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Vicinity of supermassive black holes

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Abstract. Black holes are gravitationally very simple objects, they just come with two free parameters, the mass and the spin. Mass is only relevant for scaling of lengths and times. The spin of a black hole is more relevant for physical processes near the vicinity of the horizon. While masses and spins are known for many stellar black holes, direct measurements of spins for supermassive black holes are still missing. The immediate vicinity of supermassive black holes is dominated by accretion discs and magnetic fields advected from accretion processes. Accretion discs around (supermassive) black hole consists in general of an inner hot disc, which is optically thin, and an outer optically thick standard disc extending to the self–gravity radius of about 1000 Schwarzschild radii. There is now direct evidence for this truncation of the standard disc from timing measurements of hard X–rays in microquasars. We show how these observations scale from stellar to supermassive black holes. In particular, we discuss our new understanding of the various types of AGN within the hardness–luminosity diagram. According to this, jets are launched only in the low hard states and in transitions to the very soft states.

Key words. Active Galactic Nuclei: Disks – Black Holes: frame–dragging – Black Holes: accretion – Galaxy: Black Holes – Galaxy: activity – Cosmology: observations

1. Introduction

Black holes are gravitationally very simple objects. By definition, a black hole is a global pure vacuum solution of Einstein's equations which is stationary, asymptotically flat and has an event horizon. No equation of state is needed to construct the interior of the horizon. This is in a way surprising, since astrophysical black holes are formed out of normal matter, and accreting matter will be transformed to something like gravitational field. According to the No-Hair theorem, these solutions just come with two parameters – the mass M and the angular momentum $J_{\rm H}$, or the spin parameter $a = J_{\rm H}/J_{\rm H,max}$, where $J_{\rm H,max}$ is the maximum angular momentum allowed by the existence of the horizon. In this way, astrophysical black holes fill a plane spanned by the mass in units of solar masses and the spin a on the other axis (see Fig. 1). We do not distinguish between rotating and counter-rotating objects. There are essentially now two big classes of black holes whose existence has been confirmed in the last years: the stellar black holes with masses in the range of 3 to 50 solar masses, and the supermassive ones in the centers of galaxies. In the former case, a few spins have been measured, but for the supermassive ones we still only have guesses and no real measurements.

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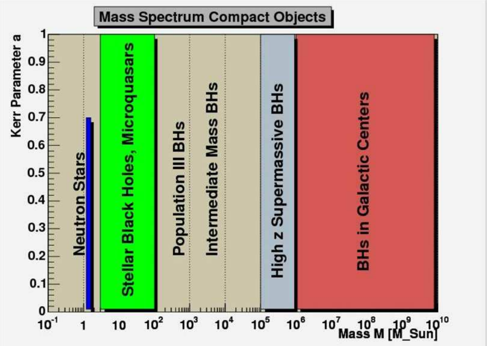

Fig. 1. Fundamental plane of compact objects spanned by mass (in units of solar masses) and spin *a* (in dimensionless units) for neutron stars, stellar and supermassive black holes [Camenzind (2006)]. The latter ones are either born as Pop III black holes or as massive black holes at high redshifts in dark matter haloes.

It turns out that the mass of a black hole only enters as a length scale in the form of the gravitational radius $r_g = GM/c^2$ and a unit of time, usually called light crossing time $lct = r_g/c$, which is 50 micro-seconds for a 10 solar mass black hole. The spin, however, is a crucial parameter which is relevant for many important phenomena near the horizon. Especially, the existence of the ergosphere is a consequence for a spinning black hole. The next parameter which enters the game is the accretion rate in units of Eddington rates. It turns out that the accretion rate alone does not uniquely specify the accretion state of a black hole. In time–dependent accretion, the accretion state will depend on the fact whether the BH is in the increasing phase or the decreasing phase of an accretion event. Since astrophysical BHs cover a whole range of accretion rates from extremely low accretion rates in elliptical galaxies upto even super–Eddington accretion in the high-redshift universe, it has been largely overlooked that a standard accretion disc is certainly not a solution for low accretion rates. In fact, the outer discs are always standard ones, while near the horizon a largely radiatively inefficient disc will be formed, sometimes called ADAF. This is a consequence of the existence of the innermost stable orbit (ISCO) around BHs. For causality reasons, accretion towards the horizon, whether pure hydro or MHD, is always hot in the sense of free–fall temperatures. These things are now well documented for X–ray binary systems (see van der Klis 2008; Done et al. 2008), but they have not been thouroughly applied to supermassive BHs. This separation of a hot inner disc from a cool outer disc goes under the name of *truncation paradigm*. The transition radius between the two discs is often called *truncation radius* (for a modern example, see Oda et al. 2007). The position of the truncation radius is not only a function of the accretion rate, but also of the history of the accretion states, in other words, truncation is a real hysteresis effect. The internal state of the disc is probably fully turbulent and similar to galactic discs. Truncation is now supported by X-ray timing.

2. How to define the vicinity of accreting black holes?

A black hole is a region in space where gravity is so strong that nothing, not even light, can escape. While they cannot be observed directly, black holes can be detected by the effect their immense gravity has on nearby matter and photons. The boundary of a black hole is called the event horizon. It is an invisible boundary, but once across it you are pulled in towards the black hole with no means of escape. The radius of this event horizon is equal to 3 km times the mass of the black hole (in units of solar masses), when it is non–rotating.

The innermost region around black holes is dominated by the accretion disc, in which magnetic fields are advected from the outer parts (Fig. 2). Accretion discs around black holes consist in general of an inner hot disc with temperatures in the range of $10^9 - 10^{12}$ K, often called ADAF, and a truncated optically thick cool outer disc with effective temperatures scaling as $T_{\rm eff} \simeq 10^5\,{\rm K}\,(R/R_{\rm ISCO})^{-3/4}$. In supermassive black holes this outer disc extends to the self–gravity radius which is typically at a few thousand Schwarzschild radii. Relativistic jets are launched only from the inner hot disc probably via magnetic processes,

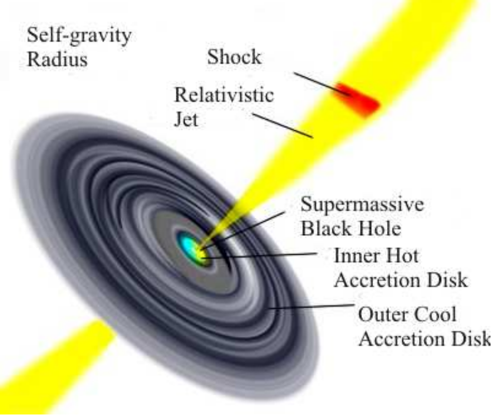

Fig. 2. Accretion discs around black holes consist in general of an inner hot disc and a truncated optically thick cool outer disc. In supermassive black holes this extends to the self–gravity radius which is typically at a few thousand Schwarzschild radii. Relativistic jets are launched only from the inner hot disc via magnetic processes, time–dependent shock structures propagate along the magnetic channels.

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The vicinity of black holes extends therefore from the horizon upto the self–gravity radius $r_{\rm sg} \simeq 1000\,r_{\rm g}$, corresponding to about 0.1 lightyear for a supermassive black hole of a few billion solar masses. Mass is accreting from the parsec–scale and appears as broad lines in Seyfert galaxies and quasars, before it reaches the outer edge of the disc. This entire structure is embedded into a nuclear star cluster in spiral galaxies, such as Seyfert galaxies (Davies et al. 2007) or into an elliptical bulge in elliptical galaxies, such as M87 in the Virgo cluster. In the latter case, no dusty torus is present and accretion occurs from the parsec–scale disc detected in HST observations.

3. Strong gravity near black holes

The strong gravity near the horizon affects physical processes in various ways. Frame–dragging due to the spin of the black hole forces plasma to corotate with the horizon and a strong outward-flowing Poynting flux is generated near the horizon. Strong gravity also affects the propagation of photons which escape from discs and jets. For the details of the Kerr geometry, see e.g. Camenzind (2007).

The spin of a black hole affects the rotational motion of plasma near the horizon. The angular frequency Ω of a plasma blob is determined by its specific angular momentum j and the frame–dragging ω

$$\Omega = \omega + \frac{\alpha^2}{R^2}\,\frac{j}{1-\omega j}\,. \tag{1}$$

Since the redshift factor α vanishes near the horizon, the angular frequency Ω is completely dominated by frame–dragging near the horizon, independent of the angular momentum in the disc. In fact, j stays roughly constant in the innermost part of an accretion disc, since angular momentum transport is no longer effective within the innermost stable orbit (ISCO). This behaviour of Ω is shown in Fig. 3 for two different spin parameters a. For low spin, a boundary layer is formed with a maximum in Ω, i.e. Ω' is positive near the horizon and a decoupling occurs between the horizon and the adjacent disc. Only for a minimum spin $a \geq 0.85$, the shear produced by differential rotation is always directed outwards also near the horizon. For a spin of 0.943 the ISCO moves even into the ergosphere in the equatorial plane.

This effect is very important for understanding the winding of magnetic fields near the horizon [Hawley (2005)]. The toroidal magnetic field $T = RB_\phi$ essentially satisfies the same diffusion equation as in Newtonian physics [Camenzind (2007)]

$$\begin{aligned}\partial_t T \;&+\; \alpha(\boldsymbol{v}_{\rm p}\cdot\nabla)T - \alpha R^2\,\nabla\cdot(T\boldsymbol{v}_{\rm p}/R^2)\\ &= \alpha R^2\,\nabla\cdot(\eta\nabla T/\gamma R^2) + \alpha R\,(\boldsymbol{B}_{\rm p}\cdot\nabla)\,\Omega\,. \end{aligned}\tag{2}$$

Radial fields advected onto the horizon of the black hole will produce via the last term a strong winding and a continuous poloidal current flowing through the inner disc.

This leads to an understanding of the Blandford–Znajek mechanism (BZ). The unavoidable rotation of plasma inside the ergosphere forces magnetic fields to rotate as well. The resulting magnetic twist propagates away from the BH, creating an outgoing Poynting

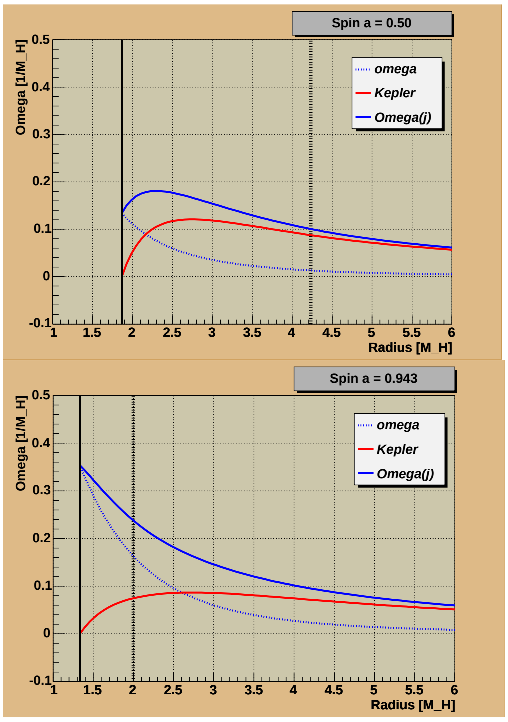

Fig. 3. Angular frequency (blue solid line) of accreting plasma near the horizon of black holes. The dotted line is the frame–dragging frequency ω. Upper: Kerr parameter $a = 0.50$; lower: Kerr parameter $a = 0.943$ (ISCO at the ergosphere, dotted vertical line).

flux. As a feedback action, magnetic forces push plasma into orbits with negative mechanical energy at infinity before they plunge into the BH (Camenzind 1996). The total flux of energy is conserved: it changes from almost purely mechanical near the horizon to Poynting flux further away, which is then ultimately transformed into mechanical energy when the flow is collimating.

Observations of the Fe K-alpha emission from the Seyfert 1 galaxy MCG-6-30-15 allow measurements of its spectral line profile at energies of 6.4 keV. Such line profiles have a characteristic narrow bright blue-shifted peak and also a wide faint gravitationally red-shifted peak. The blue shift results from the Doppler motion of the matter in the disc as it rotates around the rotating black hole (Kerr metric). The red shifted peak results from increased wavelengths as the radiation escapes from the gravitational potential well about the supermassive black hole, thus losing energy. The red peak has energies which correspond to one-third the speed of light which indicates emission with relativistic velocities. Such line profile structures tell us a great deal about plasma conditions and dynamics as well as the space-time geometry around a supermassive black hole (Camenzind 2007).

4. Accretion states, turbulence and AGN classification

Black hole candidates (BHCs) are known to show different spectral states in the X- and γ-ray domain.

4.1. Accretion states and X–ray spectra

The two main spectral states are the Low/Hard State (LHS), with the high energy spectrum described by a cut-off power-law (typically $\Gamma \sim 1.5$ and $E_{\rm cut} \sim 100$ keV), and the High Soft State (HSS) with a thermal component peaking at few keV (Fig. 4) and the high energy power-law much softer ($\Gamma > 2.2$) (Zdziarski 2000). Usually, this spectral variability is interpreted as due to changes in the geometry of the central parts of the accretion flow (see Done, Gierliński & Kubota 2007 for a recent review). In the LHS the standard geometrically thin and optically thick disc would be truncated far away from the last stable orbit (Fig. 6). In the innermost parts, a hot accretion flow is responsible for the high energy emission, via thermal Comptonisation of the soft photons coming from the truncated disc. In the HSS, the optically thick disc would extend close to the minimum stable orbit producing the dominant thermal component. The weak non-thermal emission at higher energy is believed to be due to up-scattering of the soft thermal disc emission in the inner hot disc.

The spectral evolution of the outburst of a black hole in low-mass system is often investigated by plotting the flux of the source as a function of the X-ray hardness. In this Hardness–Intensity–Diagram (HID, Fig.

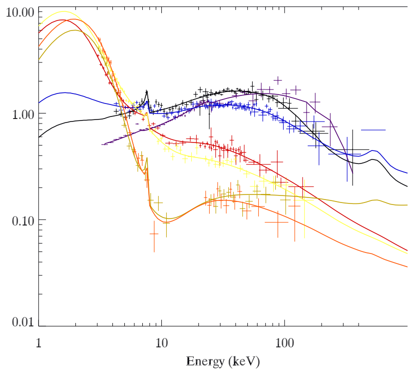

Fig. 4. Joint JEM-X, IBIS and SPI INTEGRAL energy spectra of GX 339−4 during periods 1 (black, LHS), 2 (blue, LHS), 3 (red, HIMS), 4 (yellow, HIMS), 5 (green, HSS), 7 (orange, HSS) in the 2004 outburst [Del Santo et al. 2008].

5), GX 339−4 e.g. follows a **q**-like pattern throughout the outburst (Dunn et al. 2008). The HSS and LHS correspond respectively to the left and right hand side vertical branches of the **q**. State transitions occur when the source crosses the upper or lower horizontal branches, those constitute intermediate states between the LHS and HSS. Depending on the location of the source on a horizontal branch, Belloni et al. (2005) have identified two different flavours of intermediate state: the Hard Intermediate State (HIMS) and Soft Intermediate State (SIMS). An alternative states classification defines the upper horizontal branch as VHS (see McClintock & Remillard 2006).

During a typical outburst the source starts in a faint LHS, moves upward along the LHS branch, then moves leftward towards the HSS along the VHS branch, and when luminosity decreases the source moves down along the HSS before transiting right back to the LHS along the lower horizontal branch, and then back to quiescence in the LHS. A puzzling property of this evolution is that the spectral changes in GX 339−4 lag the variations of the luminosity: hard-to-soft state transitions during the rising phase occur at higher luminosities than the soft-to-hard ones during the declining phase. This so-called "hysteresis" is also observed in many other LMXBs such as GRS 1758–258 and 1E 1740.7–2942.

In the EQPAIR model, emission of the disc/corona system is modeled by a spherical hot plasma cloud with continuous acceleration of electrons illuminated by soft photons emitted by the accretion disc. At high energies the distribution of electrons is non-thermal, but at low energies a Maxwellian distribution with temperature kT_e is established.

The properties of the plasma depend on its compactness $\ell = L\sigma_T/Rm_ec^3$, where L is the power of the source supplied by different components, R the radius of the sphere (about 10 gravitational radii) and σ_T is the Thomson cross-section. ℓ_s, ℓ_{th}, ℓ_{nth} and $\ell_h = \ell_{th} + \ell_{nth}$ correspond to the power in soft disc photons entering the plasma, thermal electron heating, electron acceleration and total power supplied to the plasma. The energy balance in the Comptonising medium depends mainly on the ratio ℓ_h/ℓ_s. For larger values of ℓ_h/ℓ_s, the energy of the electrons is on average higher and, as a consequence, spectrum from Comptonisation is harder. From the best-fit parameters, one can indeed measure lower values of ℓ_h/ℓ_s as the spectra become softer. If in the spectral fits we chose to fix $\ell_s = 10$, the variations of ℓ_h/ℓ_s are only due to changes in ℓ_h. If one considers the absolute values of F_{Compt} and F_{bb}, the thermal disc flux changes by more than one order of magnitude, while the Comptonised flux decreases by a factor of about three. The softening one observes is therefore caused by a dramatic increase in the disc thermal flux in the hot disc associated with a modest reduction of the electron heating rate. The disc emitting area and geometry of the corona are not constant during the transition. The radiating disc surface area appears smaller in the HSS (periods 5 and 7) than in the intermediate states (periods 3 and 4). This suggests that the corona becomes more compact as the disc temperature increases. This would be consistent with the truncation radius of the accretion disc moving closer to the black hole in the HSS.

4.2. HIDs and the zoo of AGN

Source states are primarily classified based on the relative location in the hardness-intensity diagram (HID) and power spectral characteristics. The following states are distinguished (see Fig. 5 for a schematic HID): the *low-hard state* (LS), characterized by a hard power-law dominated X-ray spectrum and strong, low-frequency band-limited noise in the power spectrum, the *high-soft state* (HS) with a soft, disc black-body dominated X-ray spectrum and little rapid variability, and an *intermediate state* (IMS), with both power law and disc black-body contributing appreciably to the spectrum and exhibiting the most complex variability characteristics, including most of the QPOs. All three states occur over a wide range in luminosity, although towards the lowest luminosity levels sources consistently enter the LS. Within the IMS we further distinguish a *hard intermediate state*, which shows somewhat harder X-ray spectra (although not as hard as in the LS) and power spectra with moderately strong band limited noise (BLN; somewhat weaker and at higher frequency than that in the LS), and the *soft intermediate state* with softer X-ray spectra (not as soft as in the HS) and power spectra lacking this BLN component but showing power-law noise. The hard IMS has characteristics in common with the LS and the soft IMS with the HS; the hard–soft IMS transition may be the most physically abrupt one between what may considered to be just two basic black hole states: hard and soft.

In Fig. 5 we also indicate the position of the *j*et-line which marks the transition between radio-loud and radio-quiet states (QSOs and Quasars) [Fender et al. 2004; Körding et al. 2006]. The jet-line in Fig. 5 is a generic one and in individual cases the transition between radio-loud and radio-quiet states is not always a sharp one. Radio emission in the radio-quiet (also known as "quenched" states) is not ruled out, but occurs at flux levels of up to a factor 50 lower than compared to the radio-loud states, similar to AGN. Weak radio galaxies populate then the LS branch.

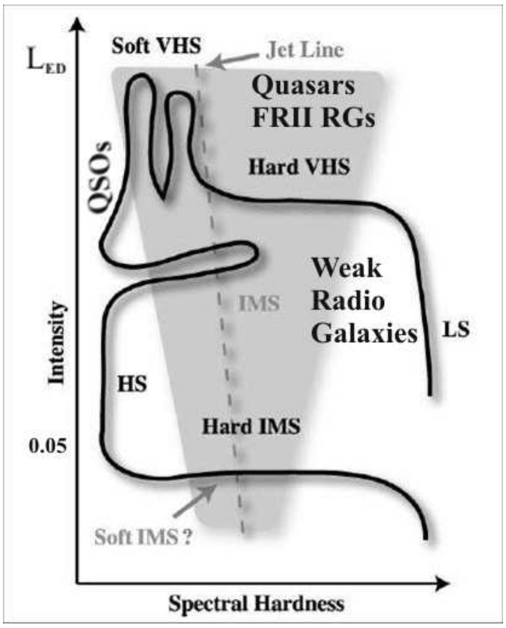

Fig. 5. The canonical black hole states, their location in the hardness-intensity diagram and location of various AGN. The track shown is an example of those that are followed by black hole transients in outburst, but persistent sources too can follow parts of such as track (such as Cyg X-1). The grey area indicates the IMS region, which we further distinguish in the hard- and soft VHS and the hard IMS. Also shown is the jet-line, indicating the transition to and from the HS. The jet-line marks a transition between radio–loud to a radio–quiet state.

4.3. High frequency turbulence

These two states of accretion are not only responsible for two drastically different components in the spectra of black hole candidates. The variability properties of the two components are also different – the cooler component is very stable, while the hotter component varies strongly over a broad range of time scales (Fig. 7). Many authors have suggested that variability properties of these spectral components are caused by the difference in the internal dynamics of the flows. Both flows are believed to be turbulent with a similar characteristic turbulence time scales – comparable to the orbital period at a given radius. The difference lays in the dynamics of the ra-

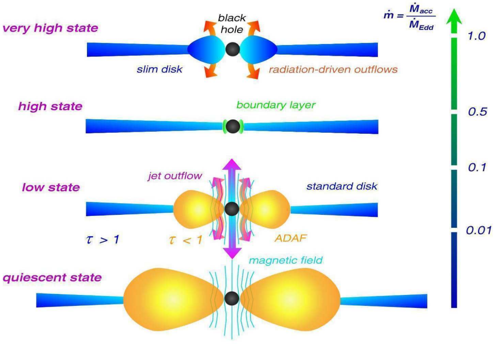

Fig. 6. Truncation paradigm: The spectral states of accreting black holes are essentially determined by the accretion rate. For high accretion rates near the Eddington rate, radiation pressure will drive outflows from the inner slim disc. For accretion rates below the Eddington rate, a hot gap appears between the horizon and the ISCO. This hot inner disc grows with decreasing accretion rate and is the source of relativistic outflows driven by magnetic processes.

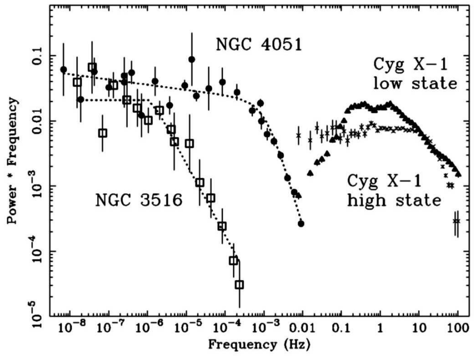

Fig. 7. Comparison of power density spectra of hard X–ray fluxes as measured for Cyg X-1 and two Seyfert galaxies [McHardy et al. 2006].

dial motion. The radial flow of matter in the cool flow (thin disc) is extremely slow and it effectively smears out and erases any perturbations introduced to it, while the radial velocity in the hotter flow is orders of magnitude faster [Titarchuk et al. 2007]. Such "faster" flow can advect perturbation, added to the flow at large distance from the black hole, down to the innermost region where most X-rays are emitted. This assumption then allows one to probe the geometry of the flow at a range of distances around the black hole, even in the regions where the flow is too cool to produce observable emission in X-rays. This model naturally explains how the characteristic amplitude of variations depends on the time scale of interest and how changes in the geometry of the accretion flow affect the observed variability. Furthermore it predicts that shorter perturbations, which are introduced to the flow at small radii, should come on top of longer perturbations produced at much larger radii. This way the amplitude of shortest variations "knows" about slower changes of the X-ray flux – in excellent agreement with observations.

4.4. Scaling to supermassive BHs

A long-standing question is whether active galactic nuclei vary like Galactic black hole systems when appropriately scaled up by mass. If so, we can then determine how AGN should behave on cosmological timescales by studying the brighter and much faster varying Galactic systems. As X-ray emission is produced very close to the black holes, it provides one of the best diagnostics of their behaviour. At characteristic time-scale, which potentially could tell us about the mass of he black hole is

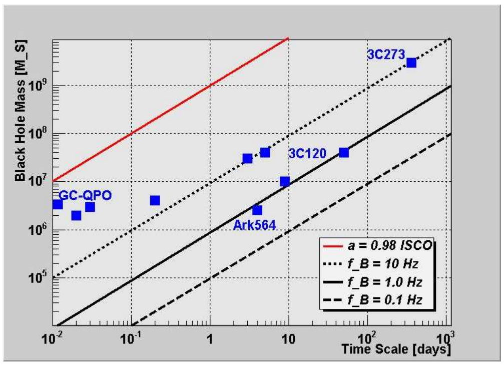

Fig. 8. The scaling of break frequency and low–frequency QPOs with mass. The break frequency observed in Seyfert galaxies is just the scaled time–scale of Cyg X-1 (solid line). Similarly, the episodic knot ejection time–scale of about one knot per year in the quasar 3C 273 is just scaled up from LF QPOs in Cyg X-1 (dotted line).

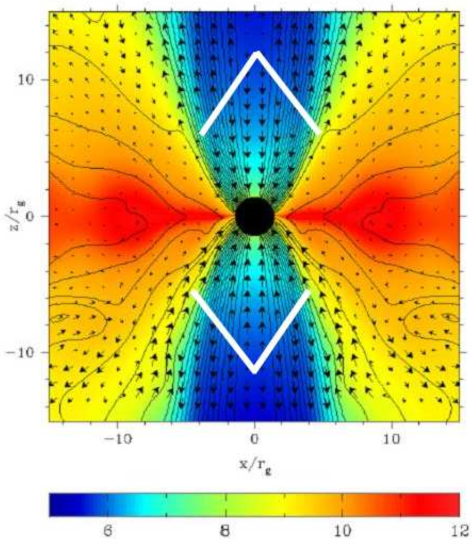

Fig. 9. Magnetosphere of rotating black holes are formed under accretion conditions. Energy and angular momentum extraction requires a plasma loading of the magnetosphere. Plasma will accrete onto the horizon within the stagnation surface (white lines), plasma escapes outside the stagnation surface.

found in the X-ray variations from both AGN and Galactic black holes. After correcting for variations in the accretion rate, the timescales can be physically linked, revealing that the accretion process is exactly the same for small and large black holes (Fig. 8). Strong support for this linkage also comes from the permitted optical emission lines in AGN whose widths (in both broad-line AGN and NLS1 galaxies) correlate strongly with the characteristic X-ray timescale, exactly as expected from the AGN black hole masses and accretion rates. AGN therefore are just scaled-up Galactic black holes [McHardy et al. (2006)].

5. On jet launching

Jets are a common outcome of accretion driven by MRI turbulence [Beckwith et al. 2008], though disc driven outflows are generally not highly relativistic. In order to tap the rotational energy of BHs, the BH magnetosphere has to be loaded by plasma in the ergosphere (Fig. 9). Spine–sheath jets are the natural structure formed – the sheath is linked to the inner disc, the spine to the black hole magnetosphere.

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