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Milagro as a solar observatory

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Abstract

The Milagro Gamma Ray Observatory, a ground-based water Čherenkov detector designed primarily for observing very high energy gamma ray sources, can also be used to study the Sun. Measurements of high energy emission from solar flares can lead to an understanding of the solar energetic particle acceleration mechanism(s), and Milagro, with enhanced data acquisition electronics, will measure solar cosmic rays in the poorly studied energy range from 10 to 300 GeV. Monte Carlo simulations show that proton and neutron solar cosmic rays at these energies will be detectable at the ground level through the single muons and/or mini showers they produce. Milagro can detect these events in a scaler counting mode similar to that of a neutron monitor. Additionally, it can operate in a telescope mode that reduces background by pointing at the source region. We also report a preliminary detection, using the Milagro prototype, Milagrito, of a ground level event (GLE) on 6 November 1997 associated with an X-class solar flare.

1. Introduction

Particle acceleration beyond 1 GeV at the Sun 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 Čherenkov detector near Los Alamos, NM, is at 2600 m elevation with a geomagnetic cutoff rigidity of ≈3.5 GeV. It is sensitive to solar hadronic cosmic rays from approximately 5 GeV to beyond 1 TeV. These primary particles are detected via Čherenkov light, produced by the secondary shower particles, as they traverse a large (80 × 60 × 8 m) water-filled pond containing 724 photomultiplier tubes (PMTs). This energy range overlaps that of neutron monitors (<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. It measures not only the rate of these events but also the incident direction of each event, thereby localizing sources. While performing these measurements, the

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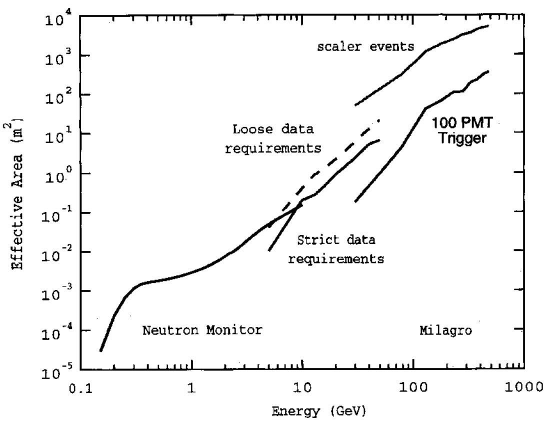

Fig. 1. Effective area for Milagro, with an IGY neutron monitor for comparison.

instrument records the rate of photomultiplier triggers from muons (the scaler mode), with an intrinsic energy threshold of about 5 GeV for the progenitor cosmic ray. The scaler mode is similar to that 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 the telescope mode will be reduced to ~10 GeV by detecting the (~300 kHz) single muons and mini muon showers. This mode of operation will be referred to as the solar telescope mode.

2. Solar Milagro: telescope and scaler modes

In solar telescope mode, the incident direction of the single muons and mini muon showers will be determined from relative timing and spacing of individual PMT hits in the pond. Initial studies, in which neural networks are applied to Monte Carlo events, predict a primary particle angular resolution between 4° and 12°. We expect the resolution to improve as the techniques are refined, since all available shower parameters have not yet been incorporated into the neural net. The effective areas for two possible data selection criteria are shown in Fig. 1. The strict data requirement will yield better angular resolution, while sacrificing effective area, while the loose data requirement will sacrifice angular resolution to achieve larger effective area. Although the effective area of the telescope mode operation is less than that of the scaler mode, the sensitivity will be dramatically increased by background reduction.

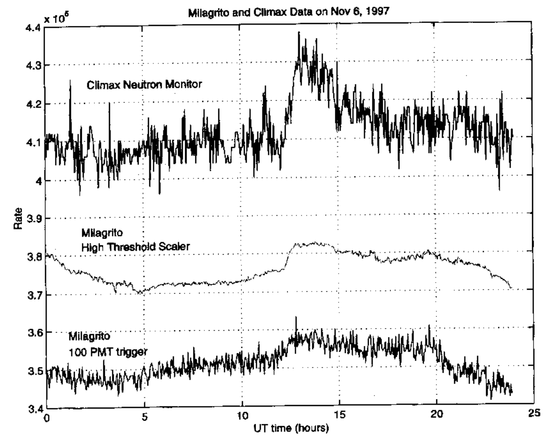

Fig. 2. Milagrito registered a rate increase coincident with that of Climax and other neutron monitors. The y-axis units have been scaled and shifted for each plot to make comparison easier. (Climax data courtesy of C. Lopate, Univ. of Chicago)

In scaler mode, Milagro will record the rate of muons, thus performing an integral measurement above threshold. These data will 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. At 10 GeV, Milagro's scaler mode will have 100 times the effective area of a neutron monitor, with the effective area rising rapidly with energy (see Fig. 1). Pressure, temperature, and other diurnal corrections must be applied to the ground level scaler rate [4]. We have begun to determine these correction factors for Milagro, and we find them to be reasonably consistent with past work with muon telescopes [5]. However, these corrections are less important for transient (i.e. solar) events that rise above background quickly and have short durations. Milagro's prototype, Milagrito, has already taken promising scaler data, described below.

3. November 6, 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 an isotropic ground level event registered by many neutron monitors. Climax, located in nearby southern 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 (see Fig. 2). If one accounts for the meteorological fluctuations, the event duration and time of maximum intensity, as seen by Milagrito, are also consistent with that of Climax. A preliminary analysis of this event indicates a proton flux above 10 GeV of $\sim$6 protons m^{-2} s^{-1}. The 100 PMT trigger, that requires primary protons exceeding 100 GeV, also experienced a rate increase, although the significance is not as great as that in scaler mode. (We point out that anomalously noisy PMTs could cause a similar scaler rate increase, but preliminary investigations seem to exclude this possibility.)

In future work, we will verify the significance of this detection and model the solar proton spectrum responsible for the increases.

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