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Timing analysis of VHE γ-rays from Cen X-3

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Abstract. Observations of Centaurus X-3 were made by the University of Durham Mark 6 telescope over a three year period from 1997 to 1999. A detailed timing analysis of the observations has been performed. A search for modulation of the γ-ray signal at the pulsar orbital period, as well as for any short-term (few hours) episodes of γ-ray emission with a periodicity near, but not necessarily coincident with, the period of X-ray pulsations has been carried out. The results are presented in the context of several possible emission scenarios.

1 Introduction

Cen X-3 is an accreting high mass X-ray binary system consisting of an O-class star being orbited by a 4.8s pulsar in a 2.1 day orbit. The parameters of this binary system have been extensively studied since its discovery in the 1970's, but particularly in the last few years with the BATSE instrument on the *CGRO* allowing the day to day variation of the spin period to be observed.

Cen X-3 has been detected in the high energy γ-ray domain (E $\geq$ 100MeV) by EGRET (Vestrand et al., 1997). Analysis of data taken in October of 1994 showed a modulation of the γ-ray signal at the BATSE determined X-ray period, but no orbital modulation of the signal (with 1/4 of γ-rays being observed during eclipse). It was not seen at any other times of observation and is therefore supposed to be a variable source of high energy emission.

VHE gamma rays (E $\geq$ 1 TeV) from Cen X-3 were first reported from observations with non-imaging telescopes by the Durham group (Brazier et al., 1990) and the Potschefstroom group (North et al., 1990). These telescopes had poor sensitivity to steady emission, with γ-ray signals extracted mostly on the basis of timing analyses and the observations are subject to controversy concerning the reliability of X-ray binary detections (Weekes, 1992). Cen X-3 is the first (and so far only) X-ray binary to have subsequently been detected as a source of E $\geq$ 400 GeV γ-rays by an imaging ACT (Chadwick et al., 1998, 2000), the University of Durham Mark 6 telescope (Armstrong et al, 1999).

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2 The Data

Observations of Cen X-3 were taken with the Mark 6 telescope over a period of three years (in March and June 1997, March and April 1998 and February 1999) yielding ~32 hours of 'on-source' data for analysis. Previous analysis showed the system to have a weak, but persistent, flux of
F$(\geq 400\mathrm{GeV}) = (2.8 \pm 1.4_{\mathrm{sys}} \pm 0.6_{\mathrm{stat}}) \times 10^{-11}$cm^{-2} s^{-1} (Chadwick et al., 2000). No modulation of the signal at the orbital or pulsar period was found. A more detailed timing analysis has subsequently been undertaken. The ephemeris used was that of Nagase et al. (1992).

3 The Timing Analysis

3.1 Orbital Modulation

Important information about the plausible site and mechanism of γ-ray production can be gleaned from testing for possible correlations of the γ-ray flux and the orbital phase of the pulsar, particularly because it is an eclipsing binary and the neutron star's companion is a very luminous star. X-ray observations show a deep eclipse of Cen X-3 for phase $|\Phi| \leq 0.12$. Bednarek (2000) shows that in the case of γ-ray production near the orbit of Cen X-3 the optical depth of VHE γ-rays on the thermal optical/UV photons of the companion star varies from $\tau_{\gamma\gamma} \sim 10$ to $\tau_{\gamma\gamma} \sim 1$ with variation of orbital phase $0.12 \leq |\Phi| \leq 0.5$. In this case a strong correlation of the γ-ray signal with the eclipse phase is expected. There is no indication of any correlation of the significances of γ-ray signal with orbital period in our data set; in fact the episode of highest significance occured during eclipse of the X-ray source.

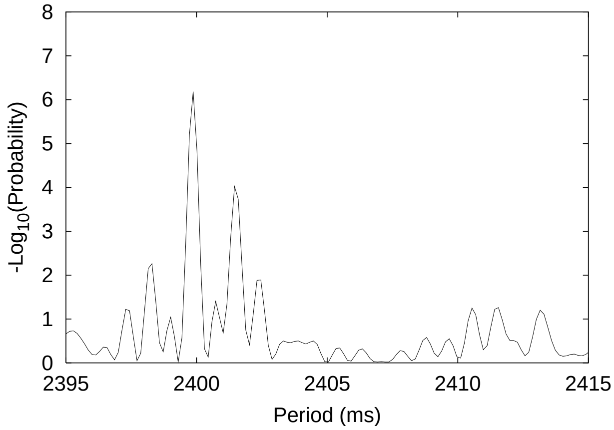

Fig. 1. Rayleigh test results applied at the half period on the 'soft cut' data from 21/2/99, with brightness >1500. The probabilities have not been adjusted for degrees of freedom.

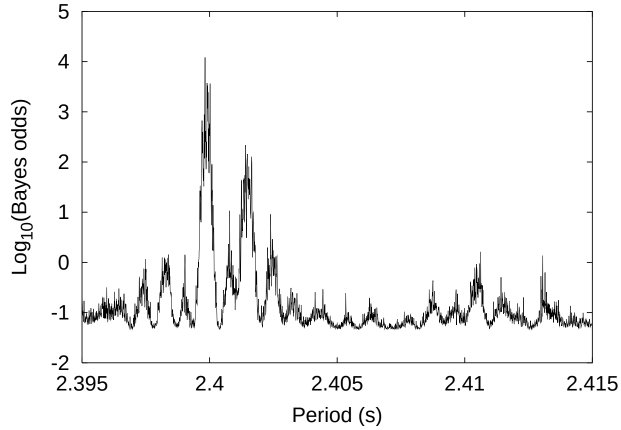

Fig. 2. Bayesian test results for the same data set as figure 1. Any Log_{10}(Bayes odds) value above 0 supports a modulated signal hypothesis more than the null hypothesis.

3.2 Pulsar Periodicity Analysis

Earlier analysis of the dataset showed no long term periodic signal from Cen X-3 (E $\geq$ 400GeV) centred on the site of X-ray emission. In this analysis we have considered the possibility of short term, variable emission (as was the case for results obtained with earlier, non-imaging telescopes) that may not be coincident with the site of X-ray emission. For this analysis the event times were adjusted to the solar system barycentre, but not to the site of X-ray emission. Instead a larger range of trial periods was searched, allowing for a doppler shifted source of VHE γ-rays up to speeds of v $\sim$1200 kms^{-1}. The search was conducted at both the period and half period, due to the inability of the Rayleigh test to cope with light curves with a double peak separated by π in phase; a trait occasionally observed in Cen X-3's X-ray light curve (Tuohy, 1976; Nagase et al., 1992; Burderi et al., 2000).

The Rayleigh power is defined as NR^2 where $N = B+G$ is the total number of events, B is the number of background cosmic-ray events, G is the number of γ-ray events and R is the ratio G/N. Any cuts made will affect the number of γ-ray events ($g = F_G G$) and background cosmic ray events ($b = F_B B$). Taking $N_{\rm cut} = b + g = F_B B + F_G G$; $R_{\rm cut} = g/N_{\rm cut}$; and $F_B B \gg F_G G$ the Rayleigh power then approximates to

$$(NR^2)_{\rm cut} \simeq \frac{F_G^2}{F_B}\frac{G^2}{B}.$$

Only the first term is affected by any cuts and this is to be maximised in order to obtain the greatest sensitivity in a periodicity search. Imaging is a very strong way of discriminating against a large cosmic ray background signal, but at the expense of losing a number of the γ-ray events that are being searched for in the first place. With the low flux of VHE γ-rays from objects like X-ray binaries any loss of γ-ray events is counter productive in a periodicity search.

We have first applied the standard Rayleigh test statistic on the data of each individual night of observation after full image parameter cuts have been applied. This analysis did not reveal any significant Rayleigh power, however this is to be expected as we see from the above discussion. Taking the average 'on-source' observation time to be 1.5 hours and the computed flux from Cen X-3 then the mean number of γ-rays for a detector with a collection area of 10^9 cm^2 and 50% efficiency (Chadwick et al., 2000) is $\sim$130. Monte Carlo simulations indicate that the fraction of γ-rays passing full image parameter cuts is $\sim$20%. For a typical count of 400 events in a night's data after image cuts have been applied only 25-30 of these could be pulsed γ-rays. The expected Rayleigh power would only be $\sim 400 \times (25/400)^2 \sim 1.6$; corresponding to a chance probability of P = exp(- Rayleigh power) ~ 0.2.

To acheive the maximum number of γ-rays we have applied, in succession, a series of significantly 'softer' image parameter cuts. Removing, at the first step, only those events with orientation $\alpha \geq 45^\circ$ from the raw data reduces the number of cosmic ray induced events by a factor of three, but does not significantly affect the number of γ-ray events. The next subset was prepared by applying the width and eccentricity parameters and by confining the location of the image in the camera (parameter distance). This procedure is rather efficient at suppressing cosmic ray events by a factor of $\sim$8-10, although it may remove some γ-ray events as well. Lastly, we searched for periodicity after discriminating for the brightness of the image ($\geq$800 and $\geq$1500 digital counts), this procedure effectively increases the energy threshold by a factor of 2 and is useful only if the γ-rays have a harder spectrum than that of cosmic rays. It is suggested through theoretical predictions that the spectra from X-ray binaries may be anamolously hard due to their absorption on the thermal optical/UV photons produced either by the compact γ-ray source (Aharonian and Atoyan, 1991, 1996), or by the optical companion star in the case of Cen X-3 (Bednarek, 2000).

The detailed analysis of these data-sets has revealed a strong Rayleigh power peak in the 'soft-cut' data-set with brightness >1500 for the observation on the 21st Feb. 1999 at a period of T = 2.3999s. This peak corresponds to a chance probability of P = 6.9 $\times 10^{-7}$ (see figure 1). Due to the large period range tested and the number of data subsets analysed the likelihood of this peak arising by chance increases when taking the number of trials into account to P$\leq 5.4 \times 10^{-3}$. This period is blue shifted from the nominal second harmonic of the X-ray period $T_0/2$ = 2.4088s (the BATSE derived X-ray period corrected for orbital motion at an orbital phase of $\Phi \simeq 0.77$) and implies, if genuine, a motion of the γ-ray source with respect to the neutron star with a velocity v $\simeq$ 1200 kms^{-1}. Note that the orbital speed of the Cen X-3 pulsar is 414 kms^{-1} and the speed of the wind driven by the companion is $\sim$ 1000 kms^{-1} (Clark et al., 1988).

In an attempt to gain better control of the hypothesis testing the analysis was repeated using a Bayesian technique (Gregory and Loredo, 1992; Orford, 2000). The attractiveness of the Bayesian technique is that the overall probability of the hypothesis of a time-modulated signal does not scale linearly with the number of trials as in the Rayleigh test, but with the ln(period range searched). The periodicity search is therefore only penalised by the fact that the period is uncertain within a range and not by the number of times that region is searched. Using the Gregory and Loredo method, the peak for the 21/2/99 data was again found at the period T = 2.3998s at $N_{\rm odds} = 1.2 \times 10^4$ more probable than a uniform distribution in time, see figure 2.

4 Discussion

No indication of any correlation of the VHE γ-ray signal with orbital phase is found, including when the pulsar is in deep X-ray eclipse. This demonstrates that any VHE γ-ray production site can not be in the close vicinity of the pulsar. The principal model possibilities for γ-ray production in Cen X-3 must be able to produce VHE radiation at distances significantly beyond the neutron star orbit (R $\geq 5 \times 10^{12}$cm). The period of pulsations found in the data of 21/2/99 is blue shifted from the nominal period by $\delta T/T \simeq 3.7 \times 10^{-3}$. Such shifts could be reasonably expected in any situation where γ-radiation is produced far from the pulsar.

A spatially extended source or a compact source model (see Atoyan et al, 2001a for further details of these models) can both in principle explain the average fluxes of HE and VHE γ-rays. Hadronic and leptonic compact source models predict a variation of the γ-ray fluxes on timescales of a few hours and 'disappearance' of the source in a few days. The spatially extended source model, however, should be quasi-stationary on timescales of at least several days (and probably weeks/months) and could not explain the phenomenon of γ-ray pulsations at the pulsar period. An important prediction for the compact source models is that any pulsed emission can only be episodic, with a typical duration no more than a few hours. For γ-rays of E $\geq$ 100 GeV which are produced at large distances this is practically a model independent requirement; however, γ-rays with E $\leq$ 10 GeV can escape from this binary when produced relatively close to the X-ray pulsar. At these energies the detection of pulsed γ-rays in the eclipse stage of the X-ray pulsar would therefore be very informative.

Image parameter cuts have traditionally been derived to maximise the DC signal from a steady, standard-candle object; a description that fits the Crab Nebula for those observatories lucky enough to have it in their sights. This work shows that the hard image parameter cuts used for maximising γ-ray significance can become destructive in a search for γ-ray periodicity. With the low flux of VHE γ-rays from objects like X-ray binaries any loss of γ-ray events is counter productive in a periodicity search. It is therefore necessary to relax any cuts made to allow the greatest number of γ-rays through the selection procedure.

Another informative feature for Cen X-3 and X-ray binaries in general could be the nature of the spectrum – in particular a very hard spectrum at both high (GeV) and very high (TeV) energies. This is consistent with, if not conclusive from, our data when making cuts for brighter (and therefore higher energy primary photon) images.

It is hoped that future observations with the next generation of γ-ray observatories, such as GLAST in the high energy domain and HESS in the very high energy region, will tidy up any lasting uncertainties about the nature of γ-rays from X-ray binary objects.

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