Central black hole mass estimates for Mkn 501 from shot noise-like X-ray and TeV flares during 1997

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Abstract

X-ray observations of accreting black hole candidates show typical shot-noise behaviour as a result of the accretion process. We have inferred the maximum likelihood estimates (MLE) of the shot noise parameters from the X-ray and TeV γ-ray spectra of Mkn 501, given a very general shot model which holds for any possible distribution of flare amplitudes, count rate of random flares, and any mean rise/decay time of flares. These parameters allow us to assess the significance of the reported 23 d periodicities in the X-ray and TeV light curves. Without such parameters one would significantly overestimate the significance of the claimed periodicities. The MLE of the mean variability timescale also allows us to estimate the mass of the cental black hole, if variations in the accretion process are translated to the jet via the dynamo process. From the "knee" in the Fourier spectrum, we infer a mass for Mkn 501 between 1 and 4 times $10^7(\delta_j/10)M_\odot$, normalised to a jet doppler factor of $\delta_j = 10$. The observed minimum variability timescale of 15 minutes imply an upper limit to the central mass of $M_{501} < 9\times10^7(\delta_j/10)M_\odot$, which is consistent with our estimates from the "knee" in the spectrum.

1 Introduction:

X-ray observations of accreting black hole candidates appear to be consistent with a steady component plus randomly occuring identical bursts or shots (see e.g. Nolan et al. 1981 with references). The accretion process may produce variability corresponding to various keplerian orbits, so that we should see the effect over a broad band of frequencies. For example, obervations of Cyg X-1 by e.g. Nolan et al. and Hayashida et al. (1998) led to an average power spectrum which is constant up to a "knee" between $f_{\rm knee}\sim 0.04$ and 0.4 Hz, above which the average power was seen to decay at a rate of f^{-1} up to a break frequency $f_{\rm break}\sim 2$ Hz, above which the power dropped faster than f^{-1}. At $f \gg f_{\rm knee}$ we probe time scales which are faster than the variability time scales associated with the central black hole, so that we can exploit the broad-band Fourier spectra to infer the mass of the central black hole. Only two AGN revealed spectral knees (NGC 4051 and MCG -6-30-15, Hayashida et al. 1998), and both were detected without f^{-1} components, so that $f_{\rm knee} = f_{\rm break}$. We will exploit the "knee" as a measure of the mass of the black hole for Mkn 501.

Wandel & Mushotzky (1986) have set a constraining mass limit based on the fastest doubling timescale $t_{2\times}$ for light crossing the system with a size of twice $5R_s$, giving

$$M_{\rm BH} < (c^3/20G)t_{2\times} \sim 10^4 t_{2\times} M_\odot. \qquad (1a)$$

The fastest rest frame variability timescale for Mkn 501 was observed to be $t_{2\times}\sim 15\delta_j$ minutes, given a jet doppler factor of $\delta_j \sim 10$ (Aharonian et al. 1999a,b). The black hole mass limit is then

$$M_{\rm BH} < 9\times10^7\left(\frac{\delta_j}{10}\right)M_\odot. \qquad (1b)$$

Hayashida et al. (1998) made plots of fP_f by using normalised, background subtracted Fourier spectra, and inferred 8 AGN masses by scaling with Cyg X-1 at that value of f (well above $f_{\rm knee}$) where $fP_f = 10^{-3}$. Whereas the X-ray light curves are well sampled inside a day, the nightly TeV observations constrain the TeV power spectra to a Nyquist frequency of 0.5 cycles/d, so that it may be difficult to achieve $fP_f = 10^{-3}$. However, TeV observations and RXTE/ASM X-ray observations over several months allow us to probe the ultra low frequency part of the spectrum up to the "knee", and *we will obtain a BH mass by scaling from observed knees seen in the two Hayashida AGNs*.

In TeV emitting BL Lac objects such as Mkn 421 and 501, we know that the X-ray and γ-ray emission must originate in the jet. The jet is however driven by the dynamo process resulting from the accretion process, so that we would also expect to see similar effects from particle acceleration sites in the jets, if variations in the accretion process also drive variations in the acceleration efficiency and particle injection process via a dynamo mechanism.

HEGRA CT1/CT2 observations of Mkn 501 (Aharonian et al. 1999b), which includes observations during periods of moonshine (Kranich et al. 1999a) allow us to construct a light curve for the 1997 high state with reduced aliasing effects relative to other observations constrained to dark moon periods. The parameters of a general shot noise model will be determined from a maximum likelihood fit to the data. This gives us the mean power vs frequency, as well as $f_{\rm knee}$. The same procedure is applied to the RXTE/ASM data over the same time period. A consistent estimate for $f_{\rm knee}$ is expected, given the significant correlation found between the X-ray and TeV light curves. An estimate of the black hole mass will be given in this case.

2 The mean Fourier power for shot-noise.

Suppose that we can describe the X-ray and TeV flares from Mkn 501 as a linear system consisting of N flares occuring at random times t_j and with random amplitudes a_j. Neither do we know the count rate λ of these flares, nor do we know the amplitude distribution. The weighting function, $h(t)$, describes the total variability timescale (including particle acceleration and loss effects). The time series can then be described by the function

$$y(t) = \sum_{j=1}^{N} a_j h(t - t_j).$$

The output power spectral density function is then given by

$$P(f) \propto \lambda \overline{a^2} \mid \int_0^\infty h(t) \exp\left[-j(2\pi f)t\right] dt|^2,$$

with $\overline{a^2} - \overline{a}^2$ the variance of the flare amplitude and $\overline{a}$ the mean flare amplitude.

Even though we are limited to $f \leq 0.5$ cycles per day, we do see the cutoff in the Fourier transform of h. We however cannot identify a unique function for h from TeV observations, sinuld also expect to seesimilar effects from particle acceleration sites in transform of h extends to $f > 0.5$ d^{-1} (see Fig. 1). We will assume a Gaussian shape for h, although other shapes (e.g. exponential decay of flares) do not produce significantly different estimates for $f_{\rm knee}$.

At very high frequencies $f \gg f_{\rm knee}$, the random errors on the TeV (and X-ray) flux measurements should dominate, and to take the effect of random noise into account, we add a constant C to the theoretical value of $P(f)$. The mean Fourier power $< P_f >$ for our shot-noise model (given a Gaussian transmission function) for the X-ray and TeV data is then modelled as

$$< P_f >= A \exp\left(-(2\pi f \tau)^2\right) + C, \tag{2}$$

where $A \propto \lambda \overline{a^2}$. We expect $C \sim 1$ when $2\pi f \tau \gg 1$ in the presence of a random noise component due to measurement error. To answer the question if C is really constant with f, we have made extensive bootstrap simulations from the data by retaining the times while shuffling the observed fluxes around. In this way we simulated the exact sampling in time, with the same distribution of flux values, whereas the time order of observed fluxes have been randomised. We find that $< P_f >= C = 1$ is indeed constant for the entire frequency range. We find the same answer if we calculate the power from the observed flux errors rather than the shuffled fluxes. Expression (2) will be used to construct maximum likelihood estimators for A, τ and C.

3 MLE parameters for the X-ray and γ-ray power spectra of Mkn 501

Extensive Monte Carlo simulations of random flares with various rise/decay times have shown that the distibution $g(z_f)$ of the observed Fourier power $z_f = P(f)$ at a given frequency f, is equal to an exponential distribution

$$g(z_f) = \frac{1}{< P_f >} \exp{(-\frac{z_f}{< P_f >})} \tag{3}$$

In the case of pure white noise with no signal ($A = 0$, and $C = 1$), we retrieve the well-known $\exp{(-z)}$ expression for the distribution of the power.

If P_i ($i = 1$ to K) are the observed power values (Lomb-Scargle normalised) corresponding to K independent frequencies (up to the Nyquist frequency), the $-\ln$ of the likelihood function L of g, given P_i, is then given by

$$\ell = \Sigma_{i=1}^{K} (\ln < P_f > + P_i / < P_f >). \tag{4}$$

The optimal parameters which describe the temporal character of Mkn 501, would be those parameters which minimise ℓ. By setting the derivatives of ℓ relative to A, C and τ equal to zero, we find three coupled expressions for A, C and τ.

We have taken relatively gap-free X-ray and γ-ray light curves of Mkn 501 during the 1997 high state (see Kranich et al. 1999b for data set definitions) covering the same time interval.

Since the γ-ray data are constrained to $f < 0.5$ per day, we have also constrained the X-ray RXTE/ASM data to the same frequencies. The unbinned X-ray data by dwell were used. Although Fig. 1 shows the binned (averaged) Fourier spectra for the X-ray and γ-ray light curves, we have used the unbinned data to derive the maximum likelihood estimates. If we inlcude the first frequency ($f = 1/T$), as well as the 23 day QPO (Kranich et al. 1999b), we find that the observed value of ℓ is unacceptably large compared to the number of degrees of freedom. Excluding these frequencies, we find that the observed values of ℓ for both X-rays & γ-rays are perfectly consistent with expectation (i.e. P_i must be i.i.d. variables.)

The optimal solutions are $A \sim 3.8$ for both X-rays and γ-rays, whereas the value of $\tau \sim .35$ d for X-rays, but ~ 0.41 d for γ-rays. The solution for $C \sim 0$ for both X-ray and γ-rays. If we extended the MLE to $f \gg 0.5$ d^{-1}, we should have seen $C \sim 1$ as a result of measurement errors. We confirmed this for X-rays alone, since the sampling of X-rays are not confined to a fixed longitude, as is the case for the TeV CT1/CT2 data. A full discussion of the MLE solutions and their errors will be given in a future paper.

The observed X-ray and γ-ray values of P_i have been binned in logarithmic intervals. The mean power (and error) for each selected frequency interval is shown in Figure 1. The best fit solutions (smooth lines) for both energies are also shown in Figure 1.

4 The central black hole mass of Mkn 501

The fact that the X-ray and γ-ray light curves are correlated (r=0.61) with a zero time lag, implies that that we should expect some agreement between the X-ray and γ-ray fits. We will not discuss the similarity of A between X-rays and γ-rays, since the power spectra were normalised according to the Lomb-Scargle technique to get rid of the effects of data gaps (see Kranich et al. 1999b with references.)

We may however compare τ: The indication that $\tau_{\rm x}$ and τ_γ differ by only ~ 20%, is consistent with the correlation found between the X-ray and γ-ray light curves - we would expect $\tau_{\rm x} \sim \tau_\gamma$, since the same disk dynamo action is responsible for X-rays and γ-rays, and variability timescales associated with the central black hole will be transmitted to the jet in the same way for X-rays and γ-rays. The only difference is that we expect all intrinsic timescales to be contracted due to doppler boosting.

The value of $\tau \sim 0.4$ days realised from X-ray and TeV observations refer to an average rise/decay timescale of 0.4 days for all flares. The intrinsic “knee” frequency for Mkn 501 for a jet doppler factor of $\delta_j \sim 10$ is then

$$f_{\rm knee} = \frac{1}{2\pi\tau\delta_j} = 4.6 \times 10^{-7} (\frac{0.4 \text{ d}}{\tau}) (\frac{10}{\delta_j}) \text{ Hz}. \tag{5}$$

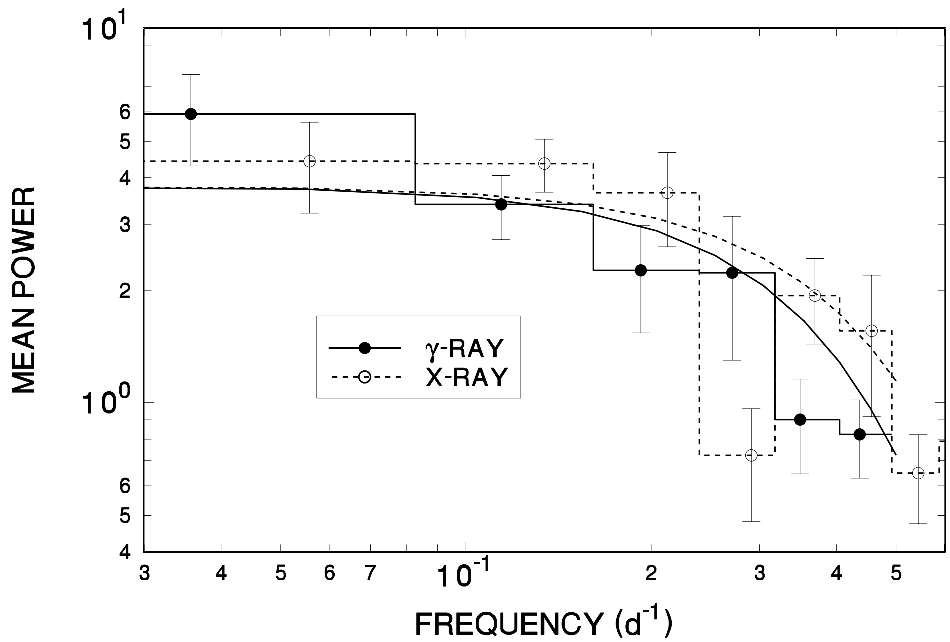

Figure 1: The mean power (normalised to Lomb-Scargle) for X-rays (RXTE/ASM - dashed lines) and TeV γ-rays (CT1 - solid lines) in logarithmic frequency intervals. Roughly 10 data points per interval. The smooth data lines represent $A_{\rm x} = A_\gamma = 3.8$, $\tau_{\rm x} = 0.35$ d, $\tau_\gamma = 0.41$ d, and $C_{\rm x} = C_\gamma = 0.0$ for both X-ray (subscript "x") and γ-ray (subscript "γ") data. The first X-ray frequency ($f_1 = 1/T$) and the 23 day periodicities (X-rays and γ-rays) were excluded from these analyses, since they are inconsistent with the shot noise model (as reflected by the large value of ℓ if they are included).

Using this "knee" frequency, we scale from the observed "knees" of NGC 4051 (6×10^{-5} Hz) and MCG -6-30-15 (4×10^{-5}), for which masses of $9 \times 10^4 M_\odot$ and $5 \times 10^5 M_\odot$ were respectively found by Hayashida et al. (1998). The corresponding scaled mass estimates for Mkn 501 from NGC 4051 and MCG -6-30-15 are

$$M_{501} = 10^7 (\frac{\delta_j}{10}) M_\odot \quad \text{and} \quad 4 \times 10^7 (\frac{\delta_j}{10}) M_\odot \tag{6}$$

respectively. These mass estimates are consistent with the upper limit of $10^8 M_\odot$ set by Equation (1).

5 Acknowledgements

O.C. de Jager would like to thank dr. Eckart Lorenz and the Max Planck Institut für Physik (München) for their kindness and hospitality.

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