Rapid Notification of TeV Transients with the Milagro Telescope

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Abstract. The Milagro telescope is a wide field of view TeV observatory that is ideally suited for the observation of transients in the 300 GeV-10 TeV band. Milagro has a very large field of view (about 2 sr), nearly continuous operation, and a fluence sensitivity that is comparable to satellite experiments. Milagro is currently performing real time searches for TeV transients, with the goal of prompt notification and multi-wavelength observation of any detected TeV transients.

THE MILAGRO OBSERVATORY

The Milagro detector is centered around a large reservoir of water located high in the Jemez mountains of New Mexico[1]. The reservoir (affectionately know as "The Milagro Pond") is approximately 4800 m^2 in size and is located at an altitude of 2600 m (8600 ft.). This reservoir is covered with a light tight cover, and instrumented with 723 photo tubes arranged in two layers (see figure 1).

When a very high energy (VHE) photon enters Earth's atmosphere, it pair produces and starts a cascade of particles that travels as a relativistic pancake through the atmosphere. This relativistic pancake is known as an extensive air shower (EAS), and passes through the light tight cover and into the Milagro Pond. The relativistic particles in the EAS front exceed the speed of light in water and emit Cherenkov radiation, primarily in the blue and near ultra-violet (charged particles in the shower front immediately Cherenkov radiate, whereas secondary gamma rays pair produce in the water, and the daughter particles radiate). The Cherenkov radiation is then detected by the photo tubes. By careful timing of the detected Cherenkov light, the direction of the incident EAS front (and thus the original photon) can be reconstructed to 0.75° on average.

Milagro's use of Extensive Air Showers offers several compelling features. Because EAS penetrate through the atmosphere, observation can be continuous. Milagro observes day and night and is immune to the weather. Shower reconstruction depends on timing, not collimation, bestowing Milagro with a very wide field of view ($\sim$2 sr.). Additionally, TeV EAS fronts have large diameters, so the effective area of Milagro is considerably larger than the physical area of the pond for much of its energy range.

The cosmic ray background is a large problem for all EAS detectors, and our long duration signals are background dominated. There are characteristic differences between gamma ray and cosmic-ray initiated showers which can be exploited to reject a portion of the cosmic ray flux. We are currently using the bottom layer of tubes to reject cosmic ray showers. This is an active area of both hardware and analysis research (see the last section on future directions for the Milagro detector).

The water Cherenkov technique used by Milagro is unique among EAS detectors, and allows us to achieve sensitivity to below 300 GeV, good background rejection, and a small angular resolution. Milagro's unique abilities are enabling the first comprehensive search for TeV transients.

REAL TIME TRANSIENT SEARCHES WITH MILAGRO

The study of gamma-ray bursts has been revolutionized by multi-wavelength observations. While afterglow observations at energies below a few keV tell us about the environment and development of the GRB fireball, observations (or lack thereof) of TeV emission can set strong constraints on the basic production mechanism of gamma-ray bursts. For example, if the observed spectral peak at BATSE energies is due to synchrotron radiation, one expects a prompt second peak in the TeV due to inverse Compton scattering[2]. The exact shape, timing, and amplitude of this second peak is highly model dependent, and can set strong constraints on the production mechanism of GRBs. It is this TeV emission peak that

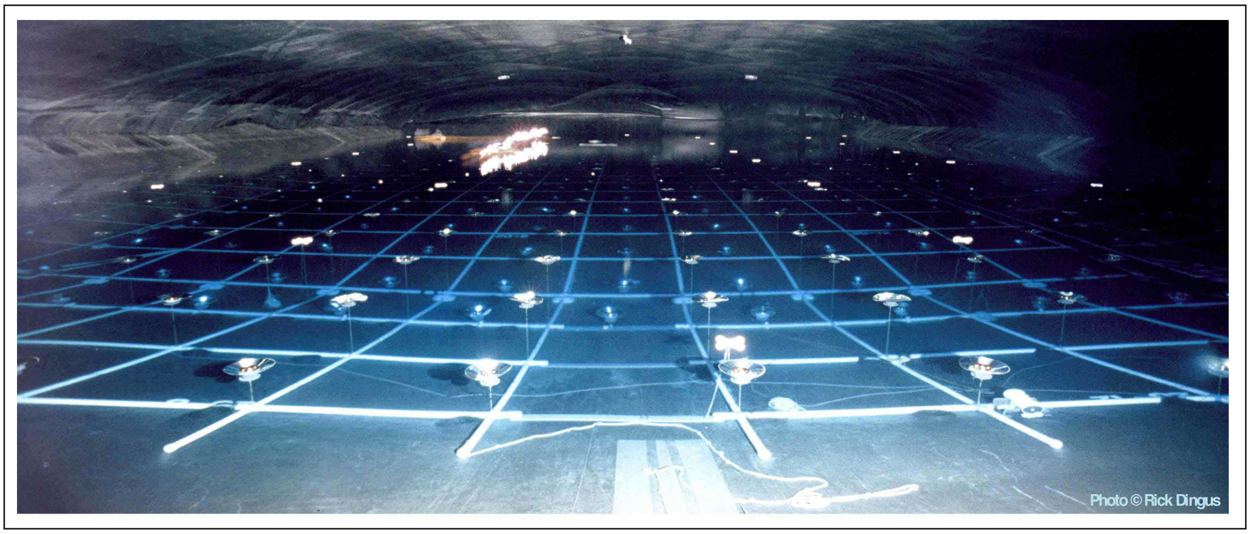

FIGURE 1. This photograph shows the Milagro reservoir (80 m x 60 m) from under the light tight cover. Clearly visible are the photo tubes arranged on a 3 m grid. The upper layer of phototubes is under 1.5 m of water, while the second layer is under 7 m of water.

Milagro is uniquely able to observe.

Unfortunately, TeV photons are absorbed over cosmological distances by pair production with IR background photons. This absorption limits the distance to which Milagro can observe GRBs to a red shift significantly less than 1, though the exact cutoff depends on the cosmological model. Though this may become of powerful tool for measuring the IR background, it hampers our ability to see most GRBs. If we were limited to doing coincidence observations with satellites, there would be very few GRBs for which we could place direct limits on the TeV emission (especially with the current low rate of GRB detections). However, Milagro is a very sensitive detector in its own right, and can search the sky for TeV transients with very little sensitivity degradation (see figure 2). An independent search for transient TeV signals has the added benefit of not biasing the search with satellite selection criteria.

The fluence sensitivity of Milagro near 1 TeV is comparable to the best GRB satellites in the keV-MeV range (again see figure 2), and extends from below 300 GeV to above 10 TeV. For the past year, Milagro has been searching the sky for transients of 250 microseconds to 40 seconds duration. This effort has recently been augmented by a new analysis that is being used for the 40 second to 2 hour time region [3]. During the past year of operation, no GRBs of 250 microseconds to 40 seconds duration have been seen by Milagro (see figure 3), but this is not unexpected due to the limited distance to which Milagro is sensitive.

Both of these analyses are now running and allow Milagro to provide prompt GCN notification of any TeV transients with a resolution of a few thenths of a degree. Any transients seen with Milagro will be ideal candidates for multi-wavelength observations because of their proximity (z<1), good localization, and the prospect of detailed observation of both the emission mechanism and the developing fireball.

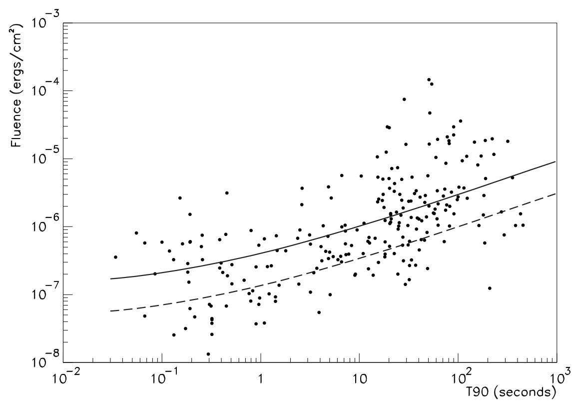

FIGURE 2. This plot shows a sample of BATSE bursts (block dots) plotted as X-ray fluence versus burst duration. The lines show the 5 sigma detection threshold of the Milagro detector for fluence at TeV energies. The dashed line is for an externally triggered GRB, while the solid line represents a blind search. Note that the trials penalty for a blind search does not make a large difference in the detection threshold, because a small increase in the number of signal photons leads to a large decrease in the Poisson probability. For example, doubling the flux of a 5 σ detection changes it to a 10 σ detection, or a factor of more than 10^{-16} in probability.

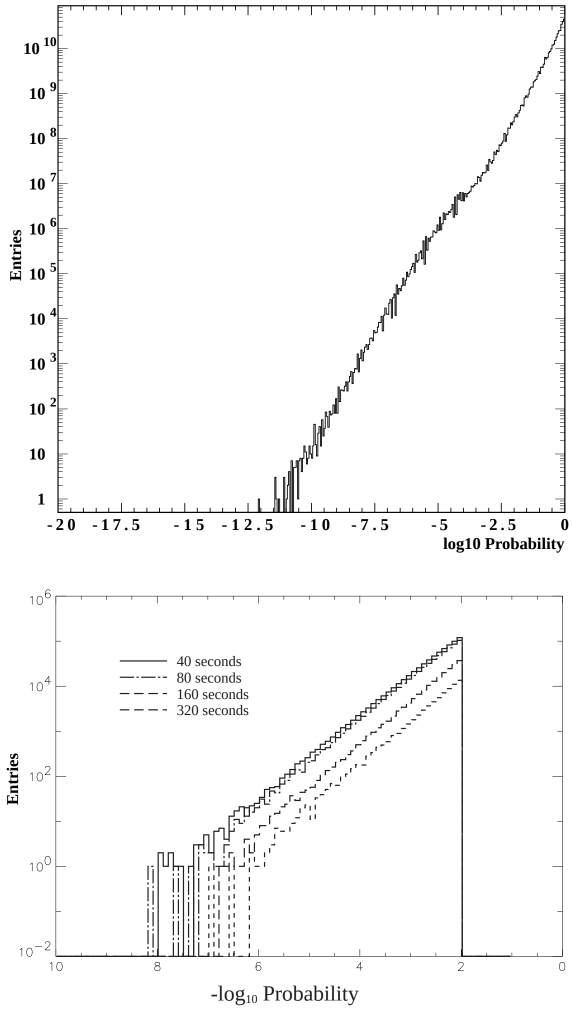

FIGURE 3. In Milagro, the real-time transient search is divided between two independent analyses. The binned analysis covers the time scale of 250 μs – 40 s, and has been running for one year. It has recently been joined by the weighted analysis (see [3]), which covers the 40 s – 2 h region. The figures above show examples of the probability distributions observed by the two analyses. These distributions are consistent with the expected background fluctuation distributions; any signals would appear as isolated points of very low probability. The top figure shows the observed probability distribution for the binned analysis on a time scale of 10 seconds, for 200 days of Milagro data. The kink in the distribution at 10^{-4} is due to a transition between sparse and fine sampling by the search algorithm. The lower figure shows the observed probability distributions for 4 separate time scales of the weighted analysis, collected over 1 day. Events with a probability greater than 10^{-2} are not recorded. No TeV transients have been observed, but both analyses are currently running and will provide prompt notification of any signals to the GRB community.

FUTURE DIRECTIONS

The Milagro Observatory is still under construction. The portion of the Milagro detector in the reservoir is complete – and is the basis for all of the data shown here – but is only the central piece of a larger detector. We are in the process of deploying $\sim$170 outrigger detectors around the central reservoir in order to complete the Milagro telescope. The final Milagro detector will have significantly better sensitivity than the current partial version.

The outrigger detectors are cylindrical water filled cisterns approximately 2.4 m in diameter and 1 m deep. Each cistern is lined with reflective Tyvek, equipped with a single photo tube, and placed on a 15 m grid around the central Milagro reservoir.

These outriggers significantly increase the size of the Milagro detector. The outriggers allow us to contain the full size of most EAS, giving us sparse sampling across the entire shower front and detailed timing and calorimetry on the portion of the EAS incident on the central Milagro pond. This combination of large scale sparse information and detailed information on one area will improve our angular resolution, our energy resolution, and allow for more sophisticated background rejection techniques.

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