Black Holes from Stars to Galaxies – Across the Range of Masses
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The supercritical accretion disk in SS 433 and ultraluminous X-ray sources

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Abstract. SS 433 is the only known persistent supercritical accretor, it may be very important for understanding ultraluminous X-ray sources (ULXs) located in external galaxies. We describe main properties of the SS 433 supercritical accretion disk and jets. Basing on observational data of SS 433 and published 2D simulations of supercritical accretion disks we estimate parameters of the funnel in the disk/wind of SS 433. We argue that the UV radiation of the SS 433 disk (~ 50000 K, $\sim 10^{40}$ erg/s) is roughly isotropic, but X-ray radiation ($\sim 10^7$ K, $\sim 10^{40}$ erg/s) of the funnel is mildly anisotropic. A face-on SS 433 object has to be ultraluminous in X-rays (10^{40-41} erg/s). Typical time-scales of the funnel flux variability are estimated. Shallow and very broad (0.1-0.3c) and blue-shifted absorption lines are expected in the funnel X-ray spectrum.

Keywords. X-rays: general – X-rays: individual (SS 433) – accretion – jets

1. Introduction

The main properties of the ultraluminous X-ray sources (ULXs) — the extremely high luminosities (10^{39-41} erg/s), diversity of X-ray spectra, strong variability, their connection with star-forming regions and surrounding nebulae. Here we continue to develop the idea that the galactic supercritical accretor SS 433 intrinsically is very bright X-ray source and it is a prototype of ULXs in external galaxies (Katz 1987, Fabrika & Mescheryakov 2001, King *et al.* 2001, Begelman *et al.* 2006, Poutanen *et al.* 2006). This means that ULXs are supercritical accretion disks in close binaries with stellar mass black holes or microquasars. We discuss possible properties of the funnel in the supercritical accretion disk of SS 433 to predict X-ray spectral features and temporal behaviour of the funnel in "face-on SS 433" stars in application to ULXs.

2. Properties of SS 433

The main difference between SS 433 and other known X-ray binaries is highly supercritical and persistent mass accretion rate ($\dot{M}_a \geqslant 10^{-4}\, M_\odot$/y) onto the relativistic star, a probable black hole ($M \sim 10 M_\odot$), which has led to the formation of a supercritical accretion disk and the relativistic jets. SS 433 properties were reviewed recently (Fabrika 2004). A total observed luminosity of SS 433 is $L_{bol} \sim 10^{40}$ erg/s. Practically all the energy is realised near the black hole. Temperature of the source is $T = (5-7)\cdot 10^4$ K, when the accretion disk is the most open to the observer and it is $T \sim 2\cdot 10^4$ K, when it is observed edge-on (Dolan *et al.* 1997). If the source SED is represented by a single blackbody source, its size is $\sim 10^{12}$ cm. The line of sight wind velocity varies from ~ 1500 km/s (the most open disk) to ~ 100 km/s (the disk is observed edge on). One may adopt the value ~ 2000 km/s for the wind velocity closer to the jets. The mass loss rate in the wind is $\dot{M}_w \sim 10^{-4}\, M_\odot$/y. The optical jets ($\sim 10^{15}$ cm) consist of dense small gas clouds, the X-ray jets ($\sim 10^{12}$ cm) consist of hot ($T \sim 10^8$ K) cooling plasma. Both the optical and X-ray jets are well collimated ($\sim 1°$). SS 433 X-ray luminosity (the cooling

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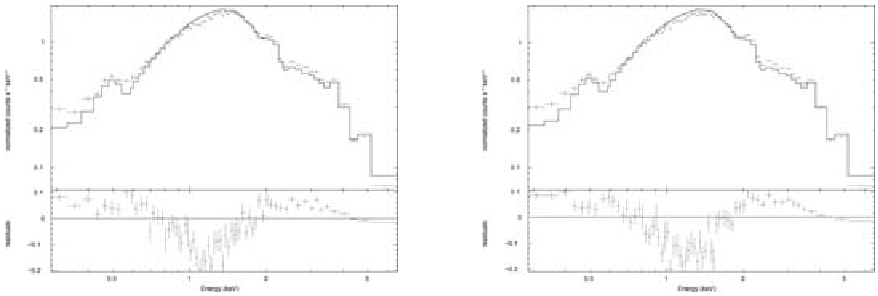

Figure 1. Simulated MCF spectra as seen with XMM MOS1 with total counts 10^5, obtained with $T_0 = 1$ keV, $\theta_f = 20°$, $V_w(r_0) = 6000$ km/s, $N_H = 0$ and $\xi = 10^4$ (left), $\xi = 10$ (right). Solid lines show the *diskbb* model fitted to the spectra. In the model spectra we found $T_{inn} = 1.55$ keV, $N_H = 1.5 \cdot 10^{21}$ cm^{-2}. The MCF spectrum is broader than the MCD (diskbb) spectrum.

X-ray jets) is $\sim 10^4$ times less than bolometric luminosity, however kinetic luminosity of the jets is very high, $L_k \sim 10^{39}$ erg/s, the jet mass loss rate is $\dot{M}_j \sim 5 \cdot 10^{-7}\, M_\odot$/y.

The jets have to be formed in a funnel in the disk or the disk wind. Supercritical accretion disks simulations (Eggum *et al.* 1985, Ohsuga *et al.* 2005, Okuda *et al.* 2005) show that a wide funnel ($\theta_f \approx 20° - 25°$) is formed close to the black hole. Convection is important in the inner accretion disk. Recent hydrodynamic simulations of super-Eddington radiation pressure-dominated disks with photon trapping (Ohsuga *et al.* 2005) have confirmed the importance of advective flows in the most inner parts of the disks. The mass accretion rate into the black hole a few times exceeds the mass loss rate in the disk wind. One may adopt a rough estimate of the accretion rate in the case of SS 433 (or the same for the gas supply rate in the accretion disk), $\dot{M}_a \sim 3 \cdot 10^{-4}\, M_\odot$/y.

3. Funnel in the supercritical accretion disk

A critical luminosity for a $10\, M_\odot$ black hole is $L_{edd} \sim 1.5 \cdot 10^{39}$ erg/s and corresponding mass accretion rate $\dot{M}_{edd} \sim 3 \cdot 10^{-7}\, M_\odot$/y. There are three factors (Fabrika *et al.* 2006) increasing observed face-on luminosity of a supercritical accretion disk. (1) inside the spherization radius the disk is locally Eddington (Shakura & Sunyaev 1973), which gives logarithmic factor $(1 + \ln(\dot{M}_a/\dot{M}_{edd})) \sim 8$; (2) the doppler boosting factor is ($\beta = V_j/c = 0.26$ in SS 433) is $1/(1-\beta)^{2+\alpha} \sim 2.5$, where α is spectral index; and (3) the geometrical funneling ($\theta_f \sim 25°$) is $\Omega_f/2\pi \sim 10$. Thus, one may expect an observed face-on luminosity of such supercritical disk $L_{edd} \sim (2-3) \cdot 10^{41}$ erg/s. On the other hand, if one adopts for the funnel luminosity, that it is about the same as SS 433 bolometric luminosity (Fabrika & Mescheryakov 2001) one obtains with the same opening angle of the funnel, the "observed" face-on luminosity of SS 433 is $L_x \sim 10^{41}$ erg/s and the expected frequency of such objects is ~ 0.1 per a galaxy like Milky Way.

The disk spherization radius (Shakura & Sunyaev 1973) in SS 433 is estimated $r_{sp} \approx 3\kappa\dot{M}_a/8\pi c \sim 2.6 \cdot 10^{10}$ cm, where the Thomson opacity for a gas with solar abundance is $\kappa = 0.35\,\mathrm{cm}^2$/g. Corresponding wind velocity is $V_w \sim (GM/r_{sp}) \sim 2300$ km/s, where we adopted the black hole mass $M = 10\, M_\odot$. The size of the hot wind photosphere and the photosphere temperature (for not a face-on observer) are estimated $r_{ph,w} = \dot{M}_w\kappa/4\pi\cos\theta_f V_w \sim 1 \cdot 10^{12}$ cm, $T_{ph,w} = (L_{bol}/4\pi\sigma\cos\theta_f r_{ph,w}^2)^{1/4} \sim 6 \cdot 10^4$ K. Both the size of the hot body and the temperature are quite close to those we observe in SS 433.

We find the jet photosphere size $r_{ph,j} = \dot{M}_j\kappa/\Omega_f V_j \sim 4 \cdot 10^9$ cm, this value indicates the bottom of the funnel, below $r_{ph,j}$ the funnel walls can not be observed. A temperature of the inner funnel walls at a level of $r_{ph,j}$ is estimated as (Fabrika *et al.* 2006, Fabrika *et al.* 2006) $T_{ph,f}$ between $\sim 1.7 \cdot 10^7$ K and $\sim 1 \cdot 10^6$ K. Such temperatures provide a

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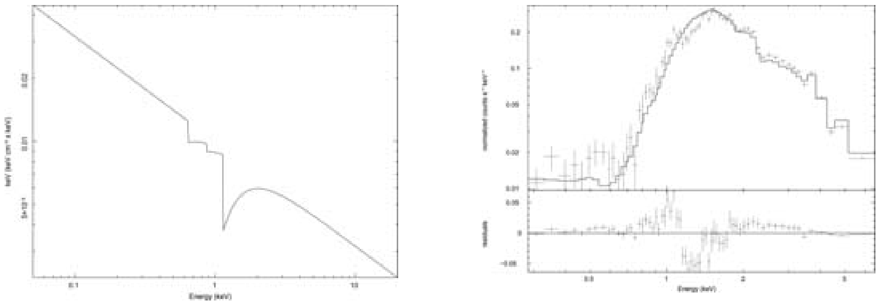

Figure 2. Possible fake broad emission/absorption features in ULXs spectral residuals. The model is a power law spectrum ($\Gamma = 2.5$) with $N_H = 1.0 \cdot 10^{22}\,\mathrm{cm}^{-2}$ and with introduced Lc edges of C VI, N VII and O VIII blue-shifted to the velocity $V_j = 0.26c$ (shown in left panel). The XMM MOS1 fit to the model ($\Gamma = 2.2$, $N_H = 1.05 \cdot 10^{22}\,\mathrm{cm}^{-2}$) and spectral residuals are shown by solid line.

high ionisation of elements needed for the line-locking mechanism (Shapiro *et al.* 1986) to operate for the jet acceleration. We conclude that the UV radiation of the SS 433 disk ($T \sim 50000\,\mathrm{K}$, $L \sim 10^{40}$ erg/s) is roughly isotropic, but its X-ray funnel radiation ($T \sim 10^6 - 10^7\,\mathrm{K}$, $L \sim 10^{40}$ erg/s) is mildly anisotropic. The same conclusions have to be done for face-on SS 433 stars (ULXs), they are expected to be very bright UV sources and their X-ray luminosities have to be even higher, up to $\sim 10^{40} - 10^{41}$ erg/s, due to the additional geometrical collimation.

Temporal variability of the SS 433 funnel is expected on time scales $r_{ph,w}/c \sim 30\,sec$ and $r_{ph,j}/c \sim 0.1\,sec$. A typical accretion disk variability power density spectrum at scales $\gg 0.1\,sec$ is expected. However the most rapid variability may be observed only for face-on SS 433 stars, in the case of SS 433 (the edge-on system), all the short-scale variability of the funnel ($\Delta t < 10 - 100\,sec$) has to be smoothed down in the funnel. Some of the expected X-ray variability patterns have been observed recently (Revnivtsev *et al.* 2005, 2006, Kotani *et al.* 2006).

4. The funnel spectrum and applications to ULXs

The multicolor funnel (MCF) model has been developed (Fabrika *et al.* 2006, Fabrika *et al.* 2006) to estimate the emerging X-ray spectrum in the funnel. The main parameters of the models are (i) the initial radius, the deepest visible level in the inner funnel walls ($r_0 = r_{ph,j}$), (ii) the walls temperature at $T_0(r_0)$, (iii) the ratio of radiation to gas pressure $\xi = aT_0^3/3k_b n_0$ at r_0, (iv) the wind velocity $V_w(r_0)$ and (v) the funnel opening angle θ_f. Photon trapping in the wind is considered by a simple comparison of advection time ($t_{mov} \sim r/v(r)$) and diffusion time ($t_{esc} \sim \beta_t r_{ph,w}/V(r)$), where β_t is a terminal wind velocity. These times are equal at the radius $r(t_{mov} = t_{esc}) = 2\dot{M}_w r_{sp}/3\cos\theta_f \dot{M}_a \sim r_{sp}$. There is a local advective radiation transfer at $r \ll r_{sp}$ and global diffusion transfer at $r \gg r_{sp}$.

In Fig. 1 we present simulated MCF spectra as seen with XMM MOS1 with total counts 10^5, obtained with $T_0 = 1\,keV$, $\xi = 10^4$ and 10, $\theta_f = 20°$, $V_w(r_0) = 6000$ km/s, $N_H = 0$ and their fittings using the *diskbb* model. This figure demonstrates that the MCF spectrum is broader than that of the MCD (diskbb). Shallow, very broad (0.1-0.3c) and blue-shifted absorption lines are expected in the funnel X-ray spectrum (Fabrika 2004, Fabrika *et al.* 2006). The absorption bands should belong to H- and He-like ions of the most abundant (O, Ne, Mg, Si, S, Fe) elements and should extend from the Kc to the Kα energies of the corresponding ions. Fig. 2 shows possible fake broad emission/absorption features which could be observed in ULXs spectral residuals. We

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have simulated a power law spectrum with introduced Lc edges of C VI, N VII and O VIII blue-shifted to the SS 433 jet velocity $V_j = 0.26c$. The optical thickness of these introduced edges corresponds to “effective” hydrogen thickness $\tau(L_c) = 20$. Spectral residuals in the figure were derived from the XMM MOS1 power law spectral model to the simulated spectrum. The fake emission/absorption features appear both due to the blue-shifts of the edges and the energetic differences between neutral and highly ionised absorptions. Residuals of such type are observed in ULXs spectra (for example, Dewangan *et al.* 2006, Roberts *et al.* 2006). The absorption edges, if they are confirmed in ULXs spectra give a possibility to measure the jet velocities in supercritical disk funnels.

Acknowledgements

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Kazuo Makishima: If the funneling model of ULXs is correct, we should observe a variety of X-ray absorption, depending on the viewing angle. In reality, we do not find such a wide range of $N_{\rm H}$. How about this point?

Sergei Fabrika: The X-ray absorption value, depending on the viewing angle, will also depend on the funnel structure and the gas ionization. Those funnels observed at larger angles may appear as super soft ULXs. Regarding the predicted broad smeared absorption features, I hope it is a consequence of signal-to-noise ratios in current data.

Richard Mushotzky: Answer to question by Kazuo Makishima: The X-ray column densities to ULX’s are very close to $N_{\rm H}$ derived from 21 cm data. There is just a paper accepted on this in ApJ.

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