THE VARIABLE SUPERORBITAL MODULATION OF CYGNUS X-1

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ABSTRACT

We study the superorbital modulation present in the Cygnus X-1 X-ray data, usually attributed to the precession of the accretion disk and relativistic jets. We find a new, strong, 326 ± 2 day period modulation starting in 2005, in Swift BAT and RXTE ASM light curves (LCs). We also investigate Vela 5B ASM and Ariel 5 ASM archival data and confirm the previously reported ∼290 day periodic modulation, therefore confirming that the superorbital period is not constant. Finally, we study RXTE ASM LC before 2005 and find that the previously reported ∼150 day period is most likely an artifact due to the use of a Fourier-power-based analysis under the assumption that the modulation has a constant period along the whole data sample. Instead, we find strong indications of several discrete changes of the precession period, happening in coincidence with soft and failed state transition episodes. We also find a hint of correlation between the period and the amplitude of the modulation. The detection of gamma rays above 100 GeV with MAGIC in 2006 September happened in coincidence with a maximum of the superorbital modulation. The next maximum will happen between 2008 July 2 and 14, when the observational conditions of Cygnus X-1 with ground-based Cerenkov telescopes, such as MAGIC and VERITAS, are optimal.

Subject headings: binaries: general — X-rays: individual (Cygnus X-1)

Online material: color figures

1. INTRODUCTION

Cygnus X-1 (Bowyer et al. 1965) is the best established candidate for a stellar mass black hole (BH). It is composed of a 21 ± 8 M\odot BH turning around an O9.7 Iab companion of 40 ± 10 M\odot (Ziołkowski 2005) in a circular orbit of 5.6 days (Brocksopp et al. 1999a). High-resolution radio imaging has unveiled the presence of a highly collimated, relativistic jet. The X-ray source displays soft and hard states and relatively frequent failed transitions between them. There is strong evidence of a high-energy nonthermal component extending up to soft gamma rays (McConnell et al. 2002; Cadolle Bel et al. 2006). The steady emission of gamma rays above 100 GeV is strongly constrained by observations with MAGIC, which has obtained, however, very strong evidence of an intense, fast flaring episode at these energies (Albert et al. 2007).

A ∼5.6 day period modulation, attributed to the orbital motion of the compact object around the companion, has been observed at various wavelengths by numerous authors (e.g., Pooley et al. 1999; Brocksopp et al. 1999a, 1999b; LaSala et al. 1998; Lachowicz et al. 2006). On the other hand, a superorbital ∼290 day period was claimed by Friedhorsky et al. (1983) on the soft X-ray data recorded by Vela 5B ASM (1969–1979) and Ariel 5 ASM (1974–1980). Later, a ∼150 day periodic variability has been reported by various authors (Pooley et al. 1999; Brocksopp et al. 1999b; Ozdemir & Demircan 2001; Benlloch et al. 2001, 2004; Lachowicz et al. 2006) using different data samples ranging between 1991 April and 2003 November. It must be noted, however, that other significant modulations with periods ∼200 and ∼420 days have been also found (e.g., Benlloch et al. 2001, 2004; Lachowicz et al. 2006).

In this Letter, we search the latest Cygnus X-1 X-ray data for periodic modulations. We also perform a critical revision of the previous results obtained from archival X-ray data. Finally, we put our results in the context of a multiwavelength description of the source.

2. DATA SAMPLES

The data samples analyzed in this work are summarized in Table 1. They are available through the High Energy Astrophysics Archive Research Center (HEASARC). We use data from four different instruments, namely, Vela 5B ASM, Ariel 5 ASM, RXTE ASM, and Swift BAT. All data are averaged into 1 day bins, except when explicitly stated. No periodic behavior is found in the X-ray data during the soft state (Wen et al. 1999; Lachowicz et al. 2006) and therefore we analyze data corresponding to the hard-state data only. The interval MJD 42338–42829 is dominated by soft flare events (Liang & Nolan 1984) and hence excluded from Vela 5B ASM and Ariel 5 ASM analyses. The soft-state periods during the operation of RXTE ASM are identified as those for which the ratio of count rates in the bands C (5.0–12.1 keV) and A (1.3–3.0 keV) is lower than 1.2 and the total count rate exceeds the mean value by more than 4 standard deviations. The mean and standard deviations are computed from the interval MJD 50660–50990 (Lachowicz et al. 2006). This excludes from the analysis the following periods (MJD): 50087–50327, 50645–50652, 51002–51026, 51369–51397, 51445–51625, 51776–51952, 52093–52584, 52762–52878, 52982–53092, 53198–53528, and 53780–53872. After this, two long intervals dominated by the hard state (samples 1 and 2 in Table 1) are defined and studied separately. Based on the results for RXTE ASM, the intervals 53414–53528 and 53780–53872 are also removed from the analysis of the Swift BAT LC.

3. ANALYSIS

We search the different data samples for periodic signals using the Lomb-Scargle (L-S) test of uniformity (Lomb 1976; Scargle 1982). The chance probability is the probability of obtaining a certain L-S test value (z0) or larger out of a purely
given by \( P_{\text{post}}(z > z_0) = e^{-z_0^2} \). When several frequencies are inspected, the post-trial probability, i.e., the probability of getting an L-S test value \( z_0 \) or higher for at least one of the scanned frequencies, is given then by \( P_{\text{post}}(z > z_0) = 1 - [1 - P_{\text{post}}(z > z_0)]^n \) where \( n \) is the number of independent scanned frequencies.

Given \( m \) data points, there is a discrete finite set of \( m/2 \) independent frequencies. For the case of evenly spaced data there is a natural set of frequencies: \( p_k = k/T \) (\( k = 1, \ldots, m/2 \)) where \( T \) is the time spanned by the data set. The values of the Fourier transform powers for the natural frequencies are independent of one another. The data set does not contain enough information to search for periodicities below \( n \) times the frequency. The horizontal line marks the line corresponding to a post-trial chance probability. Figure 1 shows the pretrial chance probabilities for such a modulation are \( 10^{-0.1} \) and \( 10^{-1} \) for RXTE ASM and Swift BAT data, respectively. Figure 1 shows the ~150 day modulation as found by Lachowicz et al. (2006) overlaid with RXTE ASM 2 LC, confirming that such a modulation does not reproduce well the data.

The phaseograms corresponding to the 326 day period are shown in Figure 3. We see that hard and soft X-ray LCs are strongly correlated, with Pearson’s correlation factor \( r = 0.97 \). A second, also strong, component with period ~1000 days is present in both data samples. This corresponds to a long-term modulation of the X-ray flux with respect to the 326 day oscillation, but cannot be established as periodic since the period is similar to the total time spanned by the observations. An alternative explanation to the ~1000 day period will be given below. Finally, a third component is seen in the RXTE ASM 2 data sample at period ~5.6 days, compatible with the orbital modulation, visible in the periodogram (Fig. 1) even before prewhitening. This mod-

### TABLE 1

**CYGNUS X-1 Analyzed Data**

| Instrument/Subsample | Energy (keV) | Operation Time | Start (MJD) | End (MJD) | Time Span (days) | Number of Points | Peak Post-trial Chance (day^-1) | Peak Pretrial Chance (day^-1) |
|----------------------|-------------|----------------|------------|-----------|-----------------|-----------------|---------------------------------|-------------------------------|
| Vela 5B/ASM          | 3–12        | 1969 May–1976 Jun | 40368      | 3675      | 1097            | 2.7 x 10^-4     | 0.15                            |
| Ariel 5/ASM          | 3–6         | 1976 Feb–1980 Feb | 42830      | 1464      | 740             | 6.8 x 10^-4     | 0.25                            |
| RXTE/ASM 1           | 2–10        | 1996 Sep–1999 Sep | 50328      | 1117      | 913             | 9.0 x 10^-4     | 0.41                            |
| RXTE/ASM 2           | 2–10        | 2005 Jun–2008 May | 53529      | 1064      | 909             | 9.4 x 10^-4     | 0.43                            |
| Swift/BAT            | 15–150      | 2005 Jun–2008 May | 53529      | 1070      | 829             | 9.3 x 10^-4     | 0.39                            |

### TABLE 2

**RESULTS FOR PERIODIC SIGNAL SEARCH**

| Sample       | \( T_p \) (days) | \( \Delta \) \( T_p \) (days) | \( A \) (%) | \( P_{\text{peak}} \) |
|--------------|-----------------|-----------------------------|-----------|----------------|
| Swift/BAT    | 326 ± 2         | 1030 ± 50                   | 25        | 10^-16 |
| RXTE/ASM 2   | 326 ± 2         | 54027.3                     | 29        | 10^-10 |
| RXTE/ASM 1 a | 53670.7         | 13                          | 5         | 10^-10 |
| RXTE/ASM 1 b | 53670.3         | 11                          | 1         | 10^-10 |
| RXTE/ASM 1 c | 51177.6         | 18                          | 10        | 10^-10 |
| RXTE/ASM 1 d | 51177.1         | 4.1                         | 4.1       | 10^-10 |
| Ariel 5/ASM  | 276 ± 3         | 42865.8                     | 14        | 10^-10 |
| Vela 5B/ASM  | 288 ± 3         | 40187.4                     | 21        | 10^-10 |

*Fig. 1—Periodograms for Swift BAT and RXTE ASM 2 Cygnus X-1 samples, showing the post-trial chance probability as a function of the scanned frequency. The horizontal line marks the line corresponding to a post-trial probability of 10^-3. The arrow marks the orbital frequency. [See the electronic edition of the Journal for a color version of this figure.]*
ulation is not seen in Swift BAT data, for which $P_{\text{prec}} \approx 10^{-2}$. On a similar energy band, Paciesas et al. (1997) claimed a modulation compatible with the orbital period in the CGRO BATSE LC between 1991 April and 1996 September, but the method used lacks a mathematical justification. Brocksopp et al. (1999b) did not find any evidence for the orbital modulation in CGRO BATSE data between 1996 May and 1998 September. Finally, Lachowicz et al. (2006), using the whole BATSE light curve, did not find any evidence for the orbital modulation in the data.

We have searched Vela 5B ASM and Ariel 5 ASM LCs for periodic modulations and found peaks at $P = 276 \pm 3$ and $288 \pm 3$ days, respectively (see Table 2), in agreement with the results obtained by Priedhorsky et al. (1983) and Lachowicz et al. (2006). By comparison with the $P = 326 \pm 2$ days periodic modulation found by Lachowicz et al. (2006). The vertical line marks the time of the TeV signal reported by Albert et al. (2007). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 2](https://example.com/f2.png)

Fig. 2.—Swift BAT and RXTE ASM 2 LCs. The shaded area shows an interval of soft state, identified by the criteria exposed in § 2, and not considered in the analysis. The thick curves are the fits by cosine functions to each subsample (see § 3). The thin curve represents the ∼150 day superorbital modulation using the ephemeris found by Lachowicz et al. (2006). The vertical line marks the time of the TeV signal reported by Albert et al. (2007). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 3](https://example.com/f3.png)

Fig. 3.—Top to bottom: Swift BAT, RXTE ASM 2, Ariel 5 ASM, and Vela 5B ASM phaseograms folded using period $P$ and time 0 values ($P$ days, $T_0$ [MJD]) = (326, 54027), (326, 54027), (276, 42866), and (288, 40187), respectively. The values of $T_0$ are obtained from the fit of a cosine function. Data points and error bars correspond, respectively, to the mean count rate and variance measured within each phase bin. The vertical, dashed line corresponds to the phase of the TeV signal reported by Albert et al. (2007). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 4](https://example.com/f4.png)

Fig. 4.—RXTE ASM 1 light curve. The vertical shaded lines show the intervals of soft or failed transition states, identified by the criteria exposed in § 2, which delimit the three subsamples (1a, 1b, and 1c) used for further analysis. The curves are the fits by cosine functions to each subsample (see § 3). [See the electronic edition of the Journal for a color version of this figure.]

The understanding of the superorbital modulation can be greatly simplified if we consider that the period can change along the observation time in a discrete way. We have analyzed separately the data between each two consecutive soft or failed transition states, i.e., three samples, namely 1a = 50328–50644, 1b = 50653–51001, and 1c = 51027–51368 (see Fig. 4). We obtain present in the Swift BAT and RXTE ASM 2 LCs, this shows that the period of the superorbital modulation is variable. The corresponding phaseograms are shown in Figure 3 (two lowest panels). Even if the relative dispersion of the points is larger due to the lower sensitivity of Ariel 5 ASM and Vela 5B ASM, the waveform is still visible. They follow a shape very similar to those found for Swift BAT and RXTE ASM 2, albeit for a different period, as one expects if the underlying physical process is the same. The correlation factor for the Swift BAT and Ariel 5 ASM (Vela 5B ASM) phaseograms is $r = 0.73$ ($r = 0.57$). However, the modulation amplitudes are significantly lower than for the case of RXTE ASM. This could have a physical explanation, but it could also happen if the periodic modulation was not present in part of the LCs, which can be certainly not excluded. On the other hand, we do not find evidence for the orbital period in the Vela 5B ASM or Ariel 5 ASM LCs. It is worth noting that, given Vela 5B ASM and Ariel 5 ASM sensitivities, we do not expect to detect an orbital modulation with an amplitude of ∼5% as the one we see in RXTE ASM 2 data. The mean relative variances of the data points in the phaseogram (which is a good estimate of the measurement error) are 46% and 13% for Vela 5B ASM and Ariel 5 ASM, respectively. Both values are well above the 5% modulation, which is hence difficult to detect. We have cross-checked this by analyzing Monte Carlo (MC) simulated LCs for Vela 5B ASM and Ariel 5 ASM. We use the same sampling as the measured LCs and simulate a 5% amplitude modulation convolved with 46% and 13% point-to-point random fluctuations, respectively. The analysis of these LCs yields no significant peak.

Finally, we have searched the RXTE ASM 1 data sample for periodic modulations, and found five significant peaks at $P = 148 \pm 1, 188 \pm 2, 310 \pm 11, 475 \pm 11,$ and $5.598 \pm 0.003$ days, all with chance probabilities lower than $10^{-10}$. The latter corresponds to the orbital modulation, whereas the other four seem to denote a complex power spectrum. We stress that some of these peaks have been found in previous studies of the RXTE ASM LC (Benlloch et al. 2001, 2004; Lachowicz et al. 2006). The understanding of the superorbital modulation can be greatly simplified if we consider that the period can change along the observation time in a discrete way. We have analyzed separately the data between each two consecutive soft or failed transition states, i.e., three samples, namely 1a = 50328–50644, 1b = 50653–51001, and 1c = 51027–51368 (see Fig. 4). We obtain

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1 We note that shorter integration times have been used for this search in the Vela 5B ASM LC since, with 1 day bins, the minimum accessible period is $P = 6.7$ days, as shown in Table 1.
According to our findings, the very much cited coincidence with soft or failed state transition phases, over with a period that changes, probably in a discrete way and in the results of analyzing the real data. We note that this effect could be also responsible for the ∼1000 day periodicity of the Swift BAT and RXTE ASM 2 data, since they also contain a soft-state episode that might have changed the period of the superorbital modulation prior to MJD = 53780.

5. DISCUSSION

We find that Cygnus X-1 displays a superorbital modulation, with a period that changes in a discrete way and in coincidence with soft or failed state transition phases, over timescales ranging from a few hundred days to several years. According to our findings, the very much cited ∼150 day period is most probably an artifact of applying a (sometimes biased) Fourier-transform-based analysis to a data sample where more than one consecutive period modulation is present. Since 2005, Cygnus X-1 has shown a very powerful and stable superorbital modulation with a period of 326 ± 2 days.

The superorbital modulation is usually attributed to the precession of the accretion disk (Priedhorsky et al. 1983) and relativistic jet (Romero et al. 2002), as a result of the tidal forces exerted by the companion star on a tilted disk (Katz 1973). A mechanism for keeping the disk tilted can be provided by radiation pressure warping (Pettersen 1977; Pringle 1996; Wijers & Pringle 1999; Ogilvie & Dubus 2001). In the case of tidally forced precession, the expected period depends on the outer radius $R$ and inclination of the disk $i$ as $P_{\text{prec}} \propto R^{3/2} \cos^{-1} i$ (Larwood 1998). Then, the longer the period the larger the precession angle, and hence also a larger modulation amplitude is expected. This is in agreement with our results for RXTE ASM, where we have found four different superorbital periods, which follow this tendency (see Table 2 and Fig. 4).

A different issue is why the precession of the disk produces a modulation in the X-ray flux. Some authors (e.g., Lachowicz et al. 2006; Ibragimov et al. 2007) have considered the possibility that the precession movement changes the optical thickness along the line of sight. They reject this possibility since it seems unlikely due to the fine-tuning required to produce the observed modulation amplitude, which in addition should depend on the energy, which is not confirmed by our results. The multiwavelength data seem to support a scenario where the emission itself is anisotropic. The precession modulation is detected at similar times with identical periods in radio, soft, and hard X-rays during the hard state. A unified picture, where the anisotropy is provided by the jet, has been proposed by Brocksopp et al. (1999b). The soft X-ray photons are produced in the disk via bremsstrahlung of thermal electrons, and are then upscattered to higher energies via Compton scattering in the hot corona or at the base of the relativistic jet (which precesses with the disk). The acceleration of electrons along magnetic field lines in the jet produces the radio emission by synchrotron emission. During the soft state, the jets and corona disappear and no modulation is observed. According to our findings, once the source goes back to the hard state, the re-constructed disk and jet have different kinematical properties, and the modulation period changes. It seems that failed transitions produce a similar effect.

MAGIC detected a fast and intense episode of emission of gamma rays above 100 GeV (Albert et al. 2007) during MJD = 54003, albeit at the limit of the telescope’s sensitivity. This happened in coincidence with the soft and hard X-ray maxima (Figs. 2 and 3) and an unusually bright outburst detected with INTEGRAL (Malzac et al. 2008). It is interesting to note that, according to the ephemeris shown in Table 2, the next passage for the precession maximum will happen at MJD = 54655 ± 2, i.e., between 2008 July 6 and 10. The observational conditions of Cygnus X-1 with ground-based Cerenkov telescopes, such as MAGIC and VERITAS, will be optimal during those days.

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REFERENCES

Albert, J., et al. 2007, ApJ, 665, L51
Benlloch, S., et al. 2001, in Exploring the Gamma-Ray Universe, ed. B. Battrick et al. (ESA SP-459; Noordwijk: ESA), 263
———. 2004, in AIP Conf. Proc. 714, X-Ray Timing 2003, ed. P. Kaaret et al. (New York: AIP), 61
Browoy, S., Byram, E. T., Chubb, T. A., & Friedman, H. 1965, Science, 147, 394
Brocksopp, C., et al. 1999a, MNRAS, 309, 1063
———. 1999b, A&A, 343, 861
Cadolle Bel, M., et al. 2006, A&A, 446, 591
Davison, A. C., & Hinkley, D. 2006, Bootstrap Methods and Their Applications (8th ed.; Cambridge: Cambridge Univ. Press)
Gallo, E., et al. 2005, Nature, 436, 819
Ibragimov, A., Zdziarski, A., & Poutanen, J. 2007, MNRAS, 381, 723
Katz, J. I. 1973, Nature Phys. Sci., 246, 87
Lachowicz, P., et al. 2006, MNRAS, 368, 1025
Larwood, L. 1998, MNRAS, 299, L32
LaSala, J., et al. 1998, MNRAS, 301, 285
Liang, E. P., & Nolan, P. L. 1984, Space Sci. Rev., 38, 353
Lomb, N. R. 1976, Ap&SS, 39, 447
Malzac, J., et al. 2008, A&A, submitted (arXiv:0805.4391v1)
McConnell, M. L., et al. 2002, ApJ, 572, 984
Ogilvie, G. I., & Dubus, G. 2001, MNRAS, 320, 485
Ozdemir, S., & Demircan, O. 2001, Ap&SS, 278, 319
Paciesas, W. S., et al. 1997, in AIP Conf. Ser. 410, Proc. 4th Compton Symp., ed. C. D. Dermer et al. (New York: AIP), 834
Pettersen, J. A. 1977, ApJ, 216, 827
Pooley, G. G., Fender, R. P., & Brocksopp, C. 1999, MNRAS, 302, L1
Priedhorsky, W. W., Terrel, J., & Holt, S. S. 1983, ApJ, 270, 233
Pringle, J. E. 1996, MNRAS, 281, 357
Romero, G. E., Kaufman Bernadó, M. M., & Mirabel, F. 2002, A&A, 393, L61
Scargle, J. D. 1982, ApJ, 263, 835
Stirling, A. M., et al. 2001, MNRAS, 327, 1273
Wen, L., Cui, W., Levine, A. M., & Bradt, H. V. 1999, ApJ, 525, 968
Wijers, R. A. M. J., & Pringle, J. E. 1999, MNRAS, 308, 207
Zio´łkowski, J. 2005, MNRAS, 358, 851