High-Energy Solar Flare Studies with HAWC and Neutron Monitors

J.M. Ryan* for the HAWC Collaboration
*Space Science Center, University of New Hampshire
†NASA/Goddard Space Flight Center

University of New Hampshire

Abstract

Solar flares can produce ions in excess of 1 GeV/nuc, both impulsively and for extended periods of time. We know this by way of the γ radiation those ions produce. We have witnessed this in several Fermi flares above 100 MeV as well as in the data from SMM and *Compton*. Our ability to deduce the nature of parent ion population responsible for the γ rays is limited by the confounding multiple processes that separate the ion population from the consequent photons. However, when neutrons (>500 MeV) are produced, which should be almost every time pions are produced, we have complementary information about the ion spectrum if those neutrons are measured. The γ rays are most closely tied to the ion spectrum near the pion production threshold, while the ground level neutrons sample the ion spectrum >1 GeV. Together these two measurements provide information on the ion spectral shape and its turnover at high energy. The turnover embodies critical information about the parameters of the acceleration process and environment. Above 500 MeV, neutrons can be detected at the ground near the subsolar point. HAWC, the High Altitude Water Čerenkov γ-ray telescope is designed to measure cosmic TeV γ-ray sources. HAWC resides on Sierra Negra in Mexico at a latitude of 19˚ and an altitude of 623 mbar. Neutron signals detected by HAWC will be from higher energy ions at the Sun, compared to the bulk of photons detected by Fermi. If a γ signal is also present in HAWC, this will be additional information with which to examine the solar ion spectrum. The neutron and γ data from HAWC and neutron monitors when combined with data from Fermi LAT/GBM will constitute the the most comprehensive measure of the high-energy solar ion spectrum.

Big Science Questions

- ***How does the high end of the flare-ion spectrum behave?***
  - The ion spectrum deduced from neutrons and gammas exhibits an exponential-like roll off. This roll off is produced by the available particle acceleration time and the finite size of the acceleration region. Thus, this spectrum roll off carries much information about the acceleration process.
- ***Do the solar neutrons relate to the interplanetary solar protons, putatively accelerated remotely in a coronal shock?***
- ***What does the spectrum and intensity of solar neutron and gammas say about particle acceleration in the flare?***

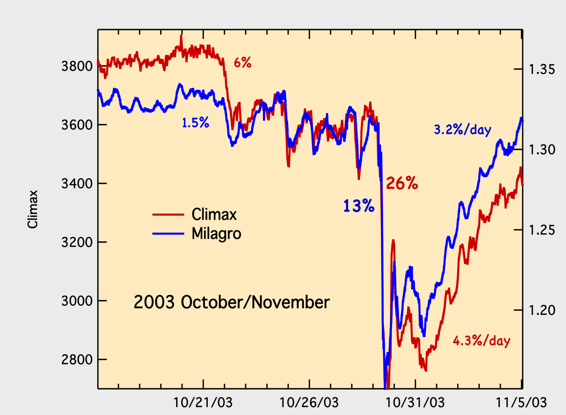
The Instrument

The HAWC instrument is an array of water-filled tanks. Each tank is light tight and is equipped with photomultiplier tubes at the bottom (looking up). Each tank detects energetic charged particles as those particles enter the tank and emit Čerenkov light. To measure TeV γ rays that produce air showers, the moving front of electrons and positrons sweeps over the array and the timing of the signals from the different tanks defines the trajectory of the air shower. The uniformity, or lack thereof, identifies the shower as being either electronic or hadronic.

Showers produced by galactic cosmic rays are identified and recorded too if they are sufficiently energetic (>100 GeV).

Lower energy (<100 GeV) particles at the top of the atmosphere produce muons with signals in a single or a few tanks. Solar protons, gammas or neutrons will produce muons and/or electron pairs that will hit and be sensed by one or a few tanks without a full shower. HAWC monitors the rate of these hits, for various levels of multiplicity, i.e., one, two, six, ... photomultiplier tubes. Thus, HAWC is a muon or electron pair detector, but behaves simultaneously like several neutron monitors with differing atmospheric cutoffs. HAWC is much like Milagro, except that Milagro used a single large pond of water equipped with many PMTs.

Milagro successfully detected several GLEs, one of which is shown at the right, as well as significant Forbush decreases. See below. **The latitude of Milagro was too high to see solar neutrons.**

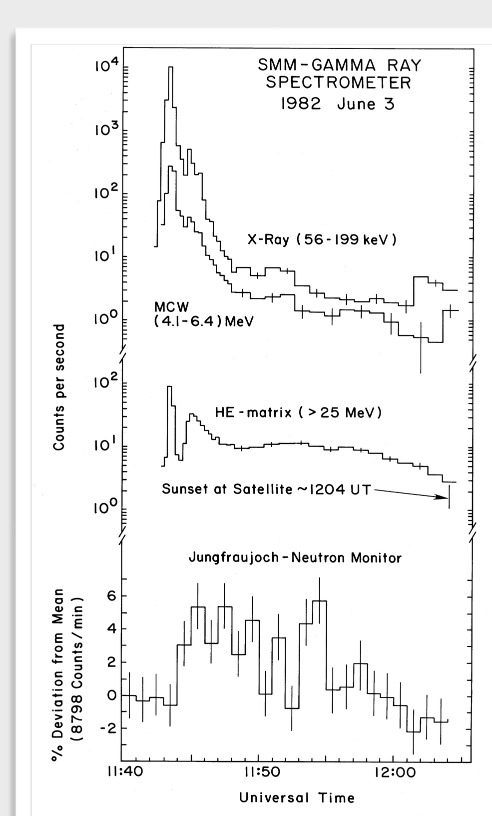


Although located near the Climax neutron monitor, Milagro responded differently than Climax to the Halloween 2003 Forbush decreases, because of its greater rigidity threshold as a muon detector.

The HAWC Experiment

Ground Level Neutrons and Gamma Rays

1982 June 3



Shown at the left is the 1982 June 3 Long Duration Gamma Ray Flare measured with the Gamma Ray Spectrometer on SMM with the associated ground level neutron signal at Jungfraujoch (latitude 46.5˚). The neutron and gamma spectra were modeled using data with little or no spectral information. The parent ion spectra that produced the neutral particles were then modeled from these data. HAWC with its different thresholds will provide neutron spectral information. If gammas are detected with HAWC, they could be combined with gamma data from Fermi. The superior spectral information would provide information on the evolution of the spectrum and the flare's ultimate acceleration efficiency.

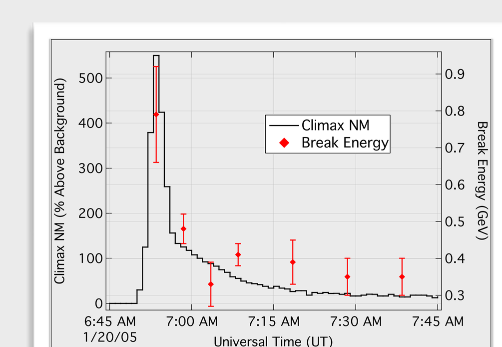
A controversy surrounds the origin of the protons/ions that produce the high-energy gamma rays. One school of thought is that trapped and continuously accelerated in the corona produces the gammas, while another school is that backward moving ground level enhancement (GLE) ions precipitate onto the photosphere producing the emission. Understanding how the spectrum of gamma rays evolves as compared to the spectrum of interplanetary (GLE) particles will support or conflict with the assumption of a single source.

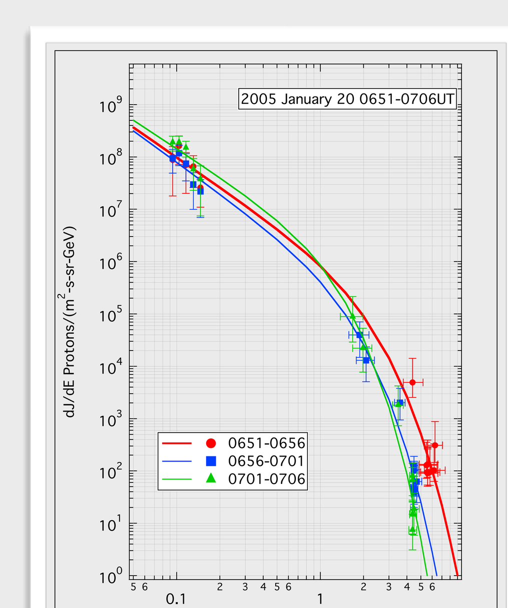
With HAWC one can measure the time-resolved spectrum much in the way that Milagro did for the 2005 January 20 GLE. For this classic solar proton GLE, Milagro in conjunction with Climax derived the intensities and spectra as shown on the right.

HAWC would do similarly with a complementary instrument in the form of the Mexico City neutron monitor as it registers solar neutrons >500 MeV.

Ground level solar gamma rays have never been observed, but with a threshold of approximately 500 MeV, the enormous collecting area of HAWC will augment any high-energy photons detected in space.

2005 January 20 GLE





HAWC Details

HAWC Advantages

- **Covers the high end of the proton or neutron spectrum**, but with enormous collecting area for excellent statistics.
- **Many data channels (different multiplicity channels) probe different energy or rigidity bands.**
- Ideally supported with its own neutron monitor—yet to be proposed. Close to Mexico City NM-64 station. **The proximity of a neutron monitor with a much different response allows us to perform spectroscopy at a single location with minimal concern for anisotropy effects between stations.**
- **Scientifically functional now!**
- **Low latitude—great for solar neutrons and gammas** for much of northern hemisphere summer.
- **High altitude—great for both solar protons, neutrons and maybe gammas.**

HAWC Parameters

- Location: between Mexico City and Veracruz
- 608 g-cm^{-2} overburden vs. 735 g-cm^{-2} for Milagro
- 12500 m^2 geometrical area vs. ~2000 m^2 for Milagro
- 8.2 GV cutoff vs. ~4 GV for Milagro
- 19˚ latitude vs. 36˚ for Milagro
- ~500 MeV Threshold detection energy for neutrons, similar for gammas
- 2-s readout of all scalers to resolve fast time structure.

Deployment Schedule

Stage	*Tanks*	*Completion Date*
HAWC 100	100	current
HAWC 300	300	Fall 2014

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