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CYGNUS X-3 AND EGRET GAMMA RAY OBSERVATIONS

M. Mori[1,2], D. L. Bertsch[1], B. L. Dingus[1,8], J. A. Esposito[1,8], C. E. Fichtel[1], S. D. Hunter[1], G. Kanbach[3], D. A. Kniffen[4], Y. C. Lin[5], J. R. Mattox[1,6], H. A. Mayer-Hasselwander[3], P. F. Michelson[5], C. v. Montigny[1,9], R. Mukherjee[1,8], P. L. Nolan[5], P. V. Ramanamurthy[1,10], E. Schneid[7], P. Sreekumar[1,8], and D. J. Thompson[1]

ABSTRACT

The Energetic Gamma Ray Experiment Telescope (EGRET) aboard the *Compton Gamma Ray Observatory* observed the Cygnus region in 14 different viewing periods during 1991 May to 1994 July. We present here our results on unpulsed and pulsed emissions of gamma rays at $E > 50$ MeV from Cyg X-3. While we detect a gamma ray source consistent with the position of Cyg X-3, there was no evidence for the characteristic ~ 4.79 hr periodicity observed in X-rays and infrared.

Subject headings: gamma rays: observations – stars: individual (Cygnus X-3)

[1]NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA
contact djt@egret.gsfc.nasa.gov

[2]Department of Physics, Miyagi University of Education, Sendai, Miyagi 980, Japan
contact m-mori3@ipc.miyakyo-u.ac.jp

[3]Max-Planck Institut für Extraterrestrische Physik, D-85748 Garching, Germany
contact gok@mpe-garching.mpg.de

[4]Department of Physics, Hampden-Sydney College, Hampden-Sydney, VA 23943, USA
contact donk@pulsar.hsc.edu

[5]Hansen Experimental Physics Laboratory, Stanford University, Stanford CA 94305, USA
contact e7.f69@forsythe.stanford.edu

[6]Astronomy Department, University of Maryland, College Park, MD 20742, USA
contact mattox@astro.umd.edu

[7]Northrop Grumman Corporation, Bethpage, NY 11714, USA
contact schneid@sage0.gsfc.nasa.gov

[8]USRA Research Associate

[9]NAS-NRC Research Associate

[10]NAS-NRC Senior Research Associate

1. INTRODUCTION

Cygnus X-3 was one of the earliest X-ray sources discovered (Giacconi et al. 1967). The object exhibits a periodicity ~ 4.79 hr in X-rays and infrared; see van der Klis and Bonnet-Bidaud (1989) and references therein. The 4.79 hr periodicity is interpreted as due to the orbital motion of the binary, based on K-band variations of emission lines (van Kerkwijk 1993). These infrared emission lines also support the idea that one member of the binary is a Wolf-Rayet star (van Kerkwijk et al. 1992). The other member of the system is likely a compact object, either a neutron star or a black hole (Cherepashchuk and Moffat 1994). The object, lying in the galactic plane, is optically obscured. Westphal et al. (1972) placed an upper limit $m_v \sim 23.9$ while Weekes and Geary (1982) found a very faint image in the I band ($\lambda > 0.8\ \mu$m) at the position of Cyg X-3; see Bonnet-Bidaud and Chardin (1988) for a review. Cyg X-3 is one of the X-ray binaries whose binary properties are not well measured. At radio frequencies, its behaviour is very bizarre. Never seen to exhibit the periodicity of 4.79 hr, its radio output can, on occasions, be as high as a few thousand times (Gregory et al. 1972) its quiescent level ~ 20 mJy at 1.5 GHz (Braes and Miley 1972); see Fig. 1. The VLA radio observations by Geldzahler et al. (1983) confirm the picture of Cyg X-3 as an emitter of jets of relativistic particles. Its position in the sky is well measured ($\alpha_{1950} = 20^{\mathrm{h}}30^{\mathrm{m}}37^{\mathrm{s}}.616 \pm 0.001^{\mathrm{s}}$ and $\delta_{1950} = 40^{\circ}47'\,12''.73 \pm 0''.01$) by radio interferometry measurements (Branson et al. 1972) and is believed to be at a distance of > 8.5 kpc from the solar system. The intense radio bursts in September 1972 from Cyg X-3 drew the attention of observatories world-wide to observe the object across the entire electromagnetic spectrum from radio to ultra high energy gamma rays. The Crimean Astrophysical Observatory group (Vladimirsky et al. 1973, Stepanian et al. 1982) detected a source of TeV gamma rays in the direction of Cyg X-3; furthermore, the gamma rays also exhibited the 4.79 hr periodicity, characteristic of Cyg X-3. This claim was soon confirmed in three other independent observations; Danaher et al. (1981), Lamb et al. (1982) and Dowthwaite et al. (1983). At lower energies of > 35 MeV, Galper et al. (1975) found a $3.5\,\sigma$ excess in the direction of Cyg X-3 in a balloon-borne observation. Subsequent balloon observations by the same group and by McKechnie et al. (1976), however, did not confirm the result. At ultra high energies of $\sim 10^{15}$ eV, Samorski and Stamm (1983) detected an excess of events, also showing the 4.79 hr periodicity, in the direction of Cyg X-3; this result was soon confirmed by Lloyd-Evans et al. (1983). Subsequently several new ground-based observations were undertaken specifically to observe Cyg X-3; see the review by Weekes (1988). Though several instances of episodal emissions were reported in the literature, the consensus now appears to be that, Cyg X-3, if it was ever a gamma ray emitter, has gone into a low state not emitting enough gamma rays at TeV and PeV energies, to be detected as a signal above the cosmic ray background e.g. see the results from the CASA-MIA experiment (Borione et al. 1995), which is the largest array designed to detect PeV energy gamma rays from Cyg X-3. The Durham group (Chadwick et al. 1985; Brazier et al. 1990) claimed to detect a periodicity of ~ 12.59 ms in the TeV gamma rays from Cyg X-3 emitted during a 600 seconds wide time window around the X-ray maximum. They, however, could detect the signal only in a few of the 4.79 hr cycles of the binary. Though Gregory et al. (1990) confirmed the 12.59 ms periodicity at $E > 100$

TeV, four other groups (Resvanis et al. 1987; Bhat et al. 1988; Fegan et al. 1989; O'Flaherty et al. 1992; Rannot et al. 1994) did not see it. The non-observation of 12.59 ms periodicity by other groups and rare detections by the Durham group are attributed to low duty cycle of the pulsar thought to be present in the Cyg X-3 binary system.

Among the satellite-borne observations, Lamb et al. (1977) reported seeing a flux of $\sim 10^{-5}$ and 4.4×10^{-6} photons cm^{-2}s^{-1} in the *SAS 2* data above energies of 35 and 100 MeV respectively, based on a $\sim 4.5\sigma$ enhancement compared to the surrounding region of the sky, as stated by the authors. The data showed evidence for the 4.79 hr periodicity, leading the authors to associate the entire excess with Cyg X-3. The *COS B* group (Hermsen et al. 1987) did not detect any signal (either pulsed or steady) from the direction of Cyg X-3, though they claim to have detected a few gamma ray sources in the Cygnus region. The Energetic Gamma Ray Experiment Telescope (EGRET) detector, with an order of magnitude higher sensitivity than the previous detectors, was launched in 1991 April aboard the Compton Gamma Ray Observatory Satellite. Data obtained during the first few months after the launch were searched for the 4.79 hr periodicity signal in gamma rays at energies > 50 MeV. The analysis showed no evidence for the signal (Michelson et al. 1992). Since then we have increased the EGRET exposure on Cyg X-3 by a factor 4. In this paper we take a fresh look at Cyg X-3 as a possible high energy gamma ray emitter both in the unpulsed and pulsed modes.

2. CYGNUS X-3 AS A POINT SOURCE

The EGRET observations up to 1992 November are summarized in the Second EGRET Catalog (Thompson et al. 1995). Briefly stated, the EGRET detector looked at the Cygnus region during 5 different viewing periods (VPs) from 1991 May to 1993 March. A maximum likelihood technique (Mattox et al. 1996) is used to fit the observed counts in various pixels (size $0^\circ.5 \times 0^\circ.5$) in the field of view in terms of energy dependent point spread function (PSF), modelled galactic and isotropic diffuse background radiation (Bertsch et al. 1993 and Hunter et al. 1996) and the possible existence of a point source. The test was repeated until an optimized solution – in terms of diffuse background, number of sources and computed fluxes from them – is obtained. The final outcome of the analysis is that there are 4 possible sources in the Cygnus region ($75^\circ < \ell < 84^\circ$ and $-1^\circ.5 < b < 3^\circ.5$) with statistical significance in the range of 7 to 17 sigma. The positions and fluxes above 100 MeV for these sources are given in Table 1. For details see Table 4 of Thompson et al. (1995).

One of the 4 sources, designated as 2EG J2033+4112 based on its epoch J2000 coordinates, has galactic co-ordinates $l = 80^\circ.19$, $b = 0^\circ.66$ with a 95% confidence error circle radius of $\sim 0^\circ.35$. This direction coincides with that of Cyg X-3 ($l = 79^\circ.85$, $b = 0^\circ.70$) within the errors, although the emission is noted in the Catalog to be possibly extended or resulting from multiple sources. One can, then, tentatively identify the source 2EG J2033+4112 with Cyg X-3. The time-averaged estimated flux of gamma rays at $E > 100$ MeV is $(8.2 \pm 0.8) \times 10^{-7}$ cm^{-2}s^{-1}. The spectral index of the differential energy spectrum is -1.9 ± 0.1.

Attention must be drawn here to the fact that the likelihood analysis attributes only 617 ± 64 events at $E > 100$ MeV to the source within an energy dependent circle containing 67% of gamma-rays (see next section) while the EGRET detector sees in the same direction a total of 6159 events above the same energy. The signal, then, constitutes only $\sim 10\%$ of the total number of events with the remaining 90% coming from the diffuse background or from other nearby sources. The source can be considered real if the error in the background is estimated to be much less than 10%, as we believe to be the case. Next, one must consider if the source is spread-out or is a true *point* source. The point spread function of the EGRET detector does not allow one to distinguish a distributed source (e.g. a local enhancement of gas and/or cosmic ray density by $\sim 10\%$) with angular size of say $\sim 1^\circ$ from a true point source with an angular size of < 1 micro-arcsec expected for a binary orbit size $\sim 10^{11}$ cm located at the distance of Cyg X-3. If any time signature (e.g. periodicity, time variability etc) similar to the one observed at lower energies is evident in the EGRET data, then one can say with confidence that one is observing a *point* source coincidental with Cyg X-3. In this case (see below) there is no evidence for any periodicity in the gamma ray events in the direction of Cyg X-3. So all one can say now is that the EGRET detector is seeing a source in the direction of Cyg X-3 within an error circle of radius $\sim 0^\circ.35$. As can be seen from Table 4 of Thompson et al. (1995), there are 4 EGRET sources in the region of the sky $75^\circ < \ell < 84^\circ$ and $-1^\circ.5 < b < 3^\circ.5$, with a total area of 45 square degrees. The error boxes of the 4 EGRET sources cover a total area of 1.7 square degrees. The chance probability for the direction of any interesting celestial source in the region falling in one of the EGRET error boxes is therefore $1.7/45 \approx 0.05$. We are not sure at the moment if the source of excess gamma rays *is* the point source Cyg X-3.

3. THE 4.79 hr PERIODICITY

We next consider if there is any evidence for the 4.79 hr periodicity, characteristic of Cyg X-3, in the event times of gamma rays in the direction of Cyg X-3. For this study we use the data from 14 VPs from 1991 May to 1994 July.

The point spread function of the EGRET detector can be characterised by an energy dependent radius, θ, of a circle containing 67% of the gamma rays. It is given by (see Thompson et al. 1993)

$$\theta = 5^\circ.85\,(E/100\,MeV)^{-0.534} \tag{1}$$

with the energy, E, in MeV. We have selected all the events with $E > 50$ MeV from the direction of Cyg X-3 within a cone of half-angle given by the above expression for the periodicity test. The recorded event times are corrected to the solar system barycenter to eliminate Doppler effects on the period. The phase of each event is then calculated using the ephemeris (cubic fit) given by

Kitamoto et al. (1995) reproduced below:

$$\begin{aligned} T_0 &= \mathrm{JD}\,2440949.8989 \pm 0.0012 \\ P_0 &= 0.19968271 \pm 0.00000024\,(\mathrm{d}) \\ \dot{P} &= (1.56 \pm 0.13) \times 10^{-9} \\ \ddot{P} &= (-8.13 \pm 1.15) \times 10^{-11}\,(\mathrm{yr}^{-1}) \end{aligned}$$

A 20 bin phasogram is made for the total of 12,550 events with $E > 50$ MeV. The EGRET exposure is not the same at all phases of Cyg X-3 due to occultation by Earth, passage of satellite through the South Atlantic Anomaly (SAA), calibrations and loss of data. Exposure of the telescope in each phase bin is calculated on the basis of the known calibration of the telescope as a function of the operating mode (see Thompson et al. 1993) and known times of occultation, passage through the SAA etc. The average exposure for each phase bin is 5.8×10^7 cm^{2}s and the bin to bin variation of the exposure is in the normalised range of 0.946 to 1.042. We have corrected the phasogram for this non-uniform exposure and shown the result in Fig. 2. As can be seen from the figure, there is no excess of events in *any* phase bin at a level of greater than 1.7 sigma, which is not significant. We, therefore, conclude that the gamma rays in the direction of Cyg X-3 do not show any evidence for the characteristic 4.79 hr periodicity. The estimated 99.9% confidence upper limits for *time-averaged* pulsed fluxes are 2.3×10^{-7} and 5.6×10^{-7} photons cm^{-2}s^{-1} above 50 MeV for a narrow (duty factor $\sim 10\,\%$) and a broad (duty factor $\sim 50\,\%$) light curve respectively, irrespective of the location of the peak position in the light curve using the H-statistic (de Jager 1994). For any *a priori* specified locations of the peaks, the 99.9% confidence limits to fluxes are lower than those given above by a factor 1.3. We have examined data from *each* viewing period for the 4.79 hr periodicity; none of them showed any significant peaks. We have also looked at phasograms at higher energy threshold; again we find no evidence for any pulsed emission.

4. THE 12.59 ms PERIODICITY

As mentioned in the introduction, the Durham group (Chadwick et al. 1985; Brazier et al. 1990) find that, in a few of the 4.79 hr cycles, gamma rays in the TeV energy range exhibit 12.59 ms periodicity in a 600 seconds' wide time window around the X-ray maximum.

Assuming the 4.79 hr periodicity is due to the orbital motion, the suspected 12.6 ms pulsation of Cyg X-3 cannot be coherent during the whole 4.79hr cycle: thus the same strategy of using 600 s windows is applied to search for an evidence of pulsation in the EGRET data. Also these narrow time windows reduce the number of events and computing time to explore the wide range of the parameter P_0 and $\dot{P}$: these values are assumed to lie in the range of (12.5979 ± 0.0005) ms and $(1.9 \pm 0.3) \times 10^{-14}$ s/s, respectively, at the epoch 1992 December 11 which is at the middle of the EGRET's best exposure VP2030 on Cygnus X-3. These values are extrapolated from those given in Brazier et al. at the epoch $\sim$ 1988 August 1.

The period search program searches the frequency which gives the maximum non-uniformity with the H-statistic (de Jager et al. 1989) within the given frequency range for each step of frequecy derivative. In the frequency domain the above P_0 and $\dot{P}$ correspond to $f_0 = (79.378 \pm 0.003)$ Hz and $\dot{f} = (1.2 \pm 0.2) \times 10^{-10}$ Hz/s: actually we searched for a little wider parameter range than this (see below). In order to reduce the number of independent searches to be practical and keep the fair number of events in 600 s windows, only the best exposure, VP2030, was used. We have a total of $\sim$ 51 windows of 600 s in VP2030 with Earth not occulting the object. Results are summarized as follows:

In 600 s windows centered on the X-ray maximum (phase 0.5776–0.6124), there are 146 events of energies greater than 50 MeV: in the range of $f = 79.371 \sim 79.384$ Hz with 0.14 μHz step and $\dot{f} = (0.6 \sim 1.8) \times 10^{-10}$ Hz/s with 0.04×10^{-10} Hz/s step, the maximum non-uniformity occurred at 79.371172 Hz and 1.52×10^{-10} Hz/s with chance probability of 1.5×10^{-7}: however, when multiplied by the number of independent searches (2.3×10^4) in each $\dot{f}$ and number of $\dot{f}$ (30), it becomes 0.1 and this is not at all significant. We also tried to search in the extended range of $f = 79.358 \sim 79.371$ Hz and $f = 79.384 \sim 79.397$ Hz with the same $\dot{f}$'s, but no significant peak appeared.

Brazier et al. also reports possible time variation of "gamma-ray maximum". To check this possibility, we also tested the periodicity for events in 600 s window before the X-ray maximum (phases 0.5602–0.5950) and after it (phases 0.5950–0.6298). Number of events are 122 and 138, respectively. Again we have no indication on periodicity in $f = 79.371 \sim 79.384$ Hz with the same $\dot{f}$'s: the lowest chance probability of 8.4×10^{-8} occurred at the former dataset at 79.372613 Hz and 7.2×10^{-11} Hz/s, which, after multiplying the number of searches, becomes 0.06 and one cannot say this is significant.

In 1989 observations, the Durham group finds further evidence of emission at the 12.59 ms period, but this time the period was $2 \sim 3\,\mu$s shorter than suggested in their 1981–1988 data (Bowden et al. 1992). On the other hand, the University of Adelaide group reports evidence for the pulsation similar but at $\sim 1\,\mu$s shorter than suggested based on their 1989 observations sensitive to $E > 100$ TeV (Gregory et al. 1990). Although it is difficult to imagine any mechanism which causes this large change in pulsar period, we tested this possibility by searching for periodicity between $79.384 \sim 79.401$ Hz, which is extrapolated using the period derivative given by Brazier et al. and covers the whole possible range, with the same $\dot{f}$'s. The result is again consistent with the null hypothesis.

In conclusion, we found no evidence of the 12.6 ms periodicity in the EGRET data: however, one should note that the periodicity search tried here is rather limited due to the large errors in the pulsar ephemeris and the low event rates in EGRET. If the periodicity is seen only rarely, as Brazier et al. reports ($\sim$ 6 occasions in 168 observations; see Protheroe 1994), the periodicity search is impossible for a small number of events (about 5 in VP2030 if the chance is similar) and many trial parameters.

5. DISCUSSION

Cyg X-3 is located in the galactic disk at a region where the emission of diffuse radiation is strong. This makes the task of distinguishing Cyg X-3 gamma ray emission from the galactic diffuse radiation background difficult. Using the *SAS 2* data, Lamb et al. (1977), as mentioned in the introduction, reported a time-averaged gamma ray flux of $(4.4 \pm 1.1) \times 10^{-6}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $E > 100$ MeV, based primarily on the 4.79 hr periodicity. From the later *COS B* observations Hermsen et al. (1987), not finding any emission, reported $2\,\sigma$ upper limits to the *total* gamma ray intensities of 7.5×10^{-7}, 6.5×10^{-7} and 4.5×10^{-7} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the energy intervals of 70 – 150 MeV, 150 – 300 MeV and 300 – 5000 MeV respectively. Here we find a *total* flux of $(8.2 \pm 0.9) \times 10^{-7}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $E > 100$ MeV which is not in conflict with the *COS B* upper limits. However this flux is a factor 5 lower than the one given by Lamb et al. (1977). The *SAS 2* data were re-examined by Fichtel et al. (1987) with an improved model for galactic diffuse radiation in the Cyg X-3 region and the authors found that the conclusions of Lamb et al. (1977) were essentially correct, assuming a single source based on the detection of the 4.79 hr periodicity. The quoted flux, however, is consistent with the combined fluxes of all the sources seen in the region by EGRET. The discrepancy between the Lamb et al. result on one hand and the *COS B* upper limits and the present flux measurements on the other may be due to the variability of the sources. Time variability of Cyg X-3 is also strongly suggested by the data at TeV and PeV energies. It may also be relevant to note here that Cyg X-3 was emitting unusually strong and frequent radio bursts 5 to 6 months prior to observations by the *SAS 2* while being relatively less active with reference to the *COS B* and EGRET observations (there was, however, a strong radio flare 2 weeks before the second EGRET observation); see Fig. 1.

Hermsen et al. (1987) set $2\,\sigma$ upper limits for time-averaged *pulsed* fluxes in the energy range 70 – 5000 MeV at the values of 9.7×10^{-7} and 1.0×10^{-7} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ in the 4.79 hr phase ranges of 0.1 – 0.9 and 0.2 – 0.3 respectively. These limits may be compared with 99.9% upper limits to the pulsed flux above 50 MeV found by us here *viz.* 2.3×10^{-7} and 5.6×10^{-7} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for light curves with narrow ($\sim 10\%$) and broad ($\sim 50\%$) peaks respectively, irrespective of location of peak position in the light curve. It is possible that Cyg X-3 *is* a source of high energy gamma rays at the level indicated in the previous paragraph with the periodicity time signature being lost due to some features of emission in the environs (out to several light-hours) of the binary system.

While the mechanisms for production of high energy gamma rays are well-known, the models for actual emission are not; see Weekes (1988) for a review. A pulsar model that could accelerate ions to energies up to 10 PeV was proposed by Eichler and Vestrand (1984); in this model particle beam energy derives from the rotational energy of the neutron star. Chanmugam and Brecher (1985) proposed a unipolar induction model in which the energy source is accretion; this model works well for neutron stars with weak magnetic field. Shock acceleration models were proposed by Eichler (1978) and Kazanas and Ellison (1986). There is also a diversity in modelling the target geometries. Vestrand and Eichler (1982) proposed that the accelerated particle beam interacts with the atmosphere of the companion star to produce gamma rays. Hillas (1984) proposed that the accelerated particle beam could lift off a thick layer of material from the companion star which then acts as an isolated target for gamma ray production. In yet another scenario, gamma rays are produced in the accretion disk itself around the neutron star by the beam particles (Eichler and Vestrand, 1985). At the moment there is no consensus on the acceleration mechanism or on the target geometry in Cyg X-3.

6. SUMMARY

In summary, we find that there is a source of gamma rays in the direction of Cyg X-3 at a time-averaged flux level of $(8.2 \pm 0.9) \times 10^{-7}$ photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at $E > 100$ MeV. Because of the lack of any time signature and finite size of EGRET error box, we cannot say with certainty that the source *is* Cyg X-3; however, the probability of chance association is small, at the level of ~ 0.05. We do not find any evidence for the 4.79 hr periodicity characteristic of Cyg X-3. The 99.9% confidence upper limits to pulsed fluxes are placed at 2.3×10^{-7} and 5.6×10^{-7} photons $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ above 50 MeV for a narrow (duty factor $\sim$ 10%) and a broad (duty factor $\sim$ 50%) light curve respectively, irrespective of the peak position in the light curve. Finally, we found no evidence for the 12.59 ms periodicity reported in the literature, but this conclusion is subject to the limitation due to the large errors in the pulsar elements and also due to the low event rates.

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Table 1. EGRET Sources in the Cygnus Region

Name	l	b	F	Other name
2EG J2019+3719	75.46	0.60	82.3 ± 7.9	2CG075+00
2EG J2020+4026	78.12	2.23	126.5 ± 8.3	2CG078+01
2EG J2026+3610	75.31	−1.18	46.8 ± 7.1	
2EG J2033+4112	80.19	0.66	82.4 ± 8.4	

Coordinates are in degrees; fluxes are photons (E> 100 MeV) $\mathrm{cm}^{-2}\mathrm{s}^{-1} \times 10^{-8}$

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Fig. 1.— Times of occurrence and peak intensities of radio bursts in Cygnus X-3 are shown. (a) covers the period 1972 to 1983; see Woodsworth (1983) for details and (b) covers the period 1990 to 1994.5; see Waltman et al. (1995) for details. Exposure times of *SAS 2* and *COS B* on Cyg X-3 are shown by the letters 's' and 'c' respectively in (a) and those of EGRET are shown by the letter 'e' in (b).

Fig. 2.— Phase histogram of event times of gamma rays at energies greater than 50 MeV arriving from the direction of Cygnus X-3 is shown by the solid line. The average and one sigma error bars are shown by the dashed and dotted lines respectively. Event numbers in each phase bin are corrected for non-uniform exposure.

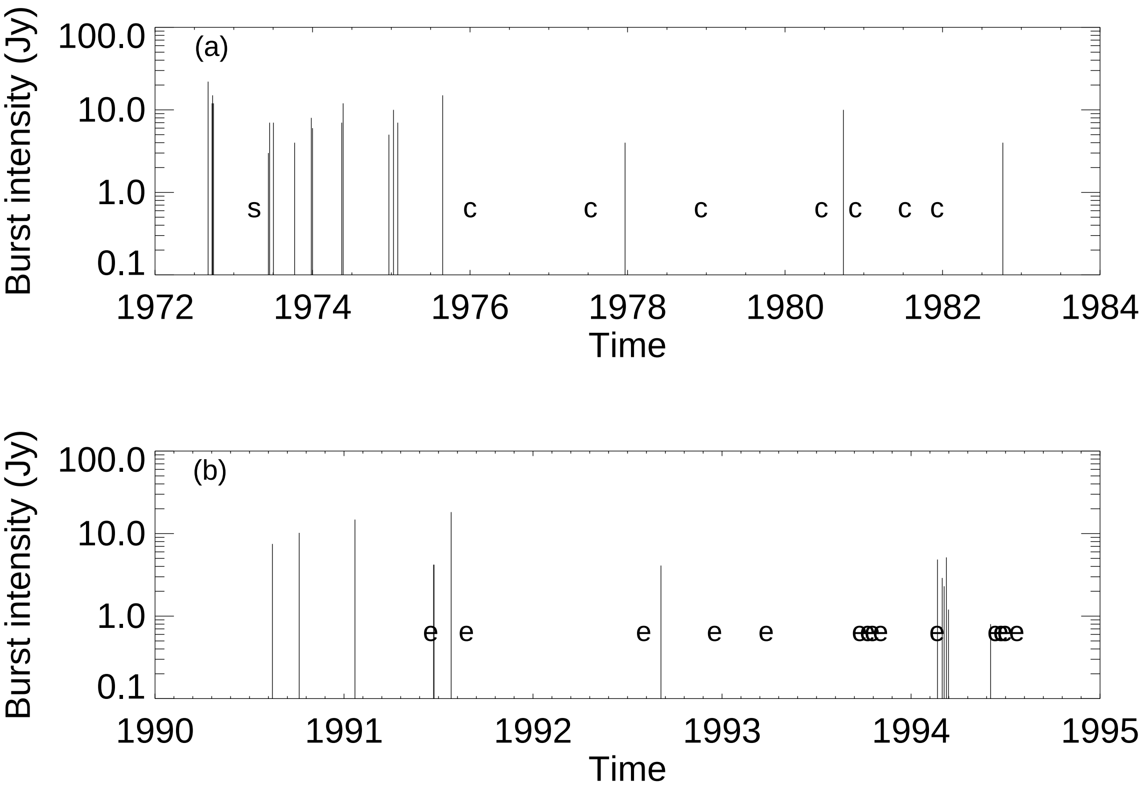

Fig. 1

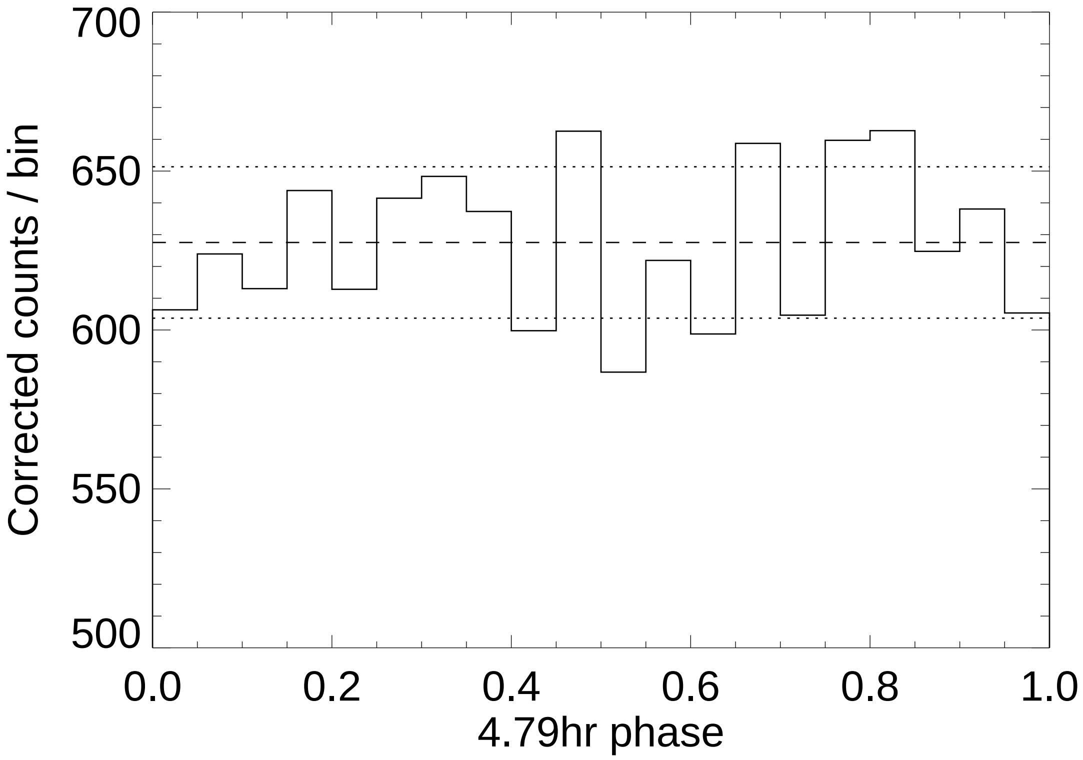
700
650
600
550
500
Corrected counts / bin
0.0
0.2
0.4
0.6
0.8
1.0
4.79hr phase

Fig. 2