of instruments may then be capable of measuring the full energy range of solar hadronic cosmic rays, with the goal of establishing a fundamental upper limit to the efficiency of the particle acceleration by the Sun. Milagro's baseline mode (air shower telescope mode) of operation measures extensive air showers above 300 GeV from either hadrons or gamma rays. A description of Milagro's capabilities as a VHE gamma ray observatory is available elsewhere (4). Milagro measures not only the rate of these events but also the incident direction of each event, thereby localizing sources. While performing these measurements, the instrument records the rate of photomultiplier hits (the scaler mode), with an intrinsic energy threshold of about 4 GeV for the progenitor cosmic ray to produce at least one hit. The scaler mode provides data that are similar to those of a neutron monitor, while the telescope mode can significantly reduce background by pointing. With a proposed fast data acquisition system (DAQ) and modified algorithms for determining incident directions of muons, the energy threshold of Milagro's telescope mode will be reduced to ~4 GeV by detecting the (~300 kHz) single muons and mini muon showers. For now, this low energy threshold can only be achieved by using Milagro in the scaler mode, which is not capable of localizing

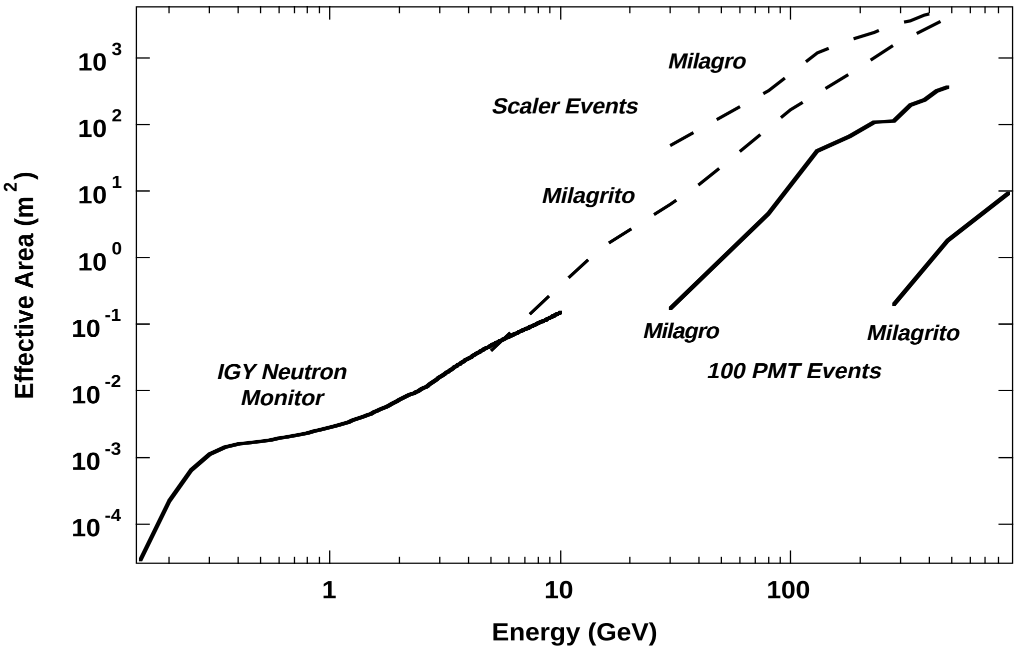

Figure 1. Preliminary, lower-limit effective area curves for Milagro and Milagrito, with a sea-level IGY neutron monitor for comparison. (The Milagro shower trigger is no longer set at 100 PMTs, but Milagrito shower data was recorded with a 100 PMT threshold.)

sources. A description of the Milagro solar telescope mode can be found in another publication (5).

SOLAR MILAGRO/MILAGRITO SCALER MODE

In the scaler mode, a substantial portion of the rate recorded by Milagro (and Milagrito) is due to muons, and an integral measurement above threshold is performed. These data provide an excellent high energy complement to the network of neutron monitors, which has been, and continues to be, a major contributor to our understanding of solar energetic particle acceleration and cosmic rays. With Monte Carlo calculations, we estimated the effective areas of Milagrito to protons incident on the atmosphere isotropically, at zenith angles ranging from 0^{o}-60^{o} (Figure 1). The effective area curves for Milagro, which have been plotted for the sake of comparison, are for beamed protons. At 10 GeV, Milagro's scaler mode is at least an order of magnitude greater than the effective area of a sea level neutron monitor, with the effective area rising rapidly with energy, while Milagrito had approximately 4 times the effective area of a neutron monitor at 10 GeV. Based on current work, these effective area curves appear to be lower limits to the instruments' actual effective area. The plotted areas were calculated using Monte Carlo events whose shower cores were thrown at, or near, the Milagro pond. We are currently calculating the complete response of the instrument by taking into account hits on the pond which are caused by hadronic showers with cores very far (> 5 km) from the detector. This effect will increase the calculated effective area, but the general shape of the curve is expected to remain unchanged.

In order to apply this area to an analysis of an observed rate, pressure, temperature, and other diurnal corrections must be applied to the ground level scaler rate (6). We have begun to determine these correction factors for Milagro/Milagrito, and we find them to be reasonably consistent with past work with muon telescopes (7). However, these corrections are less important for transient (i.e. solar) events that rise above background quickly and have short durations.

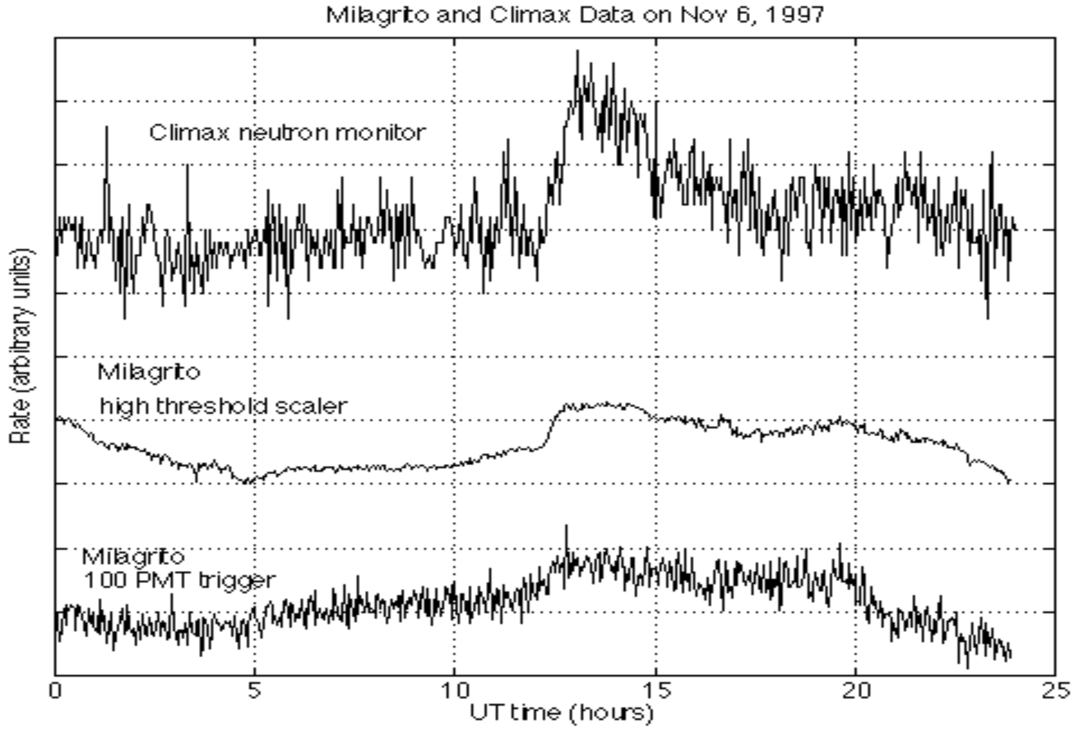

Figure 2. Milagrito registered a rate increase coincident with that of Climax during the GLE of Nov. 6, 1997. The y-axis units have been scaled and shifted for each plot to make comparison easier. (Climax data courtesy of C. Lopate, Univ. of Chicago)

6 NOVEMBER 1997 GROUND LEVEL EVENT

On 6 November 1997 at approximately 12:00 UT, an X-class flare with an associated coronal mass ejection occurred on the Sun. This produced a nearly isotropic (8) ground level event registered by many neutron monitors. A preliminary analysis of neutron monitor data for this proton event yields a spectral index of ≈5.5 at event maximum in the 1-5 GV rigidity range, assuming a power law rigidity spectrum for protons (9). Climax, located in nearby central Colorado, is the closest of these neutron monitors to Milagro/Milagrito. Milagrito, a prototype version of Milagro with less effective area, registered a scaler rate increase coincident, within error, with that measured by Climax (Figure 2). If one accounts for meteorological fluctuations, the event duration and time of maximum intensity, as seen by Milagrito, are also consistent with that of Climax. The magnitude of this rate increase was ≈22 times the RMS fluctuations of the instrument's background (RMS of fluctuations is used since the scaler background fluctuations are nearly twice that expected from Poisson statistics). It is likely that this signal is overwhelmingly due to protons, but there could be some contribution from other sources, such as iron (10) and other high Z ions.

The high threshold scaler rate increase can be used to derive characteristics of the primary proton spectrum. This is done by folding a trial power law spectrum of protons through the effective area of the detector. The parameters of the trial spectra are then varied until a good fit to the measured rate increase is achieved. When compared to the neutron monitor network's spectrum for protons < 4 GeV, the preliminary results of this analysis indicate the presence of protons in excess of 10 GeV. Further work, particularly on the effective area of the detector, is necessary to better determine the spectrum at these energies.

The 100 PMT shower trigger rate also experienced an increase, although the significance is not as great as that in scaler mode. It is not yet clear which of several possible mechanisms initiated the signal in the 100 PMT shower trigger, so the detector's sensitivity to various mechanisms is being investigated. This increase could have been caused by high energy primaries (> 100 GeV, see Figure 1) and/or secondary muons arriving from a nearly horizontal direction. If horizontal secondary muons contributed to this signal, they would have been the result of high energy proton primaries, but the effective area of the detector would be significantly different from that assumed here and cannot be used to constrain the spectrum without more extensive Monte Carlo calculations. Future work will address this issue by considering events caused by horizontally incident secondary muons, revising the preliminary effective area calculations, and recalculating the spectrum.

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