The peculiar high-mass X-ray binary Cyg X-3

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Why are high-mass X-ray binaries (HMXBs) interesting?

- Many highly interesting HMXBs, for example Cyg X-1, Cyg X-3, Vela X-1, SS 433.
- A recent discovery of the first eclipsing black-hole binary M33 X-7, with the black-hole mass of $\sim 16 M_\odot$ and the donor mass of $\sim 70 M_\odot$.
- The recently discovered binaries emitting TeV photons are all HMXBs.
- Young systems, the age of millions rather than billions of years.

Classifications

- Compact object: a neutron star (most of HMXBs) or a black hole (Cyg X-1, LMC X-1, LMC X-3, SS 433, M33 X-7, probably many of ULXs).
- Companions: O, B, supergiants, Be, WR.
- Mode of accretion: via stellar wind (e.g., Cyg X-1, Cyg X-3, M33 X-3), Roche-lobe overflow (SS 433, LMC X-4), or from a Be-star decretion disc.
- High-energy emission from accretion or from pulsar-wind/stellar-wind interaction (PSR B1259–63, LS I +61 303).

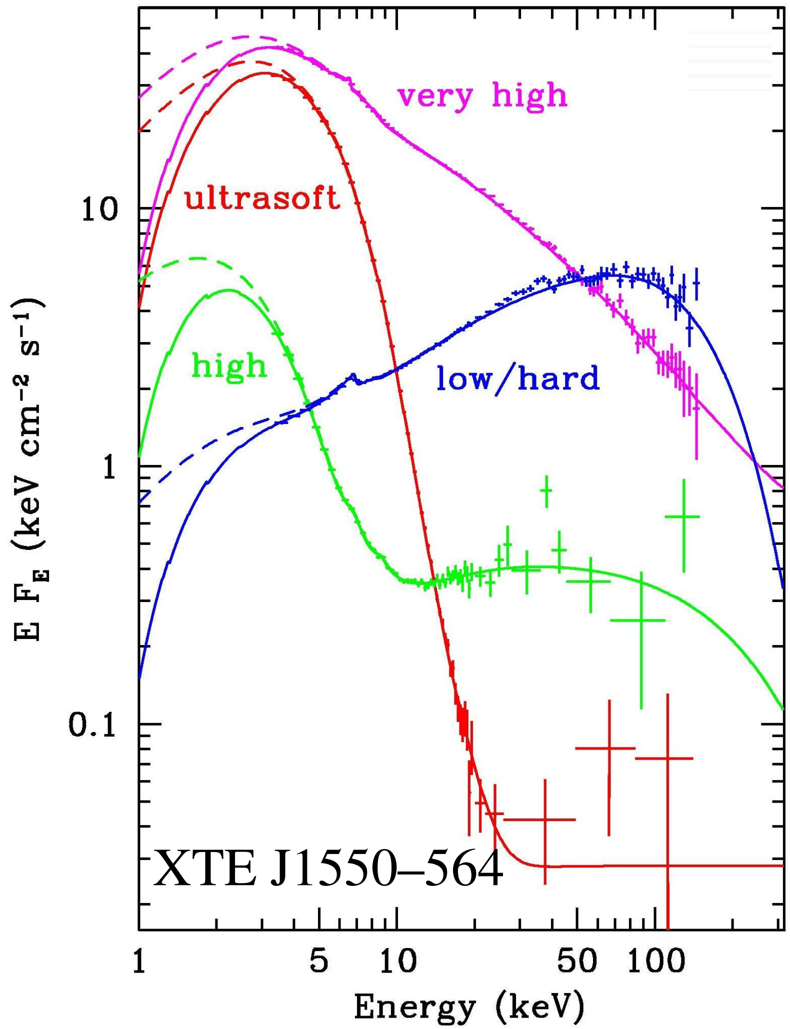
Black-hole HMXBs:

- the main difference with respect to black-hole low-mass X-ray binaries (LMXB) is the persistence of emission.
- Otherwise very similar spectral and timing properties, similar spectral states, e.g. Cyg X-1 vs. GX 339–4, in spite of the different accretion mode, wind vs. Roche lobe overflow.

Main properties of Cyg X-3

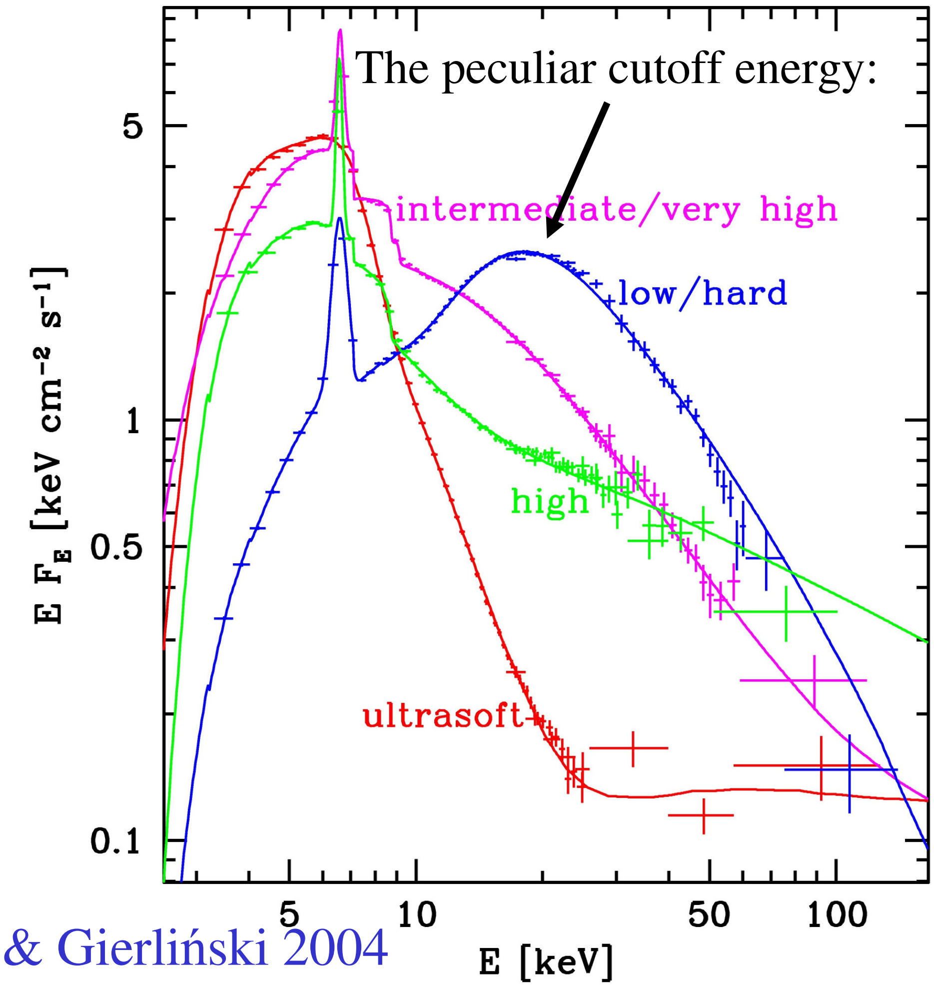
- A very luminous radio and X-ray source, the only Galactic X-ray binary with a WR donor.
- A very short 4.8 hr period .
- Strong extinction makes the donor invisible in O, X-rays very strongly absorbed.
- The X-ray spectra bear a general resemblance to those of various spectral states of black-hole binaries, but *differ in important details*.
- Peculiar power spectrum, no variability above ~1 Hz, *different* from typical X-ray binaries, where variability is seen at >100 Hz.

XTE J1550–564 – a transient black-hole LMXB



Cygnus X-3

Neutron star or a black hole?



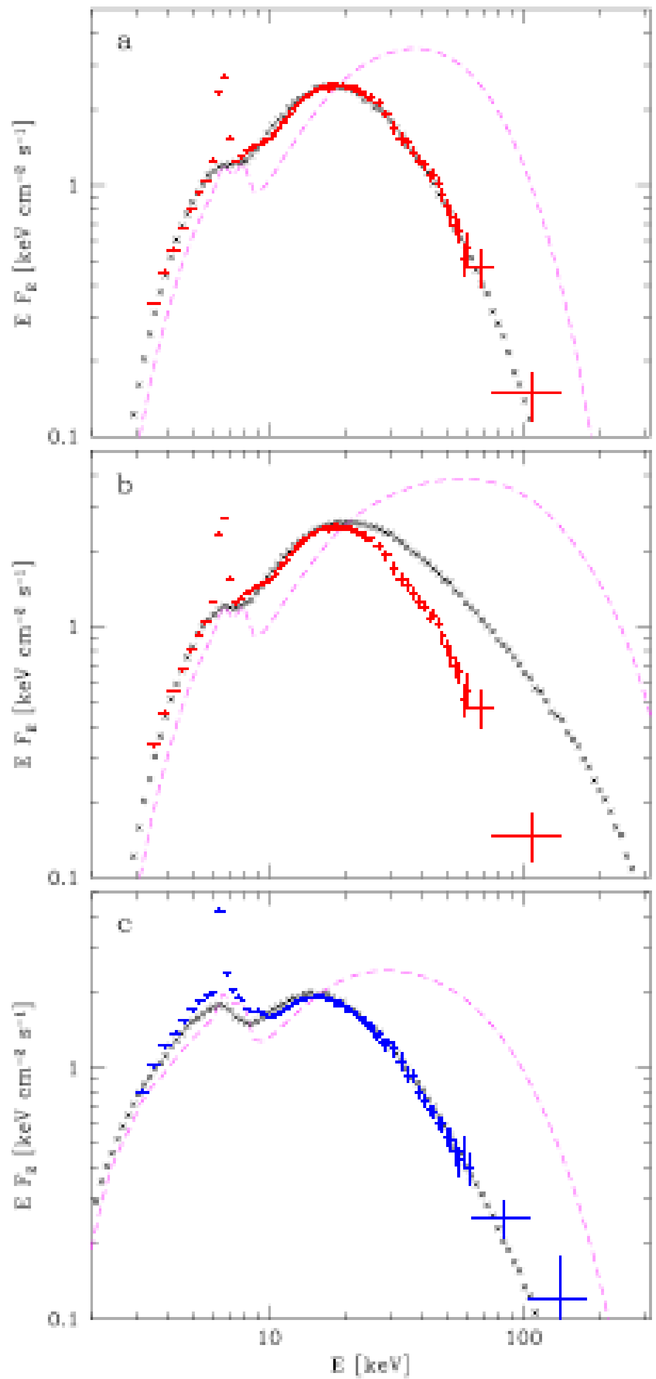
Z. & Gierliński 2004

How to explain the peculiarity of the X-ray spectra and power spectra?

- Compton scattering in a Thomson-thick medium can damp variability at high frequencies.
- Compton downscattering of hard X-rays can move the high-energy break in the hard state from ~100 keV to ~20 keV.
- In addition, scattering can explain the energy-independent orbital variability of X-rays.

The effect of Compton downscattering

Dashes: the assumed intrinsic spectrum from thermal Comptonization in a hot medium, typical for black hole binaries.
Error bars: the data for two types of the hard state.
Crosses: the spectra after Compton downscattering through an ionized cloud with $\tau_T = 5$.
The break occurs at $\sim m_e c^2 / \tau_T^2$ roughly independently of the temperature of the hot source.



Timing from Comptonization

$$G(\tau) \simeq \begin{cases} 0, & \tau < \tau_0; \\ \exp\left[p - q\tau - \left(\frac{r}{\tau}\right)^2\right] + \delta(\tau - \tau_0)e^{-\tau}, & \tau \geq \tau_0. \end{cases}$$

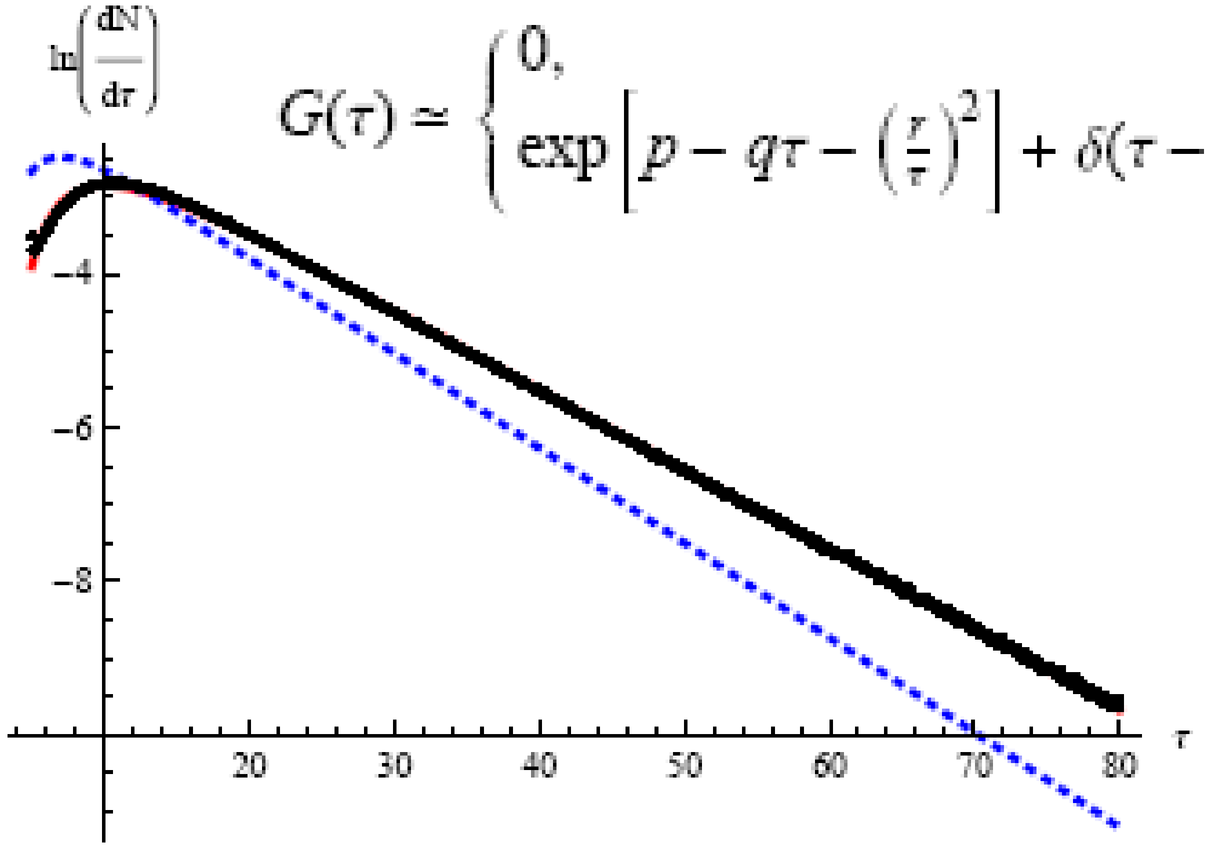


Figure 2. The distribution of the time spent by a soft photon in a spherical cloud of cold electrons with $\tau_0 = 5$, measured from the cloud center in units of the Thomson time. The black dots give Monte Carlo results and the red solid curve gives its fit, equation (2). The dotted curve gives the distribution of Lightman et al. (1981) corrected for the Poissonian distribution of the time corresponding to a given number of scatterings.

The attenuation of the power spectrum from scattering:

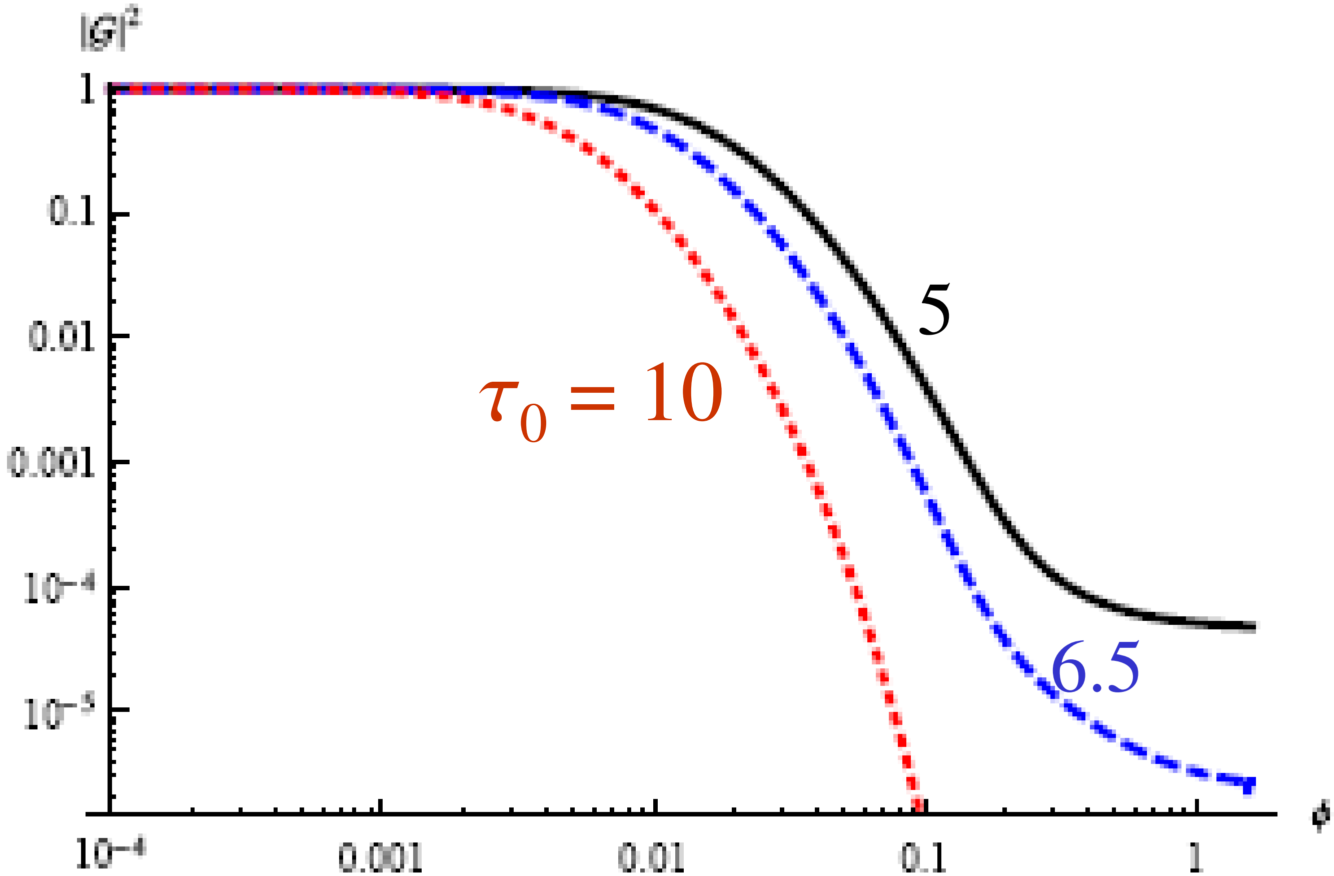


Figure 3. The squared attenuation coefficient as a function of frequency in the Thomson units ($\phi = fR/\tau_0 c$). The solid, dashed and dotted curves are for $\tau_0 = 5, 6.5, 10$, respectively. At high frequencies, $|G(\phi)| \to e^{-\tau_0}$.

The size of the scattering cloud inferred from a break in the power spectrum:

$$R \simeq \frac{c}{2\tau_0 f_c} \simeq \frac{1.5 \times 10^{10}\ \mathrm{cm}}{\tau_0 (f_c / 1\ \mathrm{Hz})}$$

The size inferred from $\tau_0 = 5$ and $f_c \sim 1$ Hz is $\sim 3\times10^9$ cm. This is $\ll$ the separation between the stars, $\sim 3\times10^{11}$ cm. Thus, the scattering cloud will be heated by the X-ray source only, and will not be cold. We find the equilibrium $kT \sim 3$ keV.

The effect of Compton scattering at $kT \sim 3$ keV

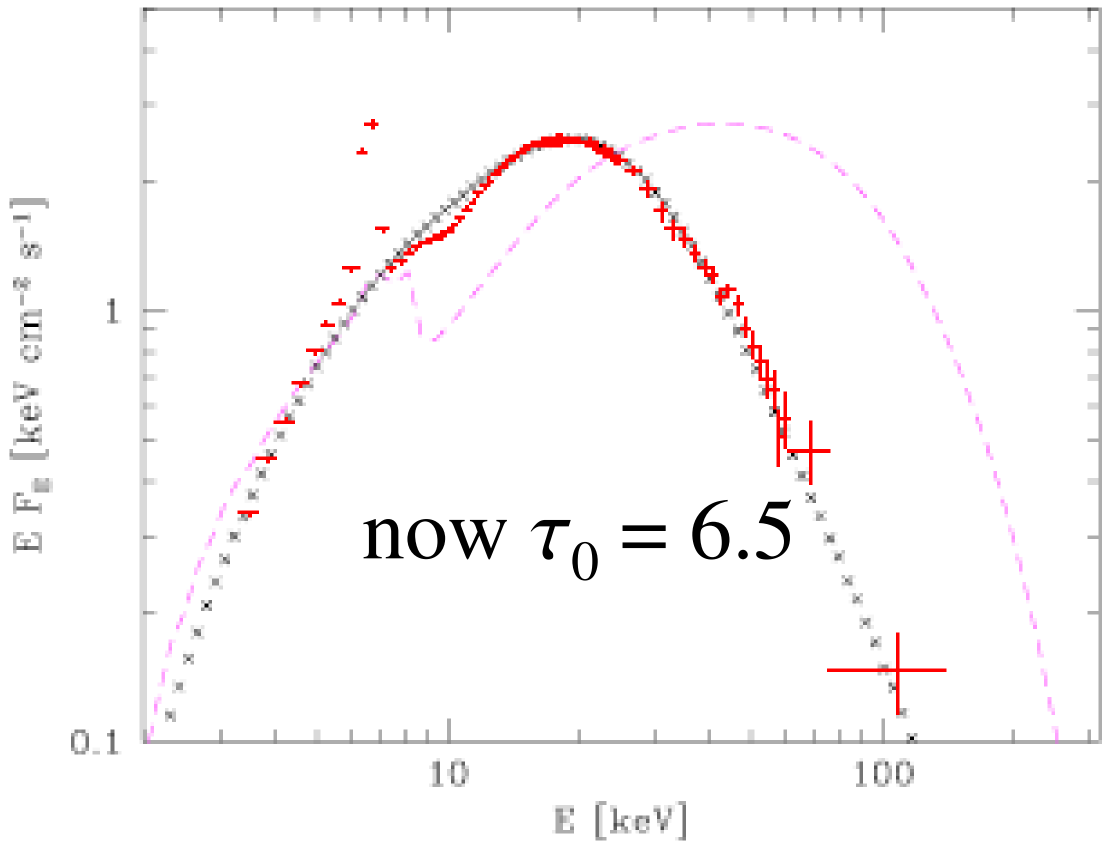


Figure 5. The average spectrum 1 compared to the downscattered thermal Compton spectrum with $kT_h = 30$ keV, $y = 1.4$, $N_H = 4 \times 10^{22}$ cm^{-2}, $kT_0 = 3$ keV, $\tau = 6.5$. The unabsorbed bolometric fluxes entering and leaving the cloud are approximately equal, thus this model satisfies thermal equilibrium.

The effect of scattering on the power spectrum:

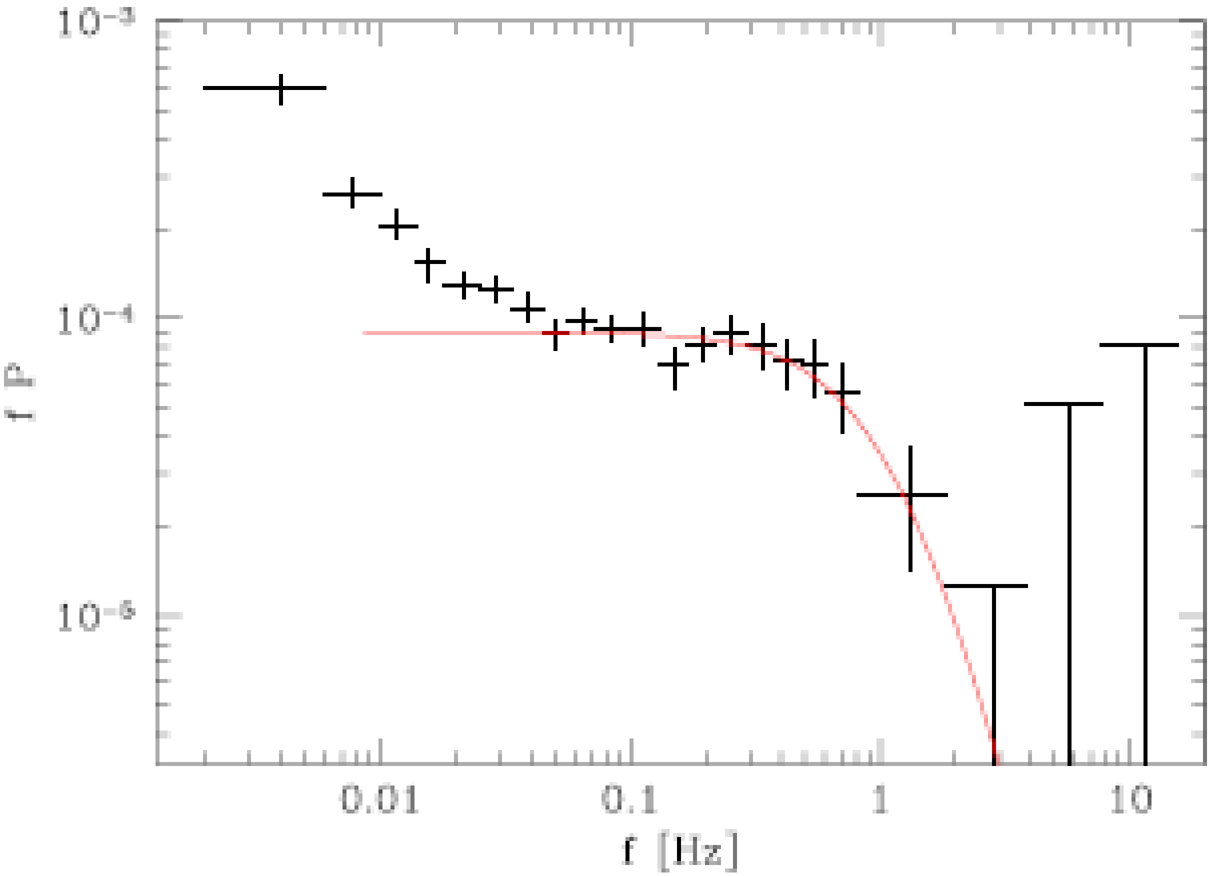


Figure 4. The average power spectrum per $\ln f$ of Cyg X-3 from the *RXTE*/PCA observations included in the average spectrum 1 (crosses). The solid curve shows a fit of $|G(\phi)|^2$ for $\tau_0 = 6.5$ to the data at $f \geq 0.04$ Hz.

The parameters of the self-consistent model:

- The Thomson depth of the cloud ≈ 6, $kT \approx 3$ keV, the size of ≈ 2×10^9 cm.
- The intrinsic hot source at $kT \approx 30$ keV and $\tau_T \sim 1$, the same as fitted in the black-hole binary GX 339–4 at a similar L.
- The intrinsic bolometric luminosity of $L \sim 10^{38}$ erg s^{-1}.
- If the black hole $M = 10M_\odot$, the Eddington ratio (for He system) is several %, typical for the hard state in black hole binaries.

Conclusions

- We have explained the peculiar X-ray spectrum and the power spectrum of Cyg X-3 as that of a standard accreting black-hole binary modified by a Thomson-thick scattering cloud.
- The size of the cloud is $\approx 2\times10^9$ cm, i.e. several hundred of Schwarzschild radii at $\sim10M_\odot$.
- The cloud may be due to accretion-disc wind, or a bulge formed by collision of the stellar wind with the disc, which size is then typical for wind-fed systems. Such a bulge is present in Cyg X-1.

Two other WR X-ray binaries recently discovered. Each probably contains a black hole.

- IC 10 X-1 (Silverman & Filippenko 2008): $M \approx$ (23–34) $M_{\odot}$, $P \approx 35$ hr, and $L \approx 3 \times 10^{38}$ erg s^{-1}, similar to that of Cyg X-3 .
- NGC 300 X-1 (Carpani et al. 2007a,b): $L \approx 10^{39}$ erg s^{-1} and $P \approx 35$ hr, similar to that of IC 10 X-1, which also suggests the presence of a black hole.

Roche lobe radius vs. WR stellar radius