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FINAL REPORT
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GUEST INVESTIGATOR STUDIES WITH THE COMPTON GAMMA RAY OBSERVATORY

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1.0 EGRET South Galactic Pole Survey.

The cumulative all-sky survey by the Compton Gamma Ray Observatory (CGRO), composed of data acquired during the first three years of the mission, included a number of regions of very limited exposure. The most glaring deficiency in coverage was toward the region of the South Galactic Pole (SGP), which received significantly less exposure than other directions— by a factor of at least 2 to 3. Furthermore, nearly all of the SGP exposure was accumulated during the first year of the mission. Since blazars are known to be time-variable, and of unknown duty cycle, a pointing of the CGRO in that direction was considered highly desirable, and long overdue. In addition, data gathered from a pointing toward the SGP and its comparison with comprehensive data available for the North Galactic Pole would be extremely valuable to investigators studying the extragalactic diffuse emission.

The reasons outlined above prompted our initiation of a Cycle 4 campaign to systematically search with EGRET and COMPTEL for gamma-ray emission from sources near the South Galactic Pole. The Cycle 4 SGP campaign consisted of two 14-day observations separated in in time by approximately 10 months. The temporal separation of the observations was requested to allow a test for possible variations in the detected sources. Our primary targets were 38 FSRQs which lie within 30 degrees of the SGP, and which satisfy the basic criteria for candidate gamma-ray AGNs (strong ($S_{5GHz} \geq$1 Jy), flat-spectrum radio sources, many of which exhibit blazar-type properties). These targets were selected from the standard references (e.g, Kühr et al. 1981), and from the available on-line databases (e.g., the NASA Extragalactic Database, NED), as the most promising AGN targets in the vicinity of the SGP. A 30° radius from the SGP was chosen as the boundary of our survey, since the selected targets would then fall within the most sensitive portion of the fields of view of EGRET and COMPTEL (i.e., within a 30° zenith angle), for a CGRO pointing directed exactly at the SGP.

Our South Galactic Pole Survey yielded a number of exciting results. The EGRET data were analyzed using the maximum likelihood techniques to estimate the intensity, spectrum, and position of gamma-ray sources in the field of view. Our analysis revealed four sources at energies >100 MeV with likelihood ratios corresponding to $> 3\sigma$ detections (Vestrand et al. 1996). One of the sources is associated with the well known gamma-ray blazar PKS 0208-512, but the other three were previously unknown.

Among the new detections was PKS 2155-304 which is often considered a prototype of the x-ray selected BL Lacs. PKS 2155-304, which was also detected at hard x-ray energies by CGRO/OSSE, is one of the brightest BL Lac objects in the sky at optical through x-ray energies and has a history of rapid, strong multiwavelength variability. As such, it has been the subject of intensive, contemporaneous, multiwavelength monitoring covering radio frequencies to x-ray energies. Correlative variability studies of that rich database suggest that the radio to x-ray continuum is synchrotron emission associated with a shock propagating in a relativistic jet. Comparing the previous upper limits with the flux above 100 MeV derived from our Cycle 4 observations ($2.73 \pm 0.70 \times 10^{-7}\gamma\ cm^{-2}s^{-1}$), we found that the gamma-ray flux from PKS 2155-304 is quite variable. Futhermore our spectral study indicates that the EGRET gamma rays comprise a separate component that is probably powered by Compton emission (Vestrand et al. 1996).

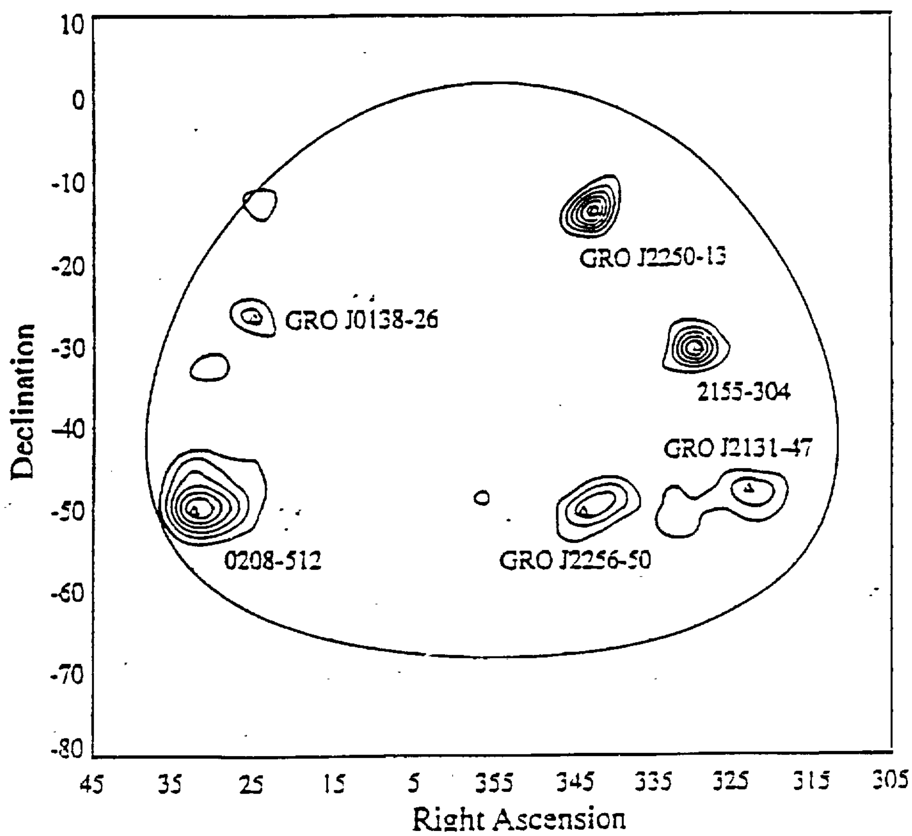

Figure 2. A Maximum likelihood map showing significant point sources detected during VP 404.0. The lowest contour represents approximately a 3σ detection significance. A 35° radius from the EGRET z-axis is also denoted.

Our discovery of high-energy gamma-ray emission from PKS 2155-304 has opened up the possibility of applying a strict test to the current paradigm for the production of nonthermal continuum radiation in BL Lacs. Furthermore, the extreme hardness of the gamma-ray spectrum measured in Cycle 4, with photons detected at energies up to 7.75 ± 1.39 GeV, combined with the proximity of this source (z=0.117), make it an ideal new candidate for detection at TeV energies. For example, we found that from 100 MeV to 10 GeV, PKS 2155-304 is roughly twice as bright and of comparable spectral hardness to Mrk 421, one of the two blazars that have been detected at TeV energies. As we pointed out in our paper describing our results that was published in the Astrophysical Journal Letters (Vestrand, Stacy, and Sreekumar, 1995, Ap. J., 454, L93), if PKS 2155-304 is detected at TeV energies, the predicted high-energy cutoff of the TeV spectrum due to photon-photon pair-production opacity can place important constraints on the poorly known intergalactic infrared energy density. To perform AGN model tests, contemporaneous multiwavelength observations were clearly needed and our work led to multiwavelength campaigns targeting PKS 2155-304 and PKS 0208-512. A paper by Stacy et al. describing the first results of our multi-wavelength campaign for PKS 0208-512 was published in Astronomy and

Astrophysics (Stacy et al. 1996).

Two other previously unknown EGRET sources were discovered by our SGP survey. Designated GRO J2250-13 and GRO J2254-30, these two unidentified high-latitude sources have likelihood "test statistic" (T_s) values of 35.4 and 18.6, respectively. Therefore even when we apply the more conservative threshold for rejecting the null hypothesis that is appropriate for unidentified sources, these sources have a significance that exceeds 3σ. We searched for likely AGN counterparts to these high-energy sources, by examining pre-existing measurements collected at other wavelengths (e.g., via the NED and SIMBAD on-line databases). We also searched more contemporaneous databases for further results relevant to these objects. In particular, the NRAO VLA Sky Survey (for sources at $\delta > -40°$), was a particularly valuable resource in this regard because it includes both spectral and polarization information that is useful in the identification of blazar-type objects. We were able to identify potential blazar counterparts but, unfortunately, were unable to make definitive associations.

From our Survey observations we also noted marginal or transient detection with EGRET of four additional objects. During the original quick-look analysis of EGRET data for VP 404 two sources were noted, at fairly high levels of significance, that were not apparent in the final integrated maps for this viewing period. We conclude that such behavior is probably generated by rapid source variability.

2.0 EGRET Observations of X-ray Binary Systems

Under grant NAG5-1561 we also began our search for high energy emission from X-Ray Binary Systems with EGRET. Using the Cycle 4 data we were able to perform phase-averaged searches for the TeV/PeV sources: 4U 0115+63 and Centaurus X-3. The XRB system 4U 0115+63 was not detected and yielded an upper limit on the phase averaged flux above 100 MeV of $\sim 1 \times 10^{-7}$ photons $cm^{-2}s^{-1}$. *However, our analysis of Cen X-3 yielded the first positive EGRET detection of the system.* Figure 2 shows an EGRET likelihood map of summed VP 402.0 and VP 402.5 data for the region near Cen X-3. The triangle denotes the position of Cen X-3 which is clearly within the 50% error contour. Furthermore, a search of the NED and SIMBAD databases revealed that Cen X-3 is the only likely source identification within the 99% error contour.

The 30 MeV-10 GeV photon spectrum we found for the phase-averaged emission from Cen X-3 (figure 3) is relatively hard, with an index of $\alpha \sim 1.8$. The flux above 100 MeV was measured to be $102.7 \pm 22.3 \times 10^{-8}$ photons cm^{-2} s^{-1}. Using the distance to the system of 8 kpc (Nagase 1989), one finds a phase-averaged luminosity above 100 MeV of $\sim 1 \times 10^{36}$ erg s^{-1}. This luminosity is comparable to the phase-averaged luminosity reported for outbursts of TeV gamma-ray emission from Cen X-3, $\sim 3 \times 10^{36}$ erg s^{-1} (North et al. 1991), an order of magnitude less than the luminosity associated with its largest outbursts of hard x-ray emission measured by BATSE (e.g. Finger et al. 1994) and two orders of magnitude less than the total soft x-ray luminosity (Nagase 1989). The results of this study were presented, along with subsequent work, in our Astrophysical Journal Letters paper detailed our detection of variable GeV gamma-ray emission from Cen X-3 (Vestrand, Sreekumar, and Mori 1997).

Under this grant we developed tools and techniques to search for modulated gamma-ray emission from XRBs. Subsequent application of this software to the Cen X-3 observations by EGRET yielded our discovery of spin-modulated GeV emission from the pulsar. Those results place important constraints on models for the particle acceleration and gamma-ray generation within the binary system.

We were also able to put limits on phase-averaged high-energy emission from several XRBs containing black holes candidates. All of the phase averaged flux limits are $< 10^{-7}$photons cm^{-2}s^{-1}. A serendipitous source, GRO J1451-43, was discovered near one of those black hole candidates and was awarded to us for further study. The low galactic latitude of the source (b=14.0) made it a potential galactic source, however we concluded that the most likely association is with the moderately bright (230 mJy at 2.7 GHz) radio galaxy, PKS 1447-433.

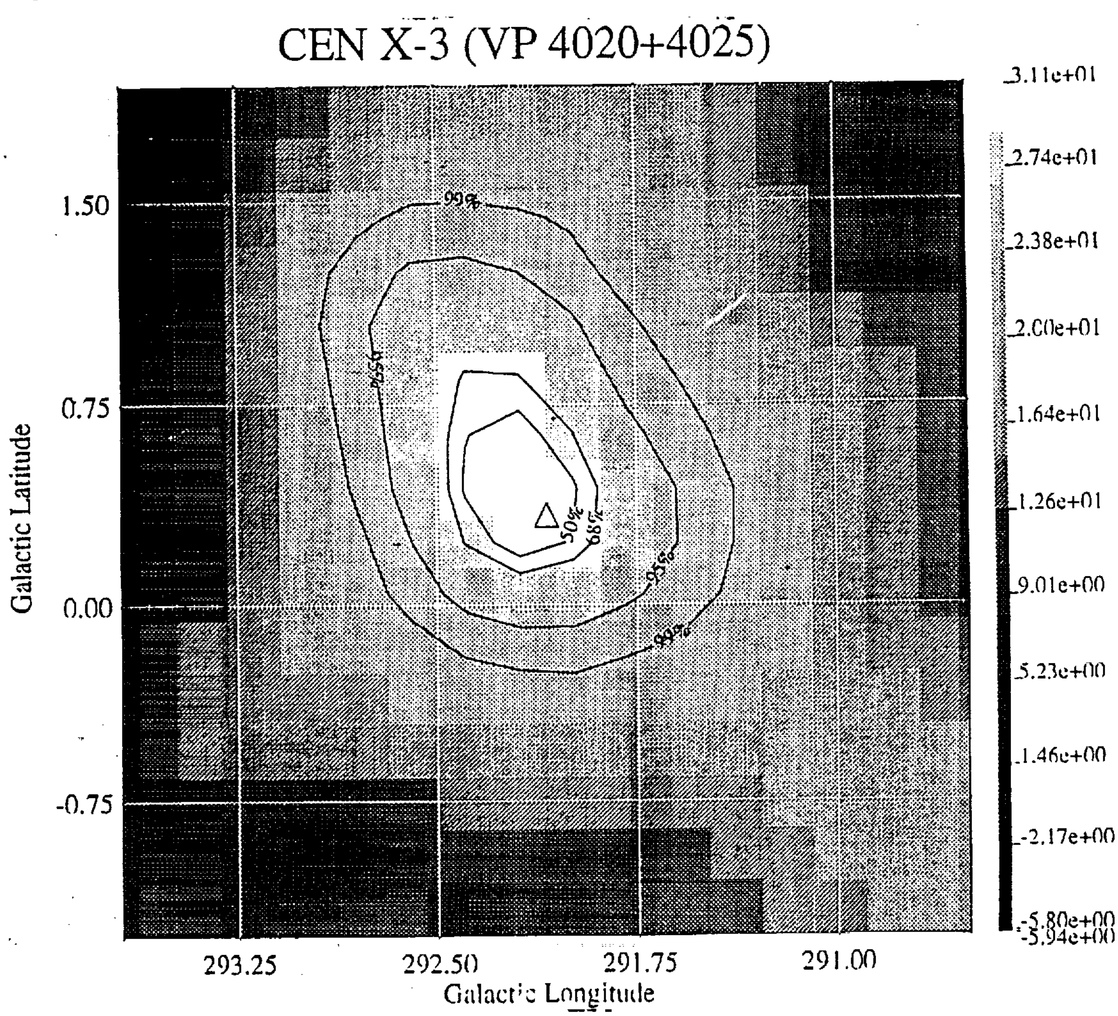

Figure 2. A Maximum likelihood map showing the Centaurus region composed from EGRET measurements taken during Cycle 4. The triangle denotes the known position of Cen X-3.

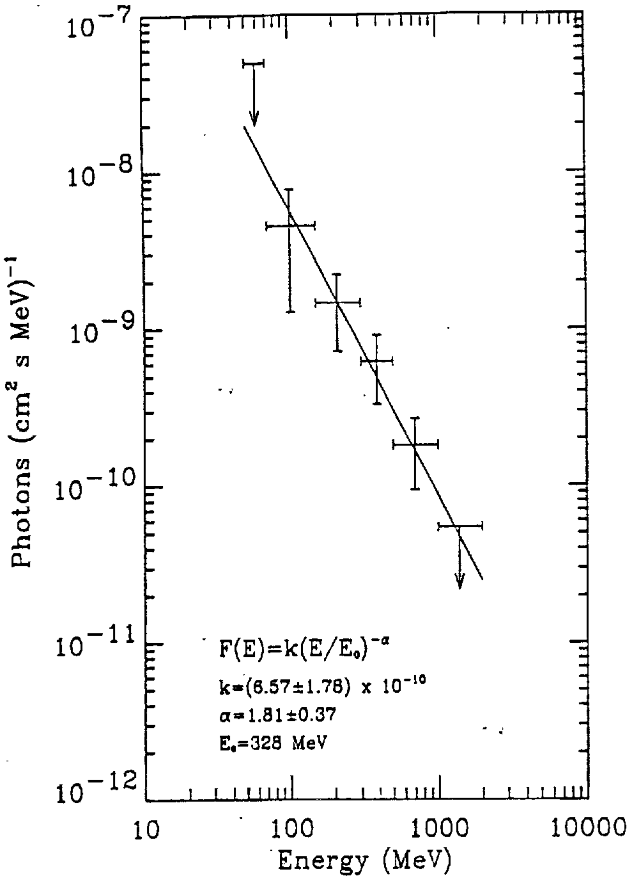

Figure 3. The EGRET spectrum derived for the outburst of gamma-ray emission from Cen X-3 The data was collected during viewing periods 402.0 and 402.5..

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