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Time-dependent analysis of Hercules X-1 observations with the HEGRA Cherenkov Telescope System

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Abstract. The X-ray binary 'Hz Her/Her X-1' was monitored with the stereoscopic system of five imaging atmospheric Cherenkov telescopes (IACTs) of the HEGRA Collaboration ($E_{thr} > 0.5\,\mathrm{TeV}$) from August 1999 to August 2000. The 1999/2000 data have been collected during the *anomalous low state* (ALS) which ceased at the end of 2000. No DC signal has been observed. A search for a periodic emission resulted in a periodicity at an orbital phase of $\Phi_{\mathrm{orb}} = 0.078$ for one run (20 min.) with a chance probability of $\approx 10^{-1}$. Further data are scheduled to be taken in 2001.

1 Introduction

The X-ray binary Hz Her/Her X-1, consisting of an accretion-powered X-ray pulsar Hercules X-1 ($1.3\,\mathrm{M}_{\odot}$), which was first discovered by Tananbaum et al. (1972), and its companion star Hz Her ($2.2\,\mathrm{M}_{\odot}$), is a well studied object in a wide range of the electromagnetic spectrum. Besides the $1.24\,\mathrm{s}$ pulsar period and the $1.7\,\mathrm{d}$ orbital period, the system shows a $35\,\mathrm{d}$ cycle of varying X-ray intensity (Scott & Leahy, 1999) which consists of two high-states of 10 days (Main-On) and a weaker one of 7 days duration (Short-On), separated by two low-states. The 35 day cycle is permanently measured by the RXTE All Sky Monitor (ASM) since 1996 (RXTE team, 2001). The lightcurve for the last three years is shown in Figure 1.

Many γ-ray observations of the source have been reported, most of them in the years 1983 to 1986, often claiming evidence for a detection in the very high energy (VHE) or some even in the ultra high energy (UHE) range. The first was the TeV detection of Hercules X-1 by the Durham group (Dowthwaite et al., 1984), who reported a 3 minute burst modulated with the $1.237\,\mathrm{s}$ pulsar period. This was followed by a claim in the UHE range by the Fly's Eye experiment on July 11, 1983 (Baltrusaitis et al., 1985). Later on, the Whipple collaboration reported many observations with evidence for pulsed emission (see Gorham et al. (1987) for a summary of the 1984-86 Whipple observations). In 1986 an outburst was observed with the Haleakala Cherenkov telescope (CT) (Resvanis et al., 1988) with a measured period similar to that of a nearly contemporary observation by the Whipple group. A simultaneous measurement of the Dugway CT together with the Whipple CT on April 4, 1984, both with evidence for pulsed emission at the same frequency, has also been reported by Chadwick et al. (1987).

Many of the measured VHE/UHE-periods showed a significant deviation of the corresponding X-ray period, mostly blue-shifted by up to $0.1 - 0.16\,\%$. Nearly all possible detections were made either during the Main-On or during the Short-On state of the 35 day cycle.

It should be mentioned, that remarkable progess has been made since these observations as regards the technique of the imaging atmospheric Cherenkov telescopes; especially the γ-hadron separation which allows an effective background reduction of hadron induced air showers (Hillas, 1985). Applying these improved techniques to the earlier sets of data partially lead to a disappearance of the periods found in earlier observations (Reynolds et al., 1990). Hence the earlier claims, even though there were many of them, should be treated with caution.

However, in the years 1994/95 a steady excess with a significance of $3.3\,\sigma$ from the direction of Hercules X-1 was measured with the HEGRA scintillator and AIROBICC array at an energy threshold of $E_{\mathrm{thr}} > 20\,\mathrm{TeV}$ (Prahl, 1999), which gave rise to further observations of Hercules X-1 with the HEGRA IACT system which will be reported here.

2 Observation

The observations of Hercules X-1 were carried out with the stereoscopic system of five imaging atmospheric Cherenkov telescopes (IACTs) of the HEGRA experiment (Daum et al., 1997), located on the Canary island of La Palma ($17°53'$ W,

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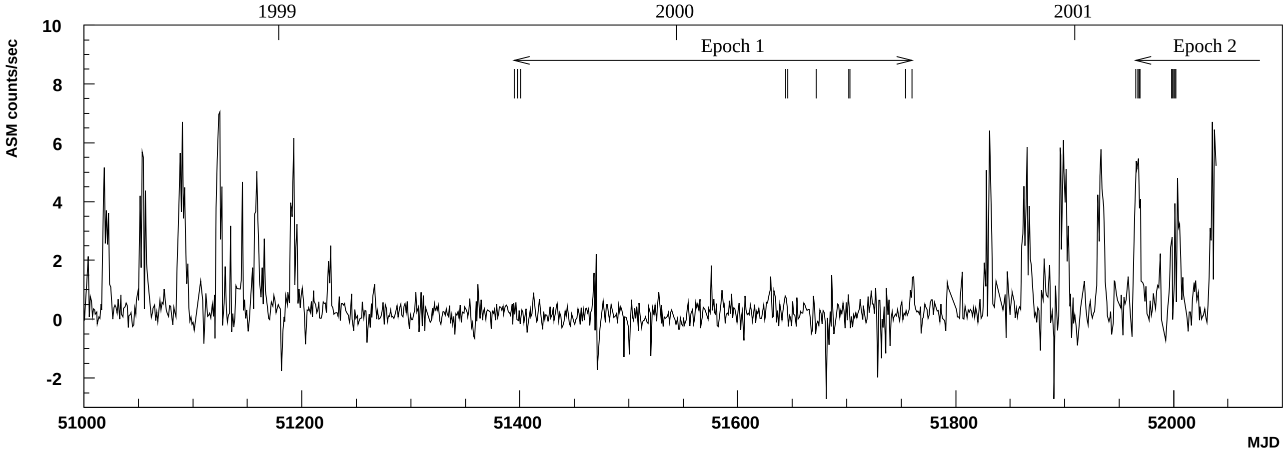

Fig. 1. The lightcurve of the *All Sky Monitor* (ASM) onboard the RXTE-satellite from Hercules X-1 for the years 1999-2001 (RXTE team, 2001). The times of the HEGRA observations are plotted as vertical lines; the data of *Epoch 1* was taken during the *anomalous low state* (ALS) and the observations of *Epoch 2* were concentrated on the high states of the 35 day cycle (peaks in the lightcurve).

$28°45'$ N, $2200\,\mathrm{m}$ a.s.l.). The stereoscopic imaging of the Cherenkov light from γ- or hadron induced air showers allows the non-ambiguous reconstruction of the shower core position and direction of the primary particle within an angular resolution of $\leq 0.1°$ (Aharonian et al., 1997). Each of the five Cherenkov telescopes consists of a $8.48\,\mathrm{m}^2$ segmentated mirror and a 271 pixel photomultiplier (PM) camera; the geometric angular field of view of one single PM and the whole camera are $0.25\,°$ and $4.3\,°$, respectively.
A single telescope triggers when two or more adjacent pixels show a signal corresponding to 6 or more photo electrons; the whole system triggers when two or more telescope trigger reach the central station within a time window of $60\,\mathrm{ns}$ (Bulian et al., 1998). The average system trigger rate and the energy threshold of the IACT System are $\sim 16\,\mathrm{Hz}$ and $E_{thr} > 500\,\mathrm{GeV}$, respectively, for observations near the zenith. The γ- hadron separation is done by comparing the image parameter *mean scaled width* (*mscw*) of the parametrized ellipse of a recorded event image with values obtained from *Monte Carlo* simulations (Aharonian et al., 1997).

The observations of Hercules X-1 were performed in the so called *Wobble* mode (Daum et al., 1997), which allows a simultaneous background measurement. The observations took place in the years 1999 ($\sim 2\,\mathrm{h}$), 2000 ($\sim 12\,\mathrm{h}$) and 2001 ($\sim 15\,\mathrm{h}$ until May, 2001) and are still to be continued. As seen in Figure 1 it is reasonable to subdivide the HEGRA observation (depicted as vertical lines in the plot) into two distinct sets of data: The data taken during the *anomalous low state* 1999/2000 (Coburn et al., 2000), further on denoted as *Epoch 1*, and the data taken in 2001 where the ALS has ceased, denoted as *Epoch 2*. Due to earlier reported claims of UHE detection from Hercules X-1, the latter observations were concentrated on the high states of the 35 day cycle which are recognizable as peaks in the ASM lightcurve shown in Figure 1.

3 Data Analysis

The HEGRA data consist of runs with 20 minutes of duration each. First, all the runs with triggerrates less than $8\,\mathrm{Hz}$ (mainly due to bad weather conditions) were excluded from the analysis. Further on, in *Epoch 2* only the data which coincided with the *High-On* states of the 35 day cycle were taken into account in the analysis in order not to weaken the statistical significance of a possible detection due to a high number of independent trials in the frequency search[1]. From *Epoch 1* all runs which survived the weather cut were selected for the analysis. After all cuts had been performed, about 12 and 10 hours of data remained for *Epoch 1* and *Epoch 2*, respectively. The mean zenith angles for the two data sets are $14.3°$ (*Epoch 1*) and $17.0°$ (*Epoch 2*), which translates into an energy threshold of $E_{\mathrm{thr},1} = 0.67\,\mathrm{TeV}$ and $E_{\mathrm{thr},2} = 0.68\,\mathrm{TeV}$, respectively.

Each event which fell within a $0.22°$ circle around the source position of Her X-1 which is given by $35°20^m33^s$ Right Ascension and $16^h57^m50^s$ Declination and which showed a *mscw*< 1.2 (γ-hadron separation) has been used in the analysis. The results are still preliminary, because the efficiency of the Rayleigh test (1) used for the periodicity search strongly depends on the following two correlated parameters: the number of analysed event times and the signal-to-noise ratio. Cutting the HEGRA events using the *mscw* cut leads to an increased signal-to-noise ratio at the expense of the amount of total events. An effective periodicity search on the other hand needs both: a good signal-to-noise ratio and a large amount of events. Hence, the optimal cut will be estimated by *Monte Carlo* simulations of the Rayleigh test be-

[1]As mentioned above, from the outset the observations of *Epoch 2* were concentrated on the high states of the 35 day cycle; but since the turn on time may vary up to $1.7\,\mathrm{d}$, an absolutely accurate coordination was not possible in advance; however, only a few percent of the data runs were exluded by this selection criterium.

haviour referring to these parameters (De Jager et al., 1989).

The data of *Epoch 1* and *Epoch 2* were analysed separately due to the distinct physical states of the Hercules X-1 system. First a search for steady emission was performed on both data sets. Afterwards, each of the 20 minute runs was searched for periodicy in a $[0.804\,; 0.81]$ Hz frequency interval after the event times had been corrected to the solar system bary center (SSBC) using the DE200 ephemeris of the JPL (JPL, 2001) and to the Hz Her/Her X-1 binary system using the orbital parameters of Deeter et al. (1991). The search for periodicity has been performed with the Rayleigh test which is given by (Mardia, 1972):

$$R(\nu) = \frac{1}{N}\sqrt{\left(\sum_{i=1}^{N}\cos 2\pi\Phi_i(\nu)\right)^2 + \left(\sum_{i=1}^{N}\sin 2\pi\Phi_i(\nu)\right)^2} \quad (1)$$

Here, N is the number of recorded events in a time series and $\Phi_i(\nu)$ is the phase of the i th event refering to a test frequency ν. The Rayleigh power is defined as $K(\nu) = NR^2(\nu)$. For $N \geq 50$ the size $2NR^2$ is distributed as χ^2 with two degrees of freedom (dof); this allows an easy handling of the Rayleigh statistics: the probability to obtain a Rayleigh power $K \geq K^*$ is given by $P(K \geq K^*) = e^{-K^*}$ which allows a sufficient probability estimation. For $N < 50$, however, this is not valid anymore (in most cases of a 20 minute run, after the γ-hadron separation has been applied, only around 10-30 events survived). For these cases Greenwood & Duran (1955) gave a polynomical correction which is in good agreement with our *Monte Carlo* simulations. For very small event times $N < 15$, however, the polynomical correction yields senseless results for large Rayleigh powers, so we decided to take the *Monte Carlo* results for the probability estimation, which are the most reliable for the span of event times occuring in this analysis.

The $[0.804\,; 0.81]$ Hz interval was scanned with a frequency stepsize of 20 steps per Independent Fourier Spacing (IFS) which yields $\Delta\nu \approx 4 \cdot 10^{-5}$ Hz for a 20 minute run. The oversampling was taken into account by a deductive overestimation factor of 3 for the probability of a particular Rayleigh power (De Jager et al., 1989). For possible very significant Rayleigh powers, additionally a separate *Monte Carlo* estimation of the chance probability will be performed taking into account the number of searched frequencies, the run duration and the oversampling.

4 Results

In the search for steady emission no DC excess could be found neither in the data of *Epoch 1* nor in the data of *Epoch 2*, as far as the latter was available already in calibrated form.

The results of the time analysis are preliminary because of the not yet optimized event cuts for the periodicity search, as mentioned in the previous section. The results of the *Epoch 2* data will be presented at the conference. Some runs of *Epoch 1* showed moderate evidence for periodicity whereas the run 18754 starting at April, 10 2000, 03:00 UTC, which corresponds to MJD 51644.125, showed the most noticeable evidence; the probability distribution is shown in Figure 2. The results of simultaneous off-source measurements from a region $+1.0°$ or $-1.0°$ in Declination away from the source position are shown as dotted lines in this plot, too. The maximum Rayleigh power of 8.40 occured at a test frequency of 0.80508 Hz and corresponds to a single chance probability of $1.19 \cdot 10^{-4}$. The X-ray pulsar frequency was measured by the RXTE satellite for MJD 51373.1 to be $(0.8079202 \pm 0.0000008)$ Hz (Vrtilek et al., 2001), so the periodicity of run 18754 is redshifted by about $0.35\,\%$[2]. It is interesting to mention that the time of observation corresponds to an orbital phase of $\Phi_{\rm orb} = 0.078$, which is near the time of egress from X-ray eclipse by the companion star Hz Her leaving the line of sight between the observer and the pulsar again.

Each test for periodicity was performed on runs of 20 minutes duration searching in a frequency band of $[0.804\,; 0.81]$ Hz; this yields a number of 7.2 independent fourier spacings (IFS). Taking the number of trials into account (analysed runs), which are 37 for *Epoch 1*, one gets - after multiplying the initial probability with a factor of 3 for oversampling - an overall chance probability of $9.06 \cdot 10^{-2}$ for the measured period in run 18754. Additionally to the periodicity, a slight excess of $1.2\,\sigma$ was found in this run (26 source and 18 underground events).

5 Discussion

Although the overall chance probability of the measured periodicity is not significant, it is interesting to note, that two earlier observations have been reported with (stronger) evidence for a periodicity at a similar orbital phase: A periodicity of (0.808586 ± 0.000027) Hz was measured by Gorham et al. (1986) with the Whippe Cherenkov telescope during the ingress of X-ray eclipse from $\Phi_{\rm orb} = 0.914$ to $\Phi_{\rm orb} = 0.962$. Due to the fact that the periodicity was seen for a long time during eclipse, they suggested a γ-ray production site away from the X-ray production site, because high energy particles could not penetrate the companion star's limb at this state of eclipse anymore. Roberts et al. (1993) also reported evidence for a periodicity in the CT of Adelaide data occuring in a run which was taken during $\Phi_{\rm orb} = 0.877 - 0.007$; the measured frequency of 0.80834 Hz was most evident during $\Phi_{\rm orb} = 0.93 - 0.974$ with a chance probability of $4 \cdot 10^{-3}$.

Two models of the companion star serving as a beam dump are described in Weekes (1988) and references therein: The interaction of high energetic particles from the pulsar with the atmosphere of the companion star crossing the line of sight is one possible mechanism, which would mainly occur at $\Phi_{\rm orb} \approx 0.2$ and $\Phi_{\rm orb} \approx 0.8$. In another scenario the charged particle beam of the pulsar separates matter from the companion which in turn serves as a beam dump itself.

[2]Due to sporadic changes in the X-ray frequency, especially during the ALS 1999/2000, an exact X-ray frequency for MJD 51644.125 could not be derived.

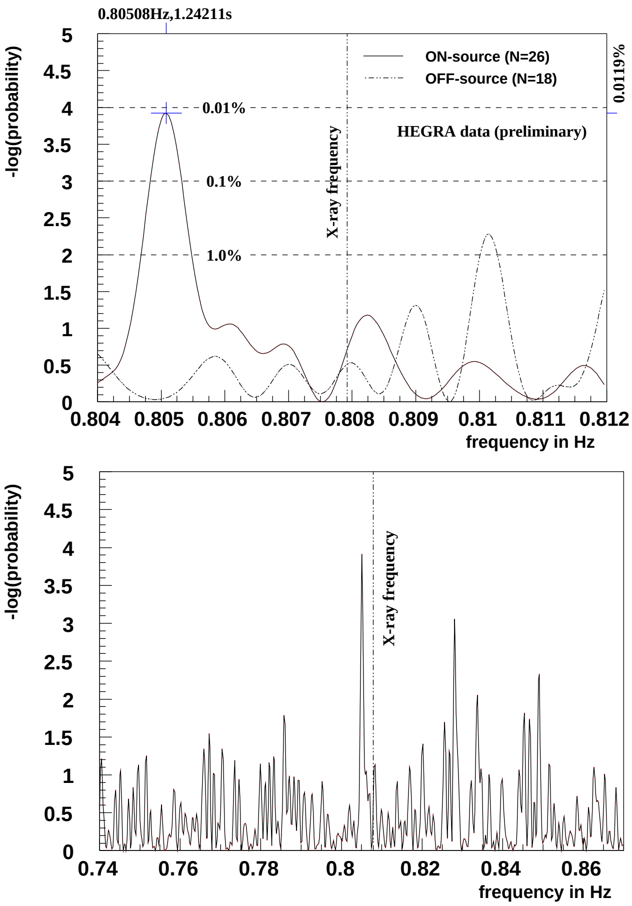

Fig. 2. The chance probability distribution of run 18754 out of *Epoch 1*, which started at April, 10 2000, 03:00 UTC (MJD 51644.125); the effect of oversampling and the number of total trials in the frequency search is not included in this probability distribution but is taken into account in the final result as described in the text. The solid line represents the signal from the source position of Her X-1 and the dotted line represents a reference off-source region observed simultaneously $+1.0^\circ$ or -1.0° in Declination away from the source position. The vertical line denotes the X-ray pulsar frequency of Her X-1 of $(0.8079202 \pm 0.0000008)$ Hz at MJD 51373.1 (Vrtilek et al., 2001). Upper plot: the results of the searched frequency interval is shown. Bottom plot: A wider frequency interval is shown for illustration purposes only.

Other reported claims of mostly blue shifted periods were explained by possible Kepler-orbiting target material out of the accretion disc near the corotation radius, which could serve as a beam dump for accelerated protons (Slane & Fry, 1989); this mechanism however would not be interrelated to the eclipse of the pulsar by the companion star.

6 Summary

A search for periodic emission from the Hz Her/Her X-1 binary in the HEGRA data of the years 1999-2001 taken with the system of five imaging air Cherenkov telescopes was performed. Since the observations took place during two distinct physical conditions of the binary system the data was separated into two distinct sets. The results presented in this paper only comprise the data of *Epoch 1* and should still be treated as preliminary. The run 18754 (20 min.) out of *Epoch 1*, which took place at $\Phi_{\rm orb} = 0.078$ near the time of X-ray eclipse egress, showed the most conspicuous evidence for periodicy in the data. The overall chance probability, however, is $9.06 \cdot 10^{-2}$.

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