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HAWC – A Bird's Eye View of the Extreme Universe

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Recent progress in the field of very-high-energy (>100 GeV) gamma-ray astrophysics has been remarkable. With the advent of the H.E.S.S. telescope and the upcoming launch of GLAST we can look forward to an even more exciting future. However there is a problem with the current suite of instruments planned to cover the highest energy range. Though capable of remarkable sensitivity, air Cherenkov telescopes are best suited to study individual sources or perform surveys over a limited area of the sky. While GLAST will detect several thousand sources and the objects that emit VHE gamma rays are generally variable, no all-sky monitor in the VHE energy region is planned. Here we present plans for an all-sky VHE instrument with dramatically improved sensitivity over the current generation of such instruments.

1. Introduction

To date two techniques have been used to construct all-sky VHE telescopes. The Tibet array [1] uses a classical array of plastic scintillators dispersed over roughly 50,000 m^2 to detect the passage of charged particles that are a component of extensive air showers (EAS). A thin layer of lead over each detector increases the sensitivity of the detector via the conversion of some of the gamma rays in the EAS. Built at extreme altitude (4300m), closer to shower maximum, the detector has sufficient sensitivity to detect the Crab Nebula in TeV gamma rays with ~1 year of observation. The Milagro [2] detector, at a more moderate altitude of 2600m, has achieved similar sensitivity with a ~4000 m^2 detector. Milagro has accomplished this by utilizing a water Cherenkov detector to detect the passage of charged particles and gamma rays in the EAS. Unlike a conventional scintillator array, a water Cherenkov detector provides almost 100% coverage of the detector area (at relatively low cost) and high sensitivity to the gamma rays in the EAS (which dominate over the electrons and positrons by a factor of ~6). In addition, a third technique is currently being developed by the ARGO [3] collaboration. Using an array of RPC chambers (that provide complete coverage of the detector area) and building at extreme altitude (4300m), ARGO expects to have 2-3 times the sensitivity of Milagro.

We are proposing to construct a large area water-Cherenkov detector at extreme altitude. Milagro was the first such instrument and considerable experience has been gained by its operation. There are several improvements to the method that can significantly increase the sensitivity of such a detector.

1. Build at extreme altitude. There are roughly 5 times as many e-m particles in an EAS at 4300m as there are at 2600m.
2. Build a large instrument. The shower front exhibits a curvature, therefore events whose centers (cores) fall outside the detector will be improperly reconstructed. This also improves background rejection (if one has a technique for rejecting background) as the larger area increases the probability of intercepting a muon or hadron present in the EAS generated by cosmic rays.
3. Optically isolate the detector elements. In a water Cherenkov detector light can propagate nearly horizontally and thereby strike a detector element far from its point of generation. This leads to reduction in the angular resolution, background rejection, and energy resolution of the detector.

While it is possible to build a very large instrument (300m x 300m), the HAWC (High Altitude Water Cherenkov) telescope, with the sensitivity to detect the Crab in ~30 minutes (60 times the sensitivity of Milagro) the cost would be $20-30M. By re-using the 900 photomultiplier tubes (PMTs) and electronics currently used by Milagro, an instrument with a sensitivity ~15 times that of Milagro can be built for under

$3M. This instrument dubbed miniHAWC will consist of a single layer of PMTs on a 5m grid placed under 4m of water. The total area of HAWC will be 22,500 m^2 (150m x 150m).

2. Detector Response

To calculate the sensitivity of miniHAWC and HAWC we utilize CORSIKA [4] to generate the extensive air showers from both gamma-ray and proton primaries and GEANT 3.2 to track the particles through the detector, generate the Cherenkov light and simulate the electronics. The primary protons and gamma rays are generated on an $E^{-2.7}$ and $E^{-2.4}$ spectrum respectively (the gamma rays are re-weighted as needed to simulate different source spectra). Both species are generated beginning at particle energies of 10 GeV and shower cores are placed uniformly in radius out to a distance of 1 km (events are re-weighted by a factor equal to their core distance to compensate for this non-uniform areal distribution in the generated events).

The events are reconstructed using the current Milagro reconstruction algorithms – with necessary geometrical changes made (PMT placement). In what follows a trigger requirement of 80 or more PMTs struck is made on all events for miniHAWC and a 50 PMT threshold is assumed for HAWC. The position of the shower core is than determined, followed by the shower direction. The direction is found by correcting the measured arrival times for shower-front curvature and a sampling affect, then fitting these corrected times to a plane. It is assumed that the times can be measured to 0.5 ns accuracy. The angular resolution function of miniHAWC is given in Figure 1, a histogram of the space angle difference between the reconstructed direction and the true direction of the triggered events. The effective angular resolution is ~0.4 degrees, almost a factor of two improvement over that of Milagro before the installation of the outrigger array.

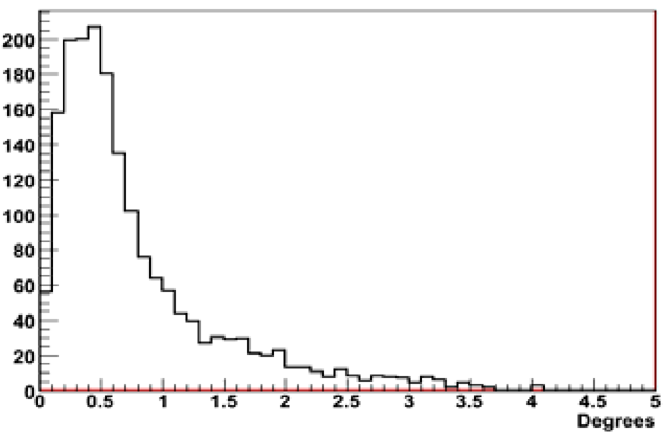

Figure 1. The angular resolution function of miniHAWC. The space angle difference between the true and reconstructed event directions is shown in the histogram.

EAS generated by hadronic particles and nuclei comprise the background in the presence of which any gamma-ray signal must be detected. Milagro has demonstrated that a water Cherenkov detector can eliminate a large fraction (~90%) of this background by detecting the penetrating component of hadronic EAS (muons and showering hadrons) [5]. For a single layer design at high altitude it is necessary to modify the parameter used by Milagro. A modified compactness parameter is defined as nPMT2/cxPE, where nPMT2 is the number of PMTs with 2 or more photoelectrons (PEs) and cxPE is the number of PEs in the tube with the most PEs, where a region 20 meter around the reconstructed shower core is removed from the search. This last requirement is needed because the core of an electromagnetic shower contains energetic particles that can deposit significant energy deep in the water reservoir. Figure 2 shows the resulting distributions for proton and gamma-ray induced air showers that satisfy the trigger requirement. By removing all events with nPMT2/cxPE less than 6.0 the sensitivity of the detector is improved by a factor of 2.7. This cut retains 54% of the gamma-ray events and 3.8% of the proton events. For comparison, the compactness parameter used in Milagro improves the sensitivity of Milagro by a factor of ~1.6.

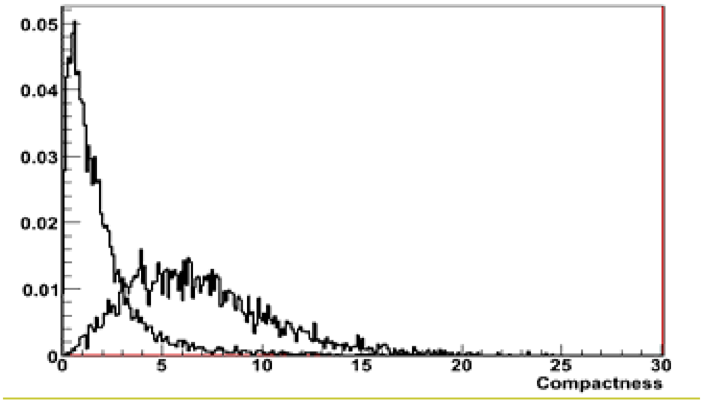

Figure 2 The compactness distribution for proton and gamma ray events in miniHAWC. Proton events are represented by the histogram that peaks near 1 and the gamma-ray events peak near a compactness of 5. The two distributions have been normalized so that the area under each curve is unity.

3. Detector Sensitivity

The sensitivity of a ground-based VHE telescope is dependent upon the spectrum of the source after the inherent source spectrum has propagated through the intervening space. Therefore it is not straight forward to optimize the design of such an instrument without a prioritization of sources of interest. These sources may be grouped into 3 broad categories, that represent the different spectra at the top of the Earth's atmosphere. Galactic source such as the Crab Nebula have a relatively hard spectrum which extend to very high energies. Active galactic nuclei (AGN) are a second source category. AGN may have inherently hard spectra, but they lie outside of our galaxy and the high-energy end of their spectra is absorbed by the intergalactic infra-red radiation fields. The redshifts of known TeV AGN are between 0.03 and 0.2 Finally, gamma-ray bursts lie at the far reaches of the universe, with redshifts ~1, and their spectra are highly absorbed, requiring a detector optimized for low-energy response. Work on such an optimization is still in progress and here only the sensitivity to a spectrum similar to that of the Crab Nebula is presented.

To calculate the sensitivity of miniHAWC to a source of VHE gamma rays, the source is followed through the sky as the Earth rotates. The response of the detector as a function of local coordinates is used to determine the event rate at each zenith angle of the source throughout its transit. This leads to a prediction of the number of gamma rays per source transit (or day). Though the transit requires 24 hours to complete, essentially all of the events come during the ~4 hours that the source spends near its direction of highest elevation. The number of background events is found by tracking proton events through the same source transit. While the number of gamma-ray events should be properly normalized, an additional normalization is used. This normalization is simply the ratio of expected events/day from the Crab Nebula in Milagro, to that observed with the detector. This methodology accounts for the detector dead-time, an average number of non-working PMTs. It is expected that any deficiencies in the Monte Carlo simulation are at least roughly accounted for with this procedure. This normalization reduces the number of predicted signal events by roughly 30%. The normalization of the background occurs in an analogous fashion. The normalization for the background is simply the background rate measured in Milagro divided by the number of events/day predicted by the Monte Carlo. This naturally accounts for the true cosmic-ray rate and again any deficiencies in the Monte Carlo.

In what follows it is assumed that the spectrum of the Crab Nebula is 2.7×10^{-11} $(E/TeV)^{-2.59}$ cm^{-2} s^{-1}. With this spectrum it is predicted that Milagro would detect the Crab Nebula at 4σ in one year of observation, in good agreement with the observations. With miniHAWC the Monte Carlo simulation predicts that a 5σ detection can be achieved in 1-2 days, a 15-fold increase in sensitivity over Milagro. Figure 3 compares the "survey sensitivity" of past, current and future instruments. This figure-of-merit is simply the field of view of an instrument divided by its point source sensitivity. For pointed instruments such as ACTs this number is multiplied by the number of viewing periods (of 50 hours each) in a year, taken as 15 for this figure. For wide-field instruments a 2 sr field-of-view in assumed and the sensitivity is averaged over the declination range of the instrument.

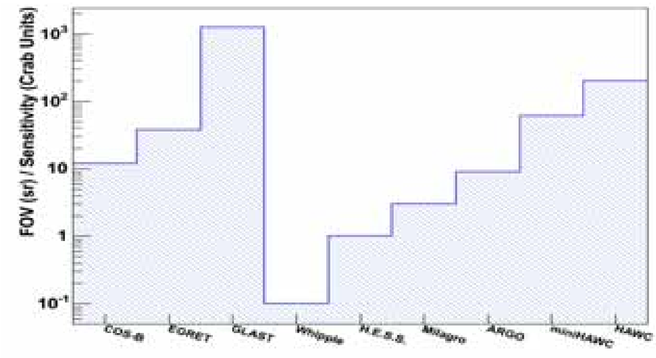

Figure 4 The survey sensitivity for past, current and future instruments. HAWC is a larger version of the miniHAWC detector discussed here.

4. Conclusions

By re-using the existing Milagro PMTs and electronics, a sensitive all-sky VHE gamma-ray telescope can be constructed at a very low cost ($2-3M). This instrument would be capable of detecting the Crab Nebula in 1-2 days and surveying the entire hemisphere at a level of ~50-60 mCrab in one year of operation. Such an instrument is required with the coming launch of GLAST and the completion of ICECUBE.

5. Acknowledgements

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