# FINAL REPORT
# NASA GRANT NAG5-7118

# BROAD-BAND MEASUREMENTS OF CEN X-3 WITH XTE AND CGRO

Prepared by:

W. Thomas Vestrand, Principal Investigator
Physics Department and Space Science Center
University of New Hampshire, Durham, NH 03824

Prepared for:

Dr. JEAN SWANK
NASA GODDARD
GREENBELT,MD

## Introduction

Since its discovery, Centaurus X-3 has played a key role in the development of our understanding of galactic x-ray binary sources. Timing analysis of the UHURU x-ray observations for the luminous Cen X-3 source (L$\sim 10^{38}$erg s$^{-1}$) revealed the first evidence for coherent x-ray pulsations from an object in a binary system (Giaconni et al. 1971; Schreier et al. 1972). It was quickly understood that the luminous pulsed x-ray emission could be generated by the accretion of matter from a companion star onto a rotating neutron star and led to the adoption of binary star models as the fundamental model for galactic x-ray sources (e.g. Pringle and Rees 1972; Lamb et al. 1973). Based on modeling and refined observations since the original measurements, we now believe that Cen X-3 is a high mass x-ray binary system that contains a disk-fed (see, however, Day and Stevens 1993) pulsar with a period of 4.84 seconds that is in a 2.087 day orbit around an O-star companion. Since the pulsar discovery, its period has been intermittently monitored and those studies show a long term spin-up of the pulsar punctuated by short intervals of spin-down (e.g. Finger et al. 1994). The implied torques are thought to originate from the interaction of an accretion disk with the magnetic field of a neutron star (Ghosh and Lamb 1979).

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.

Our discovery of GeV gamma-ray emission from Cen X-3 supports the idea that significant energetic particle acceleration occurs in XRBs and opens the possibility that the system may once again play a key role in furthering our understanding of high-energy processes in XRBs (Vestrand, Sreekumar, Mori 1997). Our observations of Cen X-3 with the EGRET instrument aboard the Compton Observatory revealed, with high statistcal significance ($\sim 6\sigma$), strong GeV emission that was not detected during earlier phases of the CGRO mission. 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 a factor of 3 less than the luminosity associated with the large outbursts of hard x-ray emission measured by BATSE (e.g. Finger et al. 1994) and a factor of 30 less than the total x-ry luminosity. Therefore, depending on the details of the gamma-ray production mechanism, up to 10% of the total power generated during accretion needs to be directed into energetic particle acceleration.

Our phase analysis of this GeV gamma-ray emission from Cen X-3 suggests that the particle acceleration is associated with the accretion-powered pulsar. The rapid variability of the pulse frequency displayed by the Cen X-3 pulsar compromises fixed frequency epoch folding or straightforward analysis with fast fourier transforms when searching the relatively long, two-week EGRET observation for spin modulation. However, by using contemporaneous BATSE x-ray measurements of the drifting pulse frequency to phase analyze the gamma-ray arrival times, we found evidence for spin modulation at a significance level comparable to a $3\sigma$ detection. The pulsar hypothesis is further supported by the fact that the spin modulation disappears when the binary orbit timing corrections are removed.

## Broad-band RXTE/CGRO Observations of Cen X-3.

The relationship between the variable x-ray properties of the Cen X-3 system and the gamma-ray state, while essential for constraining models of the system, is unknown. The GeV gamma-rays were detected during an interval when the x-ray pulsar was undergoing an interval of rapid spin-down. Is the GeV emission only present during periods of rapid spin-down? Are the hard x-ray and gamma-ray fluxes correlated? If the gamma-rays are generated near the pulsar, then photon-photon pair production can absorb GeV gamma ray photons as they traverse the x-ray radiation field in the system (e.g. Vestrand 1983). Indeed, contemporaneous BATSE x-ray observations indicate that the pulsed x-ray flux was weak during the EGRET detection. However, simultaneous observations of the total x-ray flux are not available, so it is not clear whether the total flux or just the pulsed fraction of the x-ray emission varied.

To study the relationship of the gamma-ray emission to the x-ray emission we conducted a campaign of joint Compton Observatory and RXTE Observatory Cen X-3 observation during the period 23 September to 7 October 1997. To our great disappointment, the Cen X-3 system was not detected by EGRET during the campaign.

Cen X-3 was, of course, clearly detected in our monitoring observations with RXTE. We found that the phase averaged RXTE x-ray spectra measured during the campaign could be well fit by power laws that are modified by photoelectric absorption at low energies and an exponential roll-off at high energies. The typical values we found for the spectral parameters are: power law index $\alpha$=1.0, column depth $N_H = 1.3 \times 10^{22}cm^{-2}$, e-folding energy $E_f$=12 keV, and cutoff energy $E_c$=10 keV. These spectral values are comparable to those previously observed for the system (e.g. Nagase 1989). The flux levels we measured correspond to a level of 50-100mCrab. So Cen X-3 was in a transitional state, it was not in its low state where the fluxes are typically below 25 mCrab nor was it in the high state where fluxes can exceed 200 mCrab.

Our failure to detect gamma-ray emission and our detection of the x-ray in an intermediate state makes it difficult to make any definitive conclusions about the relationship between the x-ray and gamma-ray emission with the data we gathered during the September 1997 Campaign of AO-2. However, AO-3 RXTE observations of Cen X-3 which we are currently analyzing, taken as part of a joint X-ray/TeV gamma ray campaign, show much more promise for helping us to understand high-energy particle acceleration in the system.

**References.**


Arons, J. and Tavani, M., 1993, Ap. J., **403**, 249.

Chanmugam, G. and Brecher, K., 1985, Nature, **313**, 767.

Cheng, K.S. and Ruderman, M., 1991, Ap. J., **371**, 187.

Day, C.S., and Stevens, I.R., 1993, Ap. J., **403**, 322.

Eichler, D. and Vestrand, W.T., 1984, Nature, **307**, 613.

Eichler, D. and Vestrand, W.T., 1985, Nature, **318**, 345.

Finger, M., Wilson, R.B., and Fishman, G.J., 1994, in The Second Compton Symposium, eds. C. E. Fichtel et al. (AIP:New York), p. 304.

Ghosh, P. and Lamb, F.K. 1979, Ap. J., **232**, 259.

Giaconni, R. et al. 19971, Ap. J., **167**, L67.

Kazanas, D. and Ellison, D.C., 1986, Nature, **319**, 380.

Katz, J.I. and I.A. Smith, 1988, Ap. J. **326**, 733.

Kluzniak, W., Ruderman, M., Shaham, J., and Tavani, M., 1988, Nature, **336**, 558.

Lamb, F.K., Pethick, C.J., and Pines, D. 1973, Ap. J., **184**, 271.

Lamb, F.K., Hamilton, R.J., and Miller, M.C., 1993, in "Compton Gamma-Ray Observatory", ed. M. Friedlander et al. (AIP:New York), p. 443.

Nagase, F., 1989, Publ. Astron. Soc. Japan, **41**, 1.

Nagase, F. et al., 1992, Ap. J.,**396**, 147.

North, A.R. et al. 1990, Proc. 21th ICRC, **2**, 274.

Pringle, J.E. and Rees, M. 1972, Astron. Astrop., **21**, 1.

Schreier, E. et al. 1972, Ap. J., **172**, L79.

Vestrand, W.T. and Eichler, D., 1982, Ap. J., **261**, 251.

Vestrand, W.T., Sreekumar, P. and Mori, M., 1997, Ap. J. (Letters), 483, L49.