1 Very High-Energy Gamma-Ray Astrophysics

The study of high-energy gamma rays from astrophysical sources probes some of the highest energy phenomena in the Universe, such as gamma-ray bursts (GRB), active galaxies (AGN), and pulsars. Other potential sources include more esoteric objects such as evaporating primordial black holes, topological defects, and dark matter particle annihilation and decay. Working with our collaborators, we have developed two instruments with unprecedented capabilities—the Milagro and STACEE telescopes—to advance our knowledge and understanding sources of >100 GeV (very high-energy; VHE) gamma rays. As the Milagro and STACEE projects reach maturity, we have during this past year also become involved in VERITAS (the Very Energetic Radiation Imaging Telescope Array System), an array of four imaging atmospheric Cherenkov telescopes now under construction for installation on Kitt Peak in southern Arizona.

The construction of both Milagro and STACEE has been complete for a few years. While work continues to hone the instruments, most of the emphasis now is on data collection and analysis. VERITAS represents a new generation of instruments, with sensitivity more than an order of magnitude better than previously achieved in the VHE energy band. It is scheduled to be completed in late 2006. Observations with the first of the four telescopes will commence in winter 2004–2005.

Milagro senses the quantity and timing of Cherenkov light generated by particles entering a shrouded reservoir of pure water, located at 2650 m elevation in the Jemez Mountains of New Mexico. The particles are secondaries produced by the primary VHE gamma or hadron in the atmosphere, and can be electrons, photons, muons or hadrons in varying proportions. Milagro achieves its unique sensitivity because water is a continuous active medium, which makes for a large detector with high efficiency when viewed by the two layers of photomultiplier tubes (PMTs) within the water. Both layers of PMTs have particular patterns of light deposition dependent on the nature and energy of the primary, and we are exploiting that information to achieve the best possible sensitivity. An array of 175 2.4-m diameter water tanks, or “outrigger,” are distributed over an area of 40,000 m$^2$ surrounding the central reservoir. The outrigger detectors help locate the shower core, improving the angular resolution, energy reconstruction, and background rejection.

The Milagro data have been used to search the entire sky for gamma-ray point sources. We have completed an analysis of a three-year data set, starting December 15, 2000 [1], using background rejection algorithms developed studying data from the Crab Nebula [2]. The brightest two positions on the sky are the Crab Nebula and Mrk 421. Both are established VHE gamma-ray sources, the Crab a steady one and Mrk 421 being variable.

![Figure 1: A new VHE gamma-ray source coincident with an EGRET unidentified source. The contours enclose the EGRET 68%, 90%, 95%, and 99% confidence level regions for the position of the unidentified source 3EG J0520+2556. The point labeled “This Analysis” is the best fit position from the Milagro data. The “2002 Reported Position” was obtained from an earlier, smaller Milagro data set. The source has an extent of $\sim0.8^\circ$ in the Milagro data.](image)

The next brightest point in the sky is near the location of the unidentified EGRET source...
3EG J0520+2556 [3], as shown in Figure 1. This object was not previously known to emit VHE gamma rays. An analysis which allows for the possibility that the source is extended (rather than pointlike) finds a 5.9 $\sigma$ detection with the RMS extent of the source being $0.8^\circ \pm 0.4^\circ$. At this significance, it is hard to dismiss the excess as a statistical fluctuation, and it appears that this is truly a new steady, diffuse source of VHE gamma rays. A publication is in preparation.

We have now verified the earlier indications [4] of diffuse TeV gamma-ray emission from the Galactic plane [5], and are preparing a journal article. Emission from the Galactic plane has been detected up to GeV energies by space-based detectors, and agreement with traditional theoretical models is obtained. Above 1 GeV there is a higher flux than predicted by the favored model for the spectrum and propagation of cosmic rays in the Galaxy. Ground based telescopes had previously only set upper limits on this flux at $\geq$TeV energies. A couple of recent attempts have been made to explain the excess [6, 7], and the Milagro result should help distinguish between them.

Studies of AGN with Milagro continue, extending the work of UCSC graduate student Wystan Benbow [8]. For two AGN, RGB 1725+118 and I Zw 187, we obtain upper limits (after correcting for attenuation losses in transit to Earth) below the prediction of the model of Fossati et al. [9], as adapted by Costamante and Ghisellini [10], hence constraining models of gamma-ray production in AGN [11, 12].

Pablo Saz Parkinson has joined our group as a postdoc, after completing his Ph.D. at Stanford working on the USA X-ray satellite. He is working on analysis of Milagro data coincident with GRB detected by satellites [13] and has two papers on this work in preparation. The launch of the Swift satellite on November 20, 2004, should substantially expand the number of known GRB in the Milagro field of view from the 33 now in hand.

Two papers resulting from the Ph.D. thesis work of Miguel Morales [14] have been published during the year. The first sets limits on the occurrence of bursts of VHE gamma rays lasting between 40 seconds and 3 hours, including limits on such bursts in conjunction with the population of classical GRB detected by satellites [15]. The other describes an improved analysis technique which is used in the burst search, but is much more generally applicable [16]. We have also published the results of a search for WIMP (weakly interacting massive particles; a dark matter candidate) annihilations in the vicinity of the Sun [17].

STACEE, the Solar Tower Atmospheric Cherenkov Effect Experiment, is the outgrowth of a desire to extend the capabilities of ground-based gamma-ray detectors down to 40 GeV, filling in most of the region from about 10 GeV to about 300 GeV which has previously been impossible to explore. Present generation satellite experiments do not have the collection area to measure the small fluxes of gamma-ray sources above 10 GeV, and ground-based experiments had not previously been able to detect atmospheric showers smaller than a few hundred GeV. STACEE leverages the large mirror collection area at an existing solar power facility – the National Solar Thermal Test Facility at Sandia National Laboratory in Albuquerque, New Mexico – by using the mirrors to collect Cherenkov light from atmospheric showers at night. STACEE is designed to study gamma-ray emission from 40 GeV to 500 GeV, a region which is important for determining emission mechanisms and for understanding absorption of gamma-rays by infrared background light.

Recent work with STACEE [18] has concentrated on the study of relatively nearby AGN, extending the work of UCSC Ph.D. student Lowell Boone [19, 20]. These studies have as one goal expanding our understanding of AGN jets and acceleration mechanisms. At the same time they can indirectly probe the star formation history of the universe, which is of cosmological interest. Starlight collisions with VHE gamma rays produce electron-positron pairs, removing the gamma rays from the spectrum. The amount and spectral dependence of the absorption can be calculated in cosmological models [21, 22]. AGN which are at redshifts from 0.1 to 0.5 are far enough that the spectrum should be significantly affected, but not so far as to expect all VHE gamma rays to be absorbed.

We have published a search for VHE gamma rays from W Comae [23]. As discussed by Böttcher et al. [24], leptonic and hadronic jet models make quite different predictions with respect to the VHE emission. Although no emission was detected, the upper limits exclude some hadronic production model fits to the EGRET data at lower energies.

Recent data from two other AGN – 3C 66A and Mrk 421 – are now being analyzed. The data from 3C 66A show a small, but not statistically significant, excess of events above the expected background, and so we have a paper in preparation giving upper limits on the gamma-ray flux. We are acquiring more data on this source now in an effort to understand the excess. Markarian 421 continues to be one of the brighter objects in the VHE gamma-ray sky. The STACEE data from spring 2004 show it once again in outburst, and the analysis of the data continues.

Detection of a gamma-ray burst with STACEE would be a particularly exciting result. We are leading
Figure 2: A comparison of the sensitivity of established and planned high-energy gamma-ray experiments. EGRET, GLAST and Milagro have wide fields of view and are not limited to viewing nighttime sources, so the sensitivity is based on a year’s observation in survey mode. The other projects are all pointed instruments which require dark night sky to operate, and the sensitivity is given for 50 hours observing a given source, which is about 5% of the available annual observing time. The EGRET experiment ceased operation in 2000. Whipple, STACEE, and Milagro are established projects which continue to operate. VERITAS, HESS, MAGIC and GLAST are next generation projects coming online now or over the next few years. (Figure from Ref. [27].)

The STACEE effort to respond to GRB alerts as quickly as possible, i.e. to retarget the instrument and acquire data with the minimum possible delay after the burst onset as detected by satellites [25, 26]. The typical response time is now several minutes, although we have yet to receive an alert when sky conditions allowed such a swift observation. We believe it may be possible to reduce the time to about one minute. We have obtained some support for this effort from the NASA Swift Guest Investigator Program.

A new activity of our group this year is participation in the VERITAS project [27]. As mentioned above and illustrated in Figure 2, VERITAS will achieve more than an order of magnitude improvement in VHE flux sensitivity compared to the previous generation instruments. Early results from the HESS project [28, 29], a device with a similar sensitivity to VERITAS but in the southern hemisphere and at a more advanced stage of development (thanks to quicker funding by the European agencies), already indicate that this leap in sensitivity is going to reap huge rewards in terms of science. A four telescope array of imagine atmospheric Cherenkov telescopes, VERITAS-4, is now under construction which, like STACEE, will detect the Cherenkov light produced in the atmosphere by VHE gamma-ray showers. We will participate in the operation and data analysis of that device. Plans for a next phase beyond VERITAS-4 are now being considered, and we anticipate taking a role in the development of the instrumentation for that phase as well. As Milagro and STACEE complete the work they were designed to do, we expect to devote an increasing part of the group’s effort to VERITAS.

VERITAS-4 will be completed a little less than a year before the GLAST satellite launches in 2007. As Figure 2 shows, GLAST and VERITAS cover complementary regions of the high-energy gamma-ray spectrum, and both have sensitivity at the level of ~1% of the Crab Nebula flux. The participation of SCIPP in both GLAST and VERITAS should help take advantage of these capabilities to study sources over a broad energy range and enhance the science output from both instruments.

References

[1] TeV Gamma-Ray Survey of the Northern Hemisphere Sky Using the Milagro Observatory, R. Atkins et


