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HOW TO DETERMINE THE PRECESSION OF THE INNER ACCRETION DISK IN CYGNUS X-1

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ABSTRACT

We show that changes in the orientation of the inner accretion disk of Cygnus X-1 affect the shape of the broad Fe Kα emission line emitted from this object, in such a way that eV-level spectral resolution observations (such as those that will be carried out by the ASTRO-E2 satellite) can be used to analyze the dynamics of the disk. We here present a new diagnosis tool, supported by numerical simulations, by which short observations of Cygnus X-1, separated in time, can determine whether its accretion disk actually precesses, and if so, determine its period and precession angle. Knowing the precession parameters of Cygnus X-1 would result in a clarification of the origin of such precession, distinguishing between tidal and spin-spin coupling. This approach could also be used for similar studies in other microquasar systems.

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

1. INTRODUCTION

Cygnus X-1 is a 5.6-day X-ray binary that harbors the best studied black-hole candidate in the Galaxy. The mass of the accreting compact object has been estimated as ~ 10.1 $M_\odot$ and the donor star is classified as an O9.7 Iab supergiant of ~ 17.8 $M_\odot$ (Herrero et al. 1995). The system is located at ~ 2 kpc (e.g. Gierliński et al. 1999). The black hole accretes through the wind of the companion star. Most of the time, the X-ray source is in the so-called low/hard state, characterized by a relatively weak blackbody component peaking at a few keV plus a strong hard power-law of photon index ~ 1.6. A nonthermal radio jet has been observed in this state (Stirling et al. 2001), extending up to ~ 15 mas. The jet seems to form an average angle with the line of sight of $\sim 30^\circ$ (Fender 2001) and it has been suggested that it might be precessing (Stirling et al. 2001, Romero et al. 2002). Occasionally, a transition to a high/soft state can occur. In this state, most of the radiated energy is concentrated in the blackbody component, while the power-law component becomes softer, with an index of ~ 2.8 and no jet has been observed.

The usual interpretation of the X-ray behavior of the source is that the blackbody component is originated in a cold, optically thick accretion disk, whereas the power-law component is produced in an optically thin hot corona by thermal Comptonization of disk photons (Poutanen et al. 1997, Dove et al. 1997). The hot corona fills the inner few tens of gravitational radii around the compact object and the accretion disk would penetrate only marginally into the coronal region. In the low/hard state the thermal X-ray luminosity is dominated by the corona, with typical luminosities of $\sim$ a few times 10^{37} erg/s. During the transition to the high/soft state the corona is likely ejected as the accretion disk approaches to the black hole (Fender et al. 2004). Most of the energy is then dissipated by the disk, until the inner part is engulfed by the black hole and the cycle starts again.

In the low/hard state, the disk is illuminated by hard photons from the corona resulting in the production of an Fe Kα line and a Compton reflection feature. The first detection of the line was made by Barr et al. (1985) with *EXOSAT*. They reported a broad (FWHM ~ 1.2 keV) emission line at ~ 6.2 keV width an equivalent with of ~ 120 eV. Kitamoto et al. (1990) obtained a *Tenma* GSPC which was consistent with a narrow emission line at ~ 6.5 keV with an equivalent width of $60-80$ eV. A Compton reflection feature was then found above 20 keV (see Tanaka 1991 and references therein). The *Ginga* spectrum in the $2-30$ keV range can be fitted quite well by the sum of a power-law with index ~ 1.7, a reflection component and a narrow Fe emission line at 6.4 keV with an equivalent width of ~ 60 eV (Tanaka 1991). Subsequent *ASCA* observations confirmed these results but restricting the width to $10-30$ eV (Ebisawa et al. 1996). A broad edge at $E > 7$ keV was also reported.

Recently, *Chandra* observed Cygnus X-1 with the High Energy Transmission Grating Spectrometer in an intermediate X-ray state (Miller et al. 2002). The narrow Fe line was detected at $E = 6.415 \pm 0.007$ keV with an equivalent width of $W = 16^{+3}_{-2}$ eV, along with a broad line at $E = 5.82 \pm 0.07$ keV with $W = 140^{+70}_{-40}$ eV. A smeared edge was also detected at 7.3 ± 0.2 keV. Miller et al. (2002) interpret these results in terms of an accretion disk with irradiation of the inner disk producing the broad Fe Kα emission line and edge, and irradiation of the outer disk producing the narrow line. The broad line is shaped by Doppler and gravitational effects and, to a lesser extent, by Compton reflection.

Changes in the orientation of the inner accretion disk of Cygnus X-1 would affect the shape of the broad Fe Kα emission line in such a way that eV-level spectral resolution observations of the system (such as those that will be carried out by the ASTRO-E2 satellite, for which Cygnus X-1 is already in its target list) can be used to constrain the dynamics of the disk. We present theoretical calculations of the evolution of the Fe Kα emission line during the expected precession of the disk that can be used as a diagnosis tool to solve the problem of whether the accretion disk of Cygnus X-1 actually precesses, and if so, to determine its dynamics.

2. DISK PRECESSION IN CYNGUS X-1

Several X-ray binaries present periodic behavior in their light curves on timescales larger than the orbital period. Among these systems we can mention Her X-1, SS 433, and LMC X-4. It has been suggested that these long periods correspond to the precession of the accretion disk (e.g. Katz 1973). In the case of SS 433 the precession is directly measured on the jets, so if these are attached to the accretion disk it is reasonable to expect that the disk will also display precession (Katz 1980).

The mechanism that produces the precession might be the tidal force of the companion star on the disk when it is not coplanar with the binary orbit (Katz 1973, Larwood 1998, Kaufman Bernadó et al. 2002). Uniform disk precession will occur in this case only if the sound crossing time through the disk is considerably shorter than the characteristic precession period induced by the perturbing star. This allows the bending waves (which propagate at a velocity $v \sim c_s$ through the disk) to efficiently couple the different parts of the fluid in order to adjust the precession rate to a constant value (Papaloizou et al. 1998). This is in agreement with the numerical simulations performed by Larwood et al. (1996).

The precession velocity is given by (e.g. Romero et al. 2000):

$$|\Omega_p| \approx \frac{3}{4}\frac{Gm}{r_m^3}\frac{1}{\omega_d}\cos\theta, \qquad (1)$$

where G is the gravitational constant, r_m is the orbital radius, ω_d is the inner disk angular velocity, θ is the half-opening angle of the precession cone, and m is the mass of the star that exerts the torque upon the disk. The orbital period T_m is related with the involved masses and the size of the orbit by Kepler's law:

$$r_m^3 = \frac{G(m+M)T_m^2}{4\pi^2}, \qquad (2)$$

where M is the mass of the accreting object. The ratio between the orbital and the precessing periods can be related through the disk angular velocity $\omega_d = (GM/r_d^3)^{1/2}$:

$$\frac{T_m}{T_p} = \frac{3}{4}\frac{m}{M}\kappa^{3/2}\left(\frac{M}{m+M}\right)^{1/2}\cos\theta, \qquad (3)$$

where $T_p = 2\pi/\Omega_p$ and $\kappa = r_d/r_m$. Since $\kappa < 1$, normally $T_m/T_p < 1$ too. In the case of Cygnus X-1, Brocksopp et al. (1999) have reported multiwavelength evidence for the existence of a period of 142.0 ± 7.1 days. The optical and X-ray modulation points to precession of the disk, whereas the radio variations might be originated in the jet. In the next section we show how this precession affects the Fe Kα line.

3. FE K-α LINE PROFILE DIAGNOSIS

The use of emission lines as a diagnosis tool for the state of binary systems has been proposed in the past (e.g., for an investigation on black hole binarity, see Torres et al. 2003, also Gaskell 2003), but it was never presented as a viable method to extract the precession status of microquasars. Neither theoretical simulations nor observational capabilities existed before to allow for this as a feasible goal. We here show that this is no longer the case.

For the case of Cygnus X-1, we shall assume that the time-averaged disk inclination angle is 35^0, which is in agreement with the fitting of the system's Fe line (Miller et al. 2002). Values around this time-averaged inclination angle were also found for other systems (e.g., Her X-1, LMC X-4, SMC X-1, etc. e.g., as discussed by Larwood 1998). We also assume two extreme cases for the amplitude of the disk precession: (1) the disk inclination angle precesses from 31^0 to 39^0 (very low magnitude of the precession angle); (2) the disk inclination angle precesses from 5^0 to 65^0 (large magnitude of the precession angle). The amplitude of the precession of the inner disk should not be large if it is due to the tidal force of the secondary star and if the disk (especially the outer disk region) develop a significant warp. However, if the initial spin direction of the BH is significantly different from the orbital angular momentum direction, the inner disk, which is confined to the equatorial plane of the BH (if the spin is high) due to Bardeen-Peterson effect, may precess around the total angular momentum (dominated by the orbital angular momentum) with an amplitude as large as the initial orbital inclination angle with respect to the BH equatorial plane. If we assume that the disk is rigidly precessing around the total angular momentum (dominated by the orbital angular momentum), then the amplitude of the precession is also around 30^0.

Several calculations on the disk line profiles have been performed. We use a ray-tracing technique and elliptic integrals (Rauch & Blandford 1994; see also Yu & Lu 2000; Lu & Yu 2001 and references therein) to follow the trajectories of photons from the observer, keeping track of all coordinates until the photons either intersect the accretion disk plane, disappear below the event horizon, or escape to "infinity" (operationally defined to be $r = 1000GM/c^2$ away from the BH). We then calculate the redshift factor for a photon (to the observer) emitted from a particular position on the disk. The solid angle subtended at the observer by each disk element is also calculated. We set the inner radius of the disk to be at the marginally stable orbit and the outer radius at $160GM/c^2$. We assume that the surface emissivity of line photons follows a power-law, r^{-q}, with $q = 2.5$. Both, the power-law emissivity law and the size of the disk in Schwarszchild units, are usual assumptions (see, e.g., Nandra et al. 1997). The BH spin is assumed to be $a/M = 0.998$. In microquasar systems, both the high frequency quasi-periodic oscillation and relativistic lines suggest a high spin. In any case, we proved that if we were to assume a lower spin, there is not much qualitative difference for the problem we have studied here. With the above assumptions, we sum up all the photons received by the observer, which is emitted from each disk element, and obtain the profile of emergent Fe Kα lines, with different inclination angles from the Cygnus X-1 system, as shown in the Figure 1.

4. OBSERVING THE FE LINE PROFILE VARIATIONS

The complex X-ray spectrum of Cygnus X-1 revealed by the *Chandra* observation reported in Miller et al (2002) implies that the detection of minute variations in the Fe line shape will require a high spectral resolution instrument with large throughput. In what follows, we discuss the feasibility of detecting the precession of the accretion disk with *ASTRO-E2*, and specifically with the X-ray Spectrometer (XRS) consisting of an array of semiconductor-based calorimeters delivering the best spectral resolution to date at 6 keV (pre-flight value of 6.5 eV). *ASTRO-E2* is a JAXA/NASA mission to observe X-rays with unprecedented high spectral resolution imaging detectors, which is scheduled for launch by January/February 2005. The *ASTRO-E2* Science Working Group target list includes two observations of Cygnus X-1.

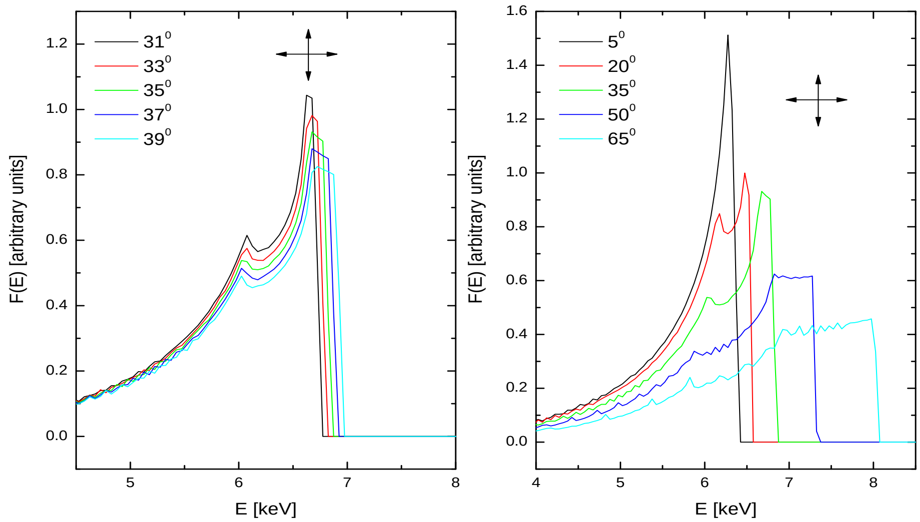

FIG. 1.— Shift in the Fe K-α line profile of Cyg X-1 as a function of different magnitudes of the precession angle. In the left panel, the line profiles (from right to left) are for inclination angles of 39^0, 37^0, 35^0, 33^0, and 31^0, respectively. In the right panel, the line profiles (from right to left) are for inclination angles of 65^0, 50^0, 35^0, 20^0, and 5^0, respectively. The total line flux of each lines is normalized to 1. The cross represents a periodicity prediction of the flux and edge of the line, following the precession angle.

As argued by Miller et al (2002) the spectrum of Cygnus X-1 is complex below 3 keV, where they did not succeed in fitting an appropriate model. All our discussion assumes the Be filter is on at the XRS. This removes low energy photons which are not needed for our purposes. In our analysis, we ignore photons below 3 keV and above 9 keV, to avoid uncertainties. In addition, we do not use the X-ray Imaging Spectrometers (XIS) on board *ASTRO-E2*, which are most sensitive to soft X-ray energies. A typical 50 ks exposure is assumed, and the (otherwise unknown) background is not included in the simulations. Prelaunch calibration redistribution matrices and efficiency curves have been downloaded from the *ASTRO-E2* web site at NASA[1].

The simulated model is that fitted by Miller et al. (2002) to the *Chandra* data. The continuum is a power law with $\Gamma = 1.8$, absorbed by a Galactic column of $N_H = 8.1\times10^{21}$ cm^{-2} (Dickey & Lockman 1990), which is absorbed by a smeared edge at 7.2 keV, with a width of 7 keV and a depth of 1.2. The narrow line component at 6.415 keV, believed to arise from the irradiated outer disk, has been simulated as a gaussian of width $\sigma_{\rm narrow} = 30$ eV. The broad line component has been simulated using the numerical models explained in the previous section, for a fixed equivalent width of 140 eV and a variety of disk inclination angles.

As expected, this model produces a very high count rate in the XRS, of the order of 60 ct/s. This count rate will be distributed among several XRS pixels, according to the PSF. Although the overall count rate is below the telemetry limit, the fraction of events that will be measured by the on-board software as medium or low resolution will be large ($\sim 30-40\%$). There are two possibilities to deal with this: either using the neutral density filter (which will decrease the overall count rate to an acceptable level of ~ 6 ct/s) or to ignore the few pixels with the higher count rates and work only with the pixels which have count rates below a few ct/s. Both of these procedures will result in an overall loss of throughput. This is why we also consider effective exposures of 10 and 5 ks.

To analyze the simulated data, we follow Miller et al (2002) to fit the continuum, by excluding the range from 4.0 to 7.2 keV. A single power law leaves enormous residuals which can be well fitted by the smeared absorption edge. In general, the edge energy is well reproduced by the fit (statistical 90% errors in the range of 50-150 eV depending on the effective exposure time), although there is substantial degeneracy between the width of the edge and its depth. This does not affect the continuum in the Fe emission line region.

Once the continuum is fitted, we include all data in the 3.0-9.0 energy band, and add a narrow gaussian emission line and a relativistic emission line (see Figure 2, left). Thanks to the superb spectral resolution of this instrument, the narrow line is very well characterized, with errors in its centroid actually limited by systematics (2 eV) rather than by statistics, even in a 5 ks exposure. The relativistic line model returns the disk inclination angle with a 90% error of 0.3 deg for a 50 ks exposure and 0.7 deg for a 5 ks exposure. This is due to the fact that the sharp drop in the blue edge of the line is very clearly marked by the XRS. Figure 2 (right panel) shows the differences in these sharp edges for a 50 ks exposure and various disk inclination angles. Note that these changes amount to about 50 eV per degree of disk inclination, and therefore the claimed limit in the systematics for line centering of 2 eV is really not an issue for this purpose. Table 1 summarizes the results of the fits to simulated data with 5, 10 and 50 ks net exposure and disk inclination of 35°.

5. CONCLUDING REMARKS

This work establishes a new diagnosis tool to solve the decade-old problem of whether the accretion disk of Cygnus X-1 (and of other microquasar systems) actually precesses or not, and if so, which is the period and precession angle. We show that the study of the periodic variations of the Fe Kα line, that would be unavoidably produced in the putatively precessing disk of the system, are observable in short (5-10 ks) exposures of the *ASTRO-E2* satellite that will be launched early in 2005. The degree of precision and confidence level up to which we will be able to determine the inclination angle of disk for each short observations, thus, the magnitude of the precession,

[1]http://astroe2.gsfc.nasa.gov/docs/astroe/prop_tools/xrs_mat.html), with the most recent updates included (as of August 4, 2004)

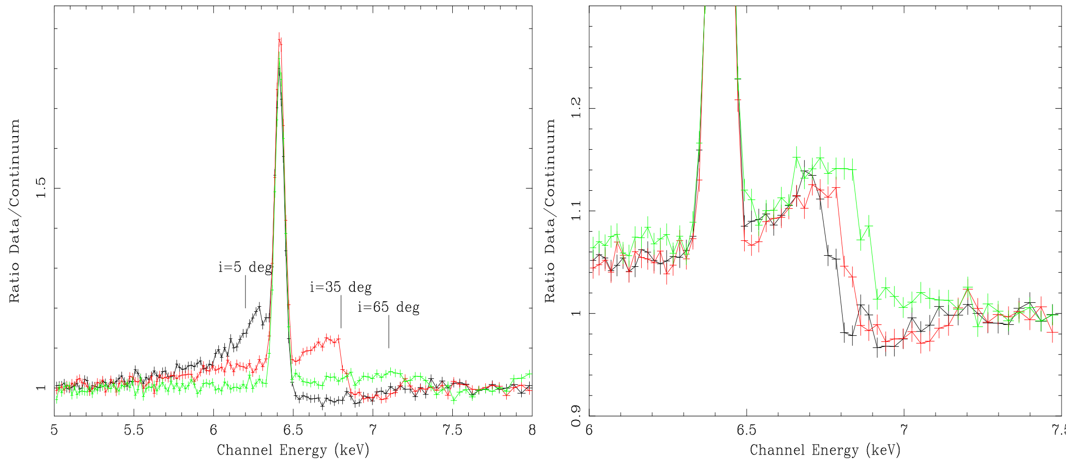

FIG. 2.— Left: Ratio of data to fitted continuum for net 50 ks exposures, assuming inner disk inclination angles of 5°, 35° and 65°. Right: Detail of the ratio of data to fitted continuum for net 50 ks exposures, assuming inner disk inclination angles of 33°, 35° and 37° with the drop of the broad line going from left to right. Data have been grouped for fitting and presentation purposes.

TABLE 1
RESULTS OF THE FITS TO SIMULATIONS, WITH 90% ERRORS, FOR VARIOUS NET EXPOSURE TIMES

Parameter	input	50 ks	10 ks	5 ks
Γ	1.80	1.80 ± 0.010	1.80 ± 0.015	1.80 ± 0.02
$E_{\rm edge}$ (keV)	7.20	7.19 ± 0.05	7.20 ± 0.10	7.12 ± 0.15
$E_{\rm narrow}(keV)$	6.415	6.414 ± 0.001	6.414 ± 0.001	6.416 ± 0.002
$\sigma_{\rm narrow}$ (eV)	30	29.3 ± 0.6	29.3 ± 1.2	32.0 ± 2.0
Disk inclination	35	35.0 ± 0.3	35.2 ± 0.6	35.3 ± 0.7

was shown to be sufficiently high as to allow a clear determination of these parameters even when the precession angle is of only a few degrees. This would disentangle the most likely origin of such precession, distinguishing between tidal and spin-spin coupling.

For different spectral states, the disk structure may be different. For example, if the disk is truncated at a much larger radius rather than the innermost stable orbit as suggested for the hard state, then the width of the Fe Kα line may significantly decrease. In any case, the variation due to disk precession from that due to the accretion mode (disk structure) will have a different temporal signature (periodicity), what would make it easy to distinguish.

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