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STACEE Observations of Active Galactic Nuclei and Other Sources

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Abstract. We describe recent observations and future plans for the Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) located at Sandia National Laboratories in Albuquerque, New Mexico. STACEE is a ground-based experiment for detecting atmospheric Cherenkov light from γ-rays in the energy range 50 to 500 GeV. We describe recent observations of active galactic nuclei such as Mrk 501, and also outline plans for the observations of other AGN, including Flat Spectrum Radio Quasars (FSRQs) detected by EGRET above 1 GeV and other BL-Lac objects. We summarize plans for observing other sources, including the Crab Nebula, other pulsars, supernova remnants, and unidentified EGRET objects. The up-to-date results from recent source observations by STACEE will be presented at the conference.

1 Intergalactic absorption and the γ-ray horizon

The energy range from 50 to 250 GeV is important for understanding many high energy astrophysical objects, especially active galactic nuclei. Great progress has been made during the last decade, but many problems remain. For example, while dozens of AGN at a variety of redshifts were detected by EGRET, only a few of the closest AGN have been detected by ground-based experiments above 250 GeV. These results imply that the power-law spectra of many AGN cut off at energies between 20 and 250 GeV, and the fact that only nearby AGN are seen at very high energies argues that the γ-rays are attenuated on their long journey to Earth. High energy γ-rays interact with photons at infrared/optical/UV energies via the pair-production process (Stecker and de Jager, 1993; Biller, 1995). The level of such extragalactic background light (EBL) from galaxies is not well known, but measurements of absorption features of AGN should provide constraints on its flux and spectral shape. These constraints in turn could give us valuable information about the epoch of galaxy formation and the composition of dark matter in the Universe (MacMinn and Primack, 1996). Absorption features might also depend upon source luminosity, especially during outbursts. Observations of this dependence would place critical constraints on the γ-ray emission mechanisms of AGN. A review of the prospects of low-threshold Cherenkov experiments to detect or severely limit the spectral energy distribution of the extragalactic background light may be found elsewhere (Vassiliev, 2000).

The importance of absorption due to intergalactic diffuse radiation is demonstrated in Figure 1 which shows a plot of the γ-ray horizon (unity optical depth) as a function of redshift. The current generation of imaging Cherenkov telescopes see only the closest AGN (those with redshifts < 0.3). However, an experiment that can obtain an energy threshold as low as about 50 GeV, such as CELESTE (Le Gallou, 2001) or STACEE, is able to look further out (to redshifts beyond 1.0). By lowering the energy threshold from 250 GeV to 50 GeV, the number of AGN available for study is increased by up to a factor of five.

2 Observations of Mrk 421 and 501 with STACEE-48

The STACEE instrument has been constructed in stages. In October, 2000, we began conducting observations with a partially completed version of the experiment called STACEE-48. In addition to source observations, a primary component of the activities during the past year has been engineering tests and verification of the performance of the newly installed optical and electronics equipment, as described elsewhere (Covault, 2001).

Observations of astrophysical objects with STACEE-48 began in December, 2000. Data were taken according to the standard on/off procedure. Each on/off pair consists of a 28 minute run tracking the target source, followed (or preceded) by a 28 minute off-source run, 7.5° in declination to the east (or west) of the source and covering the same track in azimuth and elevation as the on-source run. Thus each on/off pair includes 28 minutes of on-source data and 28-minutes

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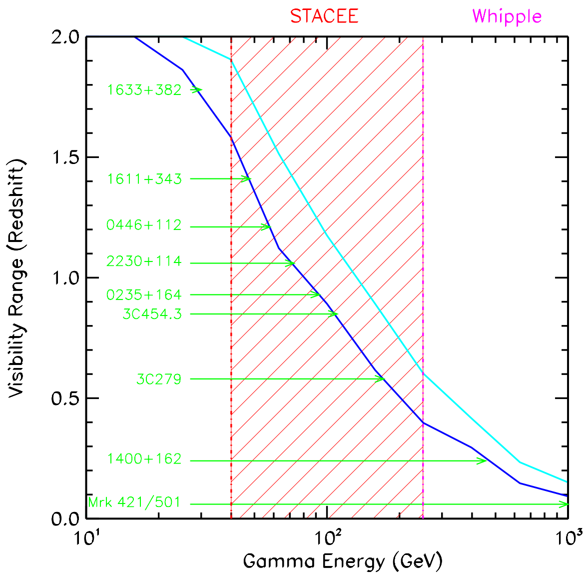

Fig. 1. Expected γ-ray horizon as a function of energy The horizon results from the absorption of γ-rays by diffuse radiation in intergalactic space. The two lines running diagonally represent the range of plausible cosmic infrared background models (see text for details). As distance increases, lower energies are required to permit detection of the source. Current Cherenkov imaging telescopes, such as Whipple, CAT, and HEGRA, are likely to detect only the closest AGN. New low-threshold (~ 50 GeV) experiments, such as CELESTE and STACEE, have the potential to detect many more sources.

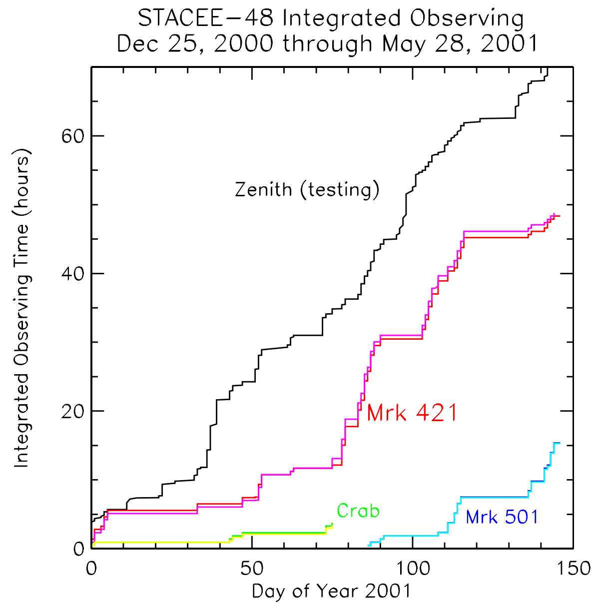

Fig. 2. Integrated observing time for STACEE-48 on various sources since December 2001. On-source and off-source data for each astrophysical object are plotted separately but track each other closely. Not included are observations made after May 28, 2001.

of off-source background.

Figure 2 shows a plot of the integrated observing time for each source observed by STACEE-48 up through the end of May 2001. On-source and off-source data are plotted separately but track each other closely for each source. STACEE now operates on a continuous basis. The results from observations made after January 2001 will be described at the Conference.

The primary astrophysical source in early 2001 was Markarian 421, which was reported to be in a γ-ray flare state. So far, STACEE-48 has collected more than 40 hours of observations on Markarian 421 in 2001. A preliminary analysis of a subset of these data show a detection of γ-rays from Markarian 421 with high statistical significance. Details of this analysis are presented elsewhere in these proceedings (Hinton, 2001).

Markarian 501 has also been observed by STACEE-48 during this past year with over 15 hours collected so far. Analysis of Markarian 501 observations is in progress, and preliminary results will be presented at the Conference. Additionally, some data (six ON-OFF pairs) were collected from the Crab for diagnostic purposes. The Crab will be an important calibration source for STACEE observations during the Winter of 2001-2002.

3 Future Observing Plans

By Fall 2001, we will be operating the complete STACEE instrument using a total of 64 heliostats with good γ-ray sensitivity in the range $\sim$ 50 GeV to 500 GeV. At this point, a three-year observational program will begin. The goal of the program will be to observe as many sources as possible to address our scientific objectives. The majority of targets planned during this interval will be AGN which will be observed over a range of redshift values. We expect to observe between four and six AGN each year. In the past, we have concentrated on the two brightest and closest X-ray selected BL Lac objects, Mrk 421 and Mrk 501. In the future, we will observe new sources as we hope to detect new sources and new source classes.

We have compiled a target list for the STACEE observing program by drawing upon source lists from several different catalogs. STACEE is located at 35° N latitude. In building the target list we keep sources in the declination range 0° to 70°. Some of the catalogs that are used to compile STACEE's observing program are listed below:

– *Third EGRET Catalog:* (Hartman, 1999) This catalog lists 271 high energy γ-ray sources, many of which are potential targets for STACEE.

– *EGRET 1 GeV Source Catalog:* (Lamb and Macomb, 1997) This catalog lists EGRET source detections above 1 GeV. At these energies, EGRET had excellent angular resolution, and source positions are very well determined. This catalog is particularly important for STACEE to obtain the positions of the unidentified high-energy EGRET sources.

– *X-ray selected blazars:* (Perlman, 1996) This catalog is an important compilation of X-ray selected BL Lac objects *not* detected by EGRET. Several of the nearby XBLs are predicted to be strong TeV γ-ray sources and could be promising candidates for STACEE. Two of the sources from this list, 1ES 1426+428 and 1ES 2344+514, have been tentatively identified as TeV sources (Horan, 2001; Badran, 2001), although they were not detected by EGRET.

STACEE's observing program will include both Galactic and extragalactic sources:

– *Pulsars:* Two pulsars detected by EGRET are attractive targets for STACEE. These are the Crab and PSR 1951+32. These are both visible from Sandia and have been detected by EGRET above 1 GeV. In addition, recent archival analysis of EGRET data has shown several high energy events (> 10 GeV) to be associated with the Geminga pulsar (Bertsch, 2001). This would make Geminga a potential target. The energy range 10 to 250 GeV is particularly interesting for pulsar studies because cutoffs in the pulsed emission are expected to occur in this range.

– *Supernova remnants (SNRs):* EGRET has reported several sources to be possibly associated with SNRs. Of these, the four that are most likely to be EGRET sources are: W44, γ-Cygni, IC 443, and Monoceros (Esposito, 1996). For the immediate future, STACEE plans to include only IC 443 in the target list, although other SNR such as Cas A are also under consideration.

– *Blazars:* The largest class of the identified EGRET sources in the Third EGRET catalog are blazars. Of these, the majority are *flat-spectrum radio quasars* (FSRQs). None of these sources have been detected above 250 GeV by the current generation of ground-based instruments, possibly due to the absorption of the high-energy γ-rays in intergalactic space. This means that we expect spectral cutoffs at lower energy for FSRQs. The handful of the blazars detected at very high energies are the nearest *X-ray selected BL Lacs* objects. STACEE has the potential for detecting FSRQs in the 50-250 GeV energy range, thus shedding light on some of the unanswered questions in AGN research and studying the IR/optical/UV extragalactic background light (EBL). Based on current EBL absorption models, STACEE should be able to see FSRQs out to redshifts of ~ 1. In Tables 1 and 2, we list some of the candidate FSRQ and BL Lac sources for possible observation by STACEE.

– *Unidentified EGRET Sources:* More than 60% of the EGRET sources are unidentified and are not clearly associated with known counterparts at other wavelengths.

Source	Longitude	Latitude	Z	Other Names
0202+149	147.95	-44.32	0.405	4C+15.05
0954+556	159.55	47.33	0.901	
1156+295	201.53	78.63	0.729	4C+29.45
1222+216	254.91	81.53	0.435	
1226+023	289.84	64.47	0.158	3C273
1725+044	27.27	20.62	0.296	
2209+236	81.83	-25.65	?	
2230+114	77.45	-38.50	1.037	CTA102
2251+158	86.05	-38.30	0.859	3C454.3
2356+196	107.01	-40.58	1.066	

Table 1. Candidate Flat Spectrum Radio Quasar (FSRQ) sources, as compiled from the Third EGRET catalog. A question mark indicates an unknown quantity.

The nature of these unidentified γ-ray sources is an outstanding mystery in high energy astrophysics. The Whipple instrument has recently observed several of these sources (3EG J0423+1707, 3EG J0450+1105, 3EG J0634+0521, 3EG J1323+2200, GeV J1907+0557, GeV J2020+3658, 3EG J2227+6122), but none have been detected above 500 GeV (Fegan, 2001). A few of the bright EGRET sources with good positions have been studied at X-ray energies and have been found to be possibly correlated with hard X-ray sources in their error boxes (e.g. Roberts et al. 2000). Some of the high energy unidentified sources in the Galactic plane could be pulsars or neutron stars. Two such identifications have recently been claimed for the EGRET sources 3EG J2227+6122 and 3EG J1835+5918 (Halpern, 2001a,b; Mirabal, 2001). STACEE has plans to observe several of the unidentified EGRET sources.

In conclusion, STACEE is currently engaged in a comprehensive program to observe a variety of galactic and extra-galactic sources. To obtain the most scientific leverage, STACEE will actively participate in several multi-wavelength observations that are planned for current and near-future ground and space-based experiments. The results from the latest analysis of the STACEE-48 observations will be presented at the conference.

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Source	Longitude	Latitude	Z	Other Names
0219+428	140.22	-16.89	0.444	3C66A
0235+164	156.46	-39.28	0.940	OD+160
0430+285	170.48	-12.58	?	
0735+178	202.16	17.88	0.424	
0829+046	219.60	23.82	0.180	
0851+202	207.19	35.43	0.306	OJ+287
1101+384	179.97	65.04	0.031	Mrk421
1219+285	197.27	83.52	0.102	ON+231
1604+159	29.18	43.84	0.357	4C+15.54
1653+394	63.60	38.86	0.033	Mrk 501
2032+107	56.12	-17.18	0.601	
2200+420	92.56	-10.39	0.069	BL Lac

Table 2. Candidate BL Lac sources, as compiled from the Third EGRET catalog. A question mark indicates an unknown quantity.

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