FINAL REPORT
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CGRO GUEST INVESTIGATOR GRANT: HIGH ENERGY OBSERVATIONS OF X-RAY BINARIES AND GAMMA-RAY BLAZARS

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1.0 CGRO Observations of X-ray Binary Systems

Numerous authors have suggested mechanisms for particle acceleration within X-Ray Binary (XRB) systems. Among the acceleration mechanisms that have been applied are pulsar acceleration(Bignami et al. 1977; Vestrand and Eichler 1982), shock acceleration at an accretion shock front (Eichler and Vestrand 1985; Kazanas and Ellison 1986), shock acceleration at a pulsar wind termination shock (Arons and Tavani 1993), plasma turbulence excited by the accretion flow (Katz and Smith 1988), and a number of electrodynamic mechanisms (Chanmugam and Brecher 1985; Kluzniak et al. 1988; Cheng and Ruderman 1991; Lamb et al. 1993). There are therefore many mechanisms which are capable of generating very energetic particles in the XRB environment.

If the reports of TeV/PeV gamma-ray generation in XRBs are correct, then one can show that the accelerated particles must be hadrons (Eichler and Vestrand 1984) and that the most likely gamma-ray production mechanism is the decay of collisionally-produced (or photoproduced) neutral pions. At these ultra-high energies, the emission is so strongly beamed that the target conditions are constrained by the requirement that the column depth be large enough to efficiently generate gamma-rays, but not so large that the gamma-rays are absorbed. These constraints naturally lead to models that explain the periodic, narrow duty-cycle pulses observed at TeV/PeV energies as arising from interactions with, either, the atmosphere of the binary companion (Vestrand and Eichler 1982; Hillas 1985), an accretion column (Eichler and Vestrand 1985) , or an accretion disk (Vestrand and Eichler 1985; Cheng and Ruderman 1989). The production of these TeV/PeV gamma-rays by the decay of pions from "leading isobars" must also be accompanied by a more isotropic emission component in the EGRET energy band from the decay of slower pions (i.e. the "pionization" component). Since the attenuation of 35 MeV-1 GeV photons by photon-photon pair production is not likely to be significant in most XRBs (Vestrand 1983; Bednarek 1993), the TeV/PeV reports therefore strongly suggest sporadic emission in the EGRET energy band.

Such considerations motivated our search for gamma-ray emission from XRBs that was supported by grant NAG5-3157. The search focused on approximately 30 well-known XRBs that were considered to be likely sources of gamma-ray emission. The sample of XRB systems that we studied can be subdivided into two categories: (1) systems containing Black Hole Candidates and (2) systems containing neutron stars that are suspected TeV/PeV gamma-ray emitters.

We searched the EGRET archives for evidence of GeV gamma-ray emission from 16 prominant black hole candidates. Despite the large of body of theoretical work that predicts the production of gamma-ray emission by stellar mass black hole candidates, we found no evidence for significant >100 MeV emission from the systems (see table 1). Our typical flux limits are L(>100 MeV)= $7 \times 10^{33} D_{kpc}^2$ erg/sec. The failure to detect Cygnus X-1, for example, limits the steady-state luminosity above 100 MeV to less than 10^{-4} of the Eddington luminosity for the system. These limits make it very unlikely that, as is sometimes proposed, black holes in XRBs are a significant source of galactic cosmic rays.

Our observations indicate that x-ray binaries containing neutron stars are a more likely source of energetic particles. Our analysis of EGRET measurements of Cen X-3 yielded the first positive detection of the system at GeV energies. The true position of Cen X-3 is within the 50% error contour of the likelihood map. 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 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 x-ray pulsar in Cen X-3 can display rapid variations in spin frequency. Intermittent monitoring of the pulsar since its discovery by the UHURU team has established a gradual spin-up of the Cen X-3 pulsar, but this long term trend is often interrupted by alternating extended intervals of both rapid spin-up and spin-down (Nagase et al. 1989; Finger et al. 1994). Indeed, contemporaneous CGRO/BATSE measurements of the x-ray pulse frequency show a strong drift during the interval that includes our EGRET detection. This rapid variability of the pulse frequency compromises fixed frequency epoch folding or straightforward analysis with fast fourier transforms when searching the relatively long, two-week gamma-ray observation for spin modulation. Instead, we employed the technique, often applied when studying isolated gamma-ray pulsars, of epoch folding the data using an ephemeris derived from contemporaneous pulse measurements made at lower energies. To model the pulse frequency drift during the GeV gamma-ray outburst, we least-squares fit the functional form $\nu(t) = \nu_\circ + \dot{\nu}_\circ (t - t_\circ) + \frac{1}{2}\ddot{\nu}_\circ (t - t_\circ)^2$

to the BATSE pulse frequency measurements (Finger 1996) for a 37 day interval that brackets the EGRET observation. The best fitting function parameters ($\chi^2 = 42.1$ for 10 degrees of freedom (DOF)) are given by: $\nu_\circ = 207.62829(\pm 0.00018)$ mHz, $\dot{\nu_\circ} = -3.004(\pm 0.385) \times 10^{-9}$ mHz s^{-1}, $\ddot{\nu_\circ} = -7.94(\pm 2.49) \times 10^{-16}$ mHz s^{-2}, and $t_\circ = 49643.0$ MJD=1994 October 18, 00:00 UT. The large χ^2 indicates that the second-order polynomial fit to the BATSE measurements is not as good as one would like, the frequency residuals are of order 0.0006 mHz, but for model simplicity we have not fit higher order polynomials.

Our search for spin modulation of the gamma-ray emission began, after correcting the SSB photon arrival times for pulsar orbital motion, with epoch folding of the arrival times based on the modeled BATSE pulse drift ephemeris. To test for deviation from a statistically flat phase distribution, we employed the H-test statistic, which makes no assumptions about binning or the shape of the light curve (DeJager et al. 1989). Test statistics were calculated for modulation at frequency values within one independent frequency step for the accumulation (i.e., (14 days)$^{-1}$=0.00083 mHz) of the BATSE derived $\nu_\circ$ value, while the pulse frequency drift terms, $\dot{\nu_\circ}$ and $\ddot{\nu_\circ}$, were fixed at the BATSE derived values. The data for VP 402.0 and VP 402.5 data show a test statistic peak at $\nu = 207.62812(\pm 0.00014)$ mHz with an amplitude that indicates a chance probability of only 0.47% that the event arrival times are consistent with a flat phasogram. If, as observed at x-ray energies (Nagase et al. 1989), the gamma-ray modulation has a broad pulse structure, then the generalized Rayleigh test with two harmonics, Z_2^2, would provide a more sensitive test for modulation (Buccheri et al. 1983). Indeed, when we apply the Z_2^2 test to the data, we again find a peak at a frequency which is consistent with the x-ray pulse frequency and an amplitude that corresponds to a chance probability for consistency with a flat phase distribution of 0.16%. Since the modulation search was limited to a range about the BATSE value which is the independent frequency step size for the accumulation, the detection significance was not devalued for independent frequency trials. We did, however, search a broader frequency range, 207.625-207.630 mHz, for other peaks and found none with comparable amplitude. The statistical tests therefore indicate gamma-ray modulation at the Cen X-3 pulsar spin frequency with a significance level comparable to a 3σ detection.

We performed a number of tests with control datasets to examine the plausibility of associating the observed modulation with the Cen X-3 pulsar. First, identical timing analyses were performed on VP 402.0 and VP 402.5 data collected at four additional positions within the EGRET field of view. Those control positions, all located more than 15° from Cen X-3, included three positions with viewing angles comparable to Cen X-3 ($\sim$15°), and one with a viewing angle of 5°. None of the control data sets showed a probability peak anywhere in a search range from 207.625 mHz to 207.630 mHz as large as the Cen X-3 peak, and no significant peaks indicating modulation in the expected BATSE pulsation frequency range were found. Second, since the pulsar timing analysis employs a binary ephemeris, we re-analyzed the data for the Cen X-3 position without including the binary orbit timing corrections. The peak within the expected BATSE frequency range disappeared when the binary correction was removed. The control results are therefore consistent with expectations for association of the observed modulation with the Cen X-3 pulsar.

2.0 Studies of Gamma-Ray Blazars

BL Lacertae (BL Lac) objects are extreme examples of active galactic nuclei (AGN). They are characterized at optical wavelengths by weak or absent emission lines, high polarization, and rapid variability. At radio frequencies they display core domination, rapid variability, and often exhibit superluminal motions. Based on the phenomenology observed at radio through x-ray energies, BL Lacertae objects are normally divided (e.g., Antonucci 1993) into two classes: radio-selected BL Lacs (RBLs) and X-ray-selected BL Lacs (XBLs). For RBLs, the spectral energy distribution from radio to x-ray energies, as in the quasar classes which comprise the broad AGN category called blazars, shows a continuous rise from radio to IR-UV energies followed by a sharp cutoff and the emergence of a distinct higher energy component. Within the framework of relativistic jet models for blazars (e.g., Blandford and Königl 1979), the two spectral components are naturally explained by synchrotron emission that dominates at low energies and a Compton component, generated by the same energetic electron population, that becomes dominant at high energies (Dermer and Schlickeiser 1992; Sikora et al. 1993; Marscher and Bloom 1994). In contrast, XBLs are distinguished by spectral energy distributions that continue to monotonically rise from radio energies all the way into the x-ray band (e.g., Stocke et al. 1991; Giommi et al. 1995). At energies below the x-ray band, XBLs also seem to have more moderate characteristics, being less luminous at radio frequencies and not showing the degree of core-domination, optical polarization, and variability found in RBLs (e.g., Perlman and Stocke 1993).

One of the key unresolved issues for understanding AGN is the relationship between XBLs and RBLs (Urry and Padovani 1995). Within the context of the "unified schemes" for AGN it has been suggested that XBLs are objects that are intermediate in orientation between RBLs, that have jets aligned near our line-of-sight, and radio galaxies, which contain jets that are viewed at large angles (e.g., Perlman and Stocke 1993). In this picture the x-ray emission is assumed to be less collimated than the radio emission—perhaps because the x-ray emission is produced deeper in an accelerating jet (e.g., Kollgaard 1994). An alternate picture, the BL Lac "reunification" hypothesis, assumes that XBLs and RBLs are being viewed at similar angles and are fundamentally the same population, but that XBLs are the fraction of the population that happen to have an unusually high cutoff energies for their energetic electron distributions (Giommi and Padovani 1994; Sambruna et al. 1996). Gamma-ray observations of XBLs can provide an important test for the orientation hypothesis because pair opacity arguments and the relative power in the spectral components can place constraints on the beaming factors (e.g., Dermer and Schlickeiser 1995). The combination of x-ray plus GeV and TeV gamma-ray measurements of nearby XBLs can test for the very high electron energies expected under the "reunification" hypothesis (Vestrand, Stacy, and Sreekumar 1995; Stecker, DeJager, and Salamon 1996).

To test the "reunification" hypothesis, we conducted a multiwavelength campaign during Cycle 7 of the CGRO observing program with the goal of simultaneously measuring the spectral energy distribution (SED) of the archetypical XBL, PKS 2155-304, from radio frequencies through GeV and TeV gamma-ray energies. This successful campaign resulted in the first detection of PKS 2155-304 at TeV gamma-ray energies (Turver et al. 1998) and measured a SED from radio frequencies to TeV gamma-ray energies that is consistent with the predictions of the "reunification" hypothesis (Vestrand et al. 1998). Further support for the "reunification" hypothesis is provided by measurements of the southern hemisphere blazar PKS 2005-489, an XBL with properties similar to PKS 2155-304 (Sambruna et al. 1995), which was also recently detected in TeV gamma-rays by the Narrabri imaging-Cherenkov telescope (K.E. Turver, 1998, private communication). Altogether, the high-energy measurements of these XBLs plus those for the two other known TeV emitting XBLs, Mrk 421 (e.g. Buckley et al. 1996) and Mrk 501 (e.g. Catanese et al. 1997), strongly support the idea that the fundamental difference between XBLs and RBLs is that the particle acceleration process is able to extend the electron energy distribution to higher energies in XBLs.

At the medium gamma-ray energies observable by COMPTEL, PKS 0208-512 has been identified as an AGN with excess MeV emission. Based on data acquired during Phase 2 of the CGRO mission, Blom et al. (1995) reported strong gamma-ray emission in the range 1-3 MeV. Further analysis of Phase 1 data for this object also showed evidence for MeV emission, although at reduced significance and intensity (Blom et al. 1996). This MeV emission would have to constitute a separate component from the GeV emission observed by EGRET, since the existing data shows a poor correlation between the intensity states in the two energy bands. Based these measurements it was proposed that PKS 0208-512 may be the prototype for a class of "MeV blazars" that occasionally are exceptionally bright MeV sources (Bloemen et al. 1995). The existence of MeV blazars would clearly have important implications for the study of the components of the cosmic diffuse background radiation (Salamon and Stecker 1994, Kappadath et al. 1995), and of the origin of the "MeV bump," that has been attributed to various classes of unresolved active galaxies.

We completed an analysis of the Cycle 4 through Cycle 6 CGRO measurements of PKS 0208-512. While we found no indication of 1-3 MeV emission from PKS 0208-512 at the level previously reported, we made a marginal first detection of this source at higher MeV energies, from 10-30 MeV (Stacy et al. 1997). The significance of this detection by COMPTEL is relatively low ($\sim 3\sigma$) and further confirming measurements are needed. However, the 10-30 MeV flux lies above the extrapolation of the spectrum we derived from simultaneous EGRET observations. If confirmed, a break in the MeV region is required to fit the measurements, as seen in previous simultaneous detections of blazars by COMPTEL and EGRET (Collmar et al. 1997).

We also discovered two previously unknown EGRET sources during our survey of archival data. 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.

3.0 References

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