THE CESSATION OF FICKERING DURING DIPS IN CYGNUS X-1

M. BALUCIŃSKA-CHURCH,1,2 T. TAKAHASHI,2 Y. UEDA,2 M. J. CHURCH,1,2 T. DOTANI,2 K. MITSUDA,2 AND H. INOUE2

Received 1996 December 10; accepted 1997 February 20

ABSTRACT

We report the discovery of the cessation of flickering in dips in the black hole candidate Cygnus X-1, detected for the first time in the ASCA observation of 1995 May 9. During this observation, particularly deep dipping took place, which resulted in strong changes in hardness ratio corresponding to the absorption of the power-law spectral component. The dead time corrected light curve with high time resolution clearly shows a dramatic decrease in the extent of flickering in the 0.7–4.0 keV band during dipping, but in the 4.0–10.0 keV band, there is relatively little change. We show that the rms flickering amplitude in the 0.7–4.0 keV band is proportional to the X-ray intensity in this band, which changes by a factor of almost 3. This is direct evidence that the strong low-state flickering is intrinsic to the power-law emission; i.e., it plays as part of the emission process. The rms amplitude is proportional to the intensity in the low-energy band, except for a possible deviation from linearity at the lower intensities. If confirmed, this nonlinearity could imply a process such as electron scattering of radiation, which will tend to smear out the fluctuations, or a process of fluctuation generation which depends on radial position in the source. Thus, timing observations during absorption dips can give information about the source region and may place constraints on its size.

Subject headings: accretion, accretion disks — binaries: close — circumstellar matter — scattering — stars: individual (Cygnus X-1) — X-rays: stars

1. INTRODUCTION

Cygnus X-1 is well known as one of the best Galactic black hole candidates, with a mass of the compact object in the range 4.8–14.7 $M_\odot$ (Herrero et al. 1995). It is highly variable, and on timescales of weeks and years, it shows at least two luminosity states: a low state in which it spends most of its time, and a high state with a much softer spectrum (see review by Tanaka & Lewin 1995). There can also be transient reductions in X-ray flux lasting several minutes, i.e., X-ray dips, during which the spectrum hardens, which shows that these are due to absorption (Kitamoto et al. 1984). The X-ray spectrum of Cygnus X-1 is complex, consisting in the low state of a hard, underlying power law, a reflection component (Done et al. 1992), and a soft excess (Balucinska & Hasinger 1991). It was previously shown that in a ROSAT observation, $kT_{bb}$ for the soft excess agreed well with the characteristic temperature of the inner accretion disk for the low-luminosity state of the source, which indicates that the soft excess was disk emission (Balucinska-Church et al. 1995). The source also shows rapid time variations on timescales from milliseconds to 10s of seconds. This rapid aperiodic variability, often called flickering, was discovered in Cygnus X-1 by Oda et al. (1971). Since then, there have been extensive studies of such variability in various black hole candidates, and it is generally accepted that the flickering phenomenon originates in the neighborhood of the inner accretion disk, although the mechanism is not clear. The strength of variability may be quantified in terms of the fractional rms amplitude $\sigma/X_\nu$, and values of 30%–50% are typical of the low state of Cygnus X-1 (Belloni & Hasinger 1990). The evidence is that this strong variability arises in the hard power-law spectral component that dominates the high state shows little variability (van der Klis 1995). In Cygnus X-1, previously no major variation of the flickering has been detected during a particular observation. This Letter contains results of a 13 hr continuous observation of Cygnus X-1 by ASCA during which strong dipping took place, and we show that the amplitude of flickering decreased dramatically in dips.

2. RESULTS

2.1. Spectral Analysis of Dip Evolution

The observation was made on 1995 May 9 by the satellite ASCA (Tanaka, Inoue, & Holt 1994). Data were collected with the GIS detectors (Ohashi et al. 1996) and the SIS detectors, although only GIS data are discussed here. At ~19:00 UT, dipping took place and lasted approximately 40 minutes. The dead time corrected light curves of the strongest dips are shown in Figure 1 in an expanded view with 1 s binning. The details of the dip light curves are given in two bands: 0.7–4.0 keV and 4.0–10.0 keV, together with the hardness ratio formed by dividing these.

Three dips can be seen, lasting 2–3 minutes, in each of which there is a strong increase in hardness ratio associated with the photoelectric absorption taking place. We have analyzed the spectral changes in dipping by dividing the data into seven intensity bands including nondip emission, selected in a time interval including the strong third dip in Figure 1, and nondip data on each side of the dip. Spectral analysis of the intensity-selected spectra in the 0.7–4.0 keV band were carried out using a blackbody to represent the soft excess and a power law to represent the hard component, since in this band, the reflection component makes little contribution. Using the nondip data, it was found that the value of the blackbody temperature of the soft excess was well constrained, with $kT_{bb} = 0.13 \pm 0.01$ keV (Balucinska-Church et al. 1997). The dip data required a model in which partial covering of the power law took place. Dipping was seen to be due primarily to
absorption of the major power-law component with $N_H$ increasing from $8.9^{+1.5}_{-1.0} \times 10^{21}$ H atom cm$^{-2}$ in nondip to $72^{+11}_{-9} \times 10^{21}$ H atom cm$^{-2}$ in the deepest part of dipping, when the partial covering fraction was $\sim 70\%$. We were not able to constrain very well possible changes in absorption of the blackbody taking place at energies below the ASCA band.

2.2. Phase of Dipping

The value of phase that we calculated for the observed dipping using the ephemeris of Gies & Bolton (1982) was $0.70 \pm 0.02$. Dipping has previously been seen at around phase zero, consistent with inferior conjunction with the companion. However, we cannot be definite about the actual phase because of the errors involved in extrapolating this ephemeris to the date of the observation. This is especially the case because of the possibility that the orbital period is changing, as suggested by Ninkov, Walker, & Yang (1987), based on analysis of all data available at that time. This will not be resolved until there is a new determination of the ephemeris. It is important to decide this point, since dipping at phase $\sim 0.7$ would imply absorption in the stellar wind of the companion.

2.3. Cessation of Flickering

The striking effect that flickering essentially stops in the deepest part of the dipping is obvious in Figure 1, particularly in the third dip, which is the strongest. In the lower energy band 0.7–4.0 keV, it can be seen that flickering on timescales longer than the 1 s binning has an amplitude of 200 counts s$^{-1}$ in nondip emission, i.e., the soft X-ray intensity rises from 200 to 400 counts s$^{-1}$. However, in dipping it can be seen that this amplitude decreases considerably. The effect is less obvious in the higher energy band 4.0–10.0 keV, although there may be some small decrease in amplitude at the third dip.

We have also plotted the data as a function of time in the observation by evaluating the rms amplitude of the variability in 1 s bins in a running 85 s section of data and also evaluating a running mean of the intensity in these 85 s sections. This is shown in Figure 2 for the lower energy band 0.7–4.0 keV. The middle panel shows the unintegrated light curve with 1 s binning, and the bottom panel shows the integrated average values in 85 s time bins. There is some underestimation of the depth of dipping in the averaged light curve and also of the depth of dipping in the rms amplitude plot as a result of smoothing over a long time bin. However, it is clear that there is a good correspondence between amplitude and intensity.

To demonstrate the effect more clearly, the data are replotted in Figures 3(left) and 3(right). In Figure 3(left), the X-ray intensities in the soft band and the hard band are plotted against hardness ratio, so that dipping corresponds to the high values of hardness ratio. It is clear that the peak-to-peak variation in the X-ray intensity falls sharply as dipping takes place. This is shown more clearly in Figure 3(right) in which the rms amplitude of intensity variation is plotted against hardness ratio for the two energy bands. This was produced by evaluating the rms deviation of the variability of the data selected within a narrow band of hardness ratio. First, it can be seen that the nondip value of the amplitude of 60 counts s$^{-1}$ with a nondip count rate of 200 counts s$^{-1}$ in the low band gives a fractional rms amplitude of 30%, which is quite typical for the low state of Cygnus X-1. There is a strong decrease of the amplitude at low energy but with little change at high energies.

To show this more clearly, we plot rms amplitude against X-ray intensity for the two energy bands in Figure 4. Poisson noise is subtracted from the rms, and an approximate correction to the intensity is also made for the dust-scattered halo in the band 0.7–4.0 keV based on the work of Predehl & Schmitt (1995). The scattered component is not expected to show flickering as this will be smoothed out by the variable time delays. We estimate that the contribution to the intensity of

![Image](https://example.com/image.png)
the nonflickering component in this energy band is \( \sim 6\% \). The data in the low band are generally consistent with a simple relationship between the variability and intensity that changes by almost a factor of 3 owing to photoelectric absorption. However, the points at lowest dip intensity fall below a linear relationship, and in terms of the 1 \( \sigma \) errors plotted, the lowest two points are an average of 1.8 \( \sigma \) below the straight line. Thus, the presence of a departure from linearity is likely, but not proved. In the high-energy band, the amplitude remains constant, and there is little change in intensity since the increase in \( N_e \) in the dip has little effect in this band.

Thus, the reduction in rms amplitude simply reflects the decreasing power-law intensity in the dips due to photoelectric absorption, which is strong in the low-energy band but has little effect in the high band. Furthermore, if in the 0.7–4.0 keV band the rms amplitude is divided by the intensity, the fractional rms amplitude is approximately constant, as expected from the approximate linearity of Figure 4(left),

Fig. 2.—Top: rms flickering amplitude evaluated in an 85 s time bin running through the observation. Middle: the unsmoothed X-ray light curve in the 0.7–4.0 keV band. Bottom: running 85 s means of the light curve.

Fig. 3.—Left: Intensity vs. hardness ratio in the same two energy bands as in Fig. 1. Right: rms flickering amplitude in counts s\(^{-1}\) vs. hardness ratio.
which indicates the simple relation between amplitude and intensity.

3. DISCUSSION

We have demonstrated for the first time the cessation of flickering during deep dipping in Cyg X-1. The fractional rms amplitude of the variability is about 30% in the nondip emission, a typical value for the low state. In the 0.7–4.0 keV energy band, there are two spectral components: the soft excess blackbody and the power law. Taking typical parameters for the soft excess, as determined from ASCA and ROSAT (Balucińska-Church et al. 1995), we can estimate that this contributes only 8% of the count rate in the 0.7–4.0 keV band. Thus, it is clear that the power law must be involved in the variability, and the linearity implies that the variability originates in the power-law emission region, not external to this.

Second, we have shown that the change in the strength of variability is simply related to the total intensity (dominated by the power-law component), which changes by almost a factor of 3 in the 0.7–4.0 keV energy band owing to photoelectric absorption. This is consistent with the simple expectation that, if the intensity falls by a given factor due to photoelectric absorption, then absorption will reduce the variability by the same factor. The departure from linearity in Figure 4, if substantiated, may reveal further information about the source, and so we discuss below possible reasons for this nonlinearity. First, we have not attempted to correct the data for the contribution to the flickering or to the intensity of the soft excess. The flickering in this component may well be very much less than in the power law. However, because the soft excess, with $kT_{\text{bb}} = 0.13$ keV, contributes only at the lowest energies in the ASCA band (below 1.5 keV), it will be totally removed by absorption at an early stage of dipping. Thus, at total intensities below 150 counts s$^{-1}$ in Figure 4, only the power-law component remains, and the plot becomes a plot of power-law rms versus power-law intensity, and so the curvature below 100 counts s$^{-1}$ is unlikely to be related to the soft excess spectral component. This depends only on the reasonable assumption that this component originates in the central part of the source and so is covered by the absorber during dipping. However, there are effects that can lead to curvature in the plot at low values of intensity. First, the geometry of the absorber causing the absorption dip may be such as to cover the central part of the emission regions only, as suggested by our result that the partial covering fraction rises to only 70% in the deepest parts of dips. If the process generating the flickering were to fall off with distance from the center of the emission region, then the uncovered part of the emission will have reduced flickering in dipping, which would lead to curvature in the plot.

Second, electron scattering close to the source region could produce an effect. If part of the power-law X-ray emission gets scattered, then the fast variability will tend to get smeared out. In 1 s time bins, we are determining the rms of longer lasting shots more than $\sim$200 ms in length, although the exact timescale depends on the shot profile. Kitamoto et al. (1984) argued from the timescales of ingress to and egress from dipping in high time resolution Tenma observations that the major source region was smaller than $4 \times 10^8$ cm. Scattering in this region would introduce a variable delay of up to 13 ms, which would cause some reduction of flickering in the scattered component for the longer shots. However, a region of size $4 \times 10^8$ cm is very small in comparison with typical sizes of accretion disk coronae, for example, and if the scattering region was only as large as $4 \times 10^7$ cm, there would be a delay of 130 ms that would cause a major reduction of flickering in the scattered component. Then, as the source is only 70% covered in deep dipping, this component would not be completely absorbed but would have reduced variability, which would lead to curvature in the plot of rms versus intensity.

![Fig. 4.—Root mean square amplitude vs. X-ray intensity (left) in the 0.7–4.0 keV band and (right) in the 4.0–10.0 keV band.](image-url)
Analysis of the present data constitutes only a first attempt at investigating the results of absorption on the fast aperiodic variability. In principle, this can provide information on the origins of the variability, on the relation between the spectral components and the variability, on the extent to which the source is covered by the absorber, and on possible effects such as electron scattering. Further more detailed work may resolve some of these aspects.

REFERENCES

Balucinska, M., & Hasinger, G. 1991, A&A, 241, 439
Balucinska-Church, M., Belloni, T., Church, M. J., & Hasinger, G. 1995, A&A, 302, L5
Balucinska-Church, M., et al. 1997, in Proc. of Conf. on X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas, ed. F. Makino & K. Mitsuda (Tokyo: Universal Academy), 487
Belloni, T., & Hasinger, G. 1990, A&A, 227, L33
Done, C., Mulchaey, J. S., Mushotzky, R. F., & Arnaud, K. A. 1992, ApJ, 395, 275
Gies, D. R., & Bolton, C. T. 1992, ApJ, 260, 240
Herrero, A., Kudritzki, R. P., Gabler, R., Vilchez, J. M., & Gabler, A. 1995, A&A, 297, 556

Kitamoto, S., et al. 1984, PASJ, 36, 731
Ninkov, Z., Walker, G. A. H., & Yang, S. 1987, ApJ, 321, 425
Oda, M., et al. 1971, ApJ, 166, L1
Ohashi, T., et al. 1996, PASJ, 48, 157
Predehl, P., & Schmitt, J. H. M. 1995, A&A, 293, 889
Tanaka, Y., Inoue, H., & Holt S. S. 1994, PASJ, 46, L37
Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126
van der Klis, M. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 252