Spectral transition for ULXs - super-Eddington luminosity from rapidly spinning moderate mass BHs?

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Abstract. The X-ray luminosity of ultraluminous compact X-ray sources (ULXs) reaches 10^{39-40} erg/s. To avoid super-Eddington luminosity high black hole masses of up to 100 M_{solar} are required. But severe problems are encountered with this interpretation. We suggest that the high luminosities are truly super-Eddington, but that the source of energy is not accretion, but magnetic extraction of energy from a rapidly rotating spinning black hole. The dissipation of this energy fills the corona above the disk with moderately relativistic particles, part of which impinge on the accretion disk underneath and provide its super-Eddington luminosity. At the same time the super-Eddington radiation pressure from below is confined by the particle impact pressure from above. We discuss requirements and derive order of magnitude estimates for magnetic field strength, particle density, relativistic γ-factor and surface density of the disk.

1 Observations of ULXs and interpretations

In the arms of nearby spiral galaxies luminous point-like X-ray sources were detected. Due to their variability these sources are thought to be single objects. The X-ray luminosity reaches 10^{39-40} erg/s. These objects are therefore called ultraluminous compact X-ray sources (ULXs). If accretion is the source of energy and the Eddington luminosity should not be exceeded relatively high black hole masses, of up to 100 M_{solar} are required. ASCA spectroscopy brought further information for several sources. The majority of the spectra can be reproduced by a multi-color accretion disk. The observed high inner disk temperatures are a severe problem. To solve this problem the inner disk geometry around a rapidly rotating black hole was discussed. Another approach uses the concept of a slim accretion disk. - For a review see Makishima, 2001, these Proceedings.

The discovery of spectral transitions from ultraluminous compact X-ray sources strongly supports the scenario of accreting black holes. We show in Figure 1 the distribution of X-ray sources in soft state (standard accretion disk reaches inward to the last stable orbit) or hard state (standard disk outside + coronal flow/ADAF in the inner region) in the $L_x - M$ plane. ULXs are drawn where their luminosity would be the Eddington luminosity.

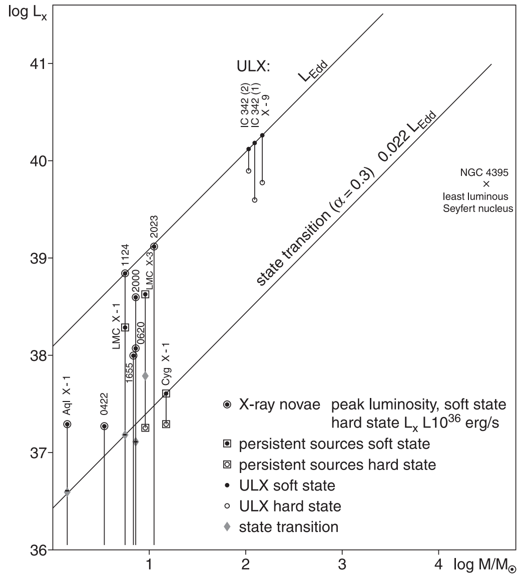

Fig. 1. X-ray luminosity as a function of black hole mass for LMXRBs, HMXRBs and ULXs. For comparison the least luminous Seyfert nucleus is added in the diagram. The upper line indicates the Eddington luminosity, the lower line the luminosity of spectral transition, soft state above, hard state below

2 ULXs moderate mass black holes, but truly super-Eddington luminosity ?

The discovery of hard/soft spectral transitions, expected for an accretion rate $\dot{M} \approx \frac{1}{10}\dot{M}_{\rm Edd}$ (compare modeling of spectral transitions by Esin et al. 1997; analysis of the transition by Meyer & Meyer-Hofmeister 2000) implies an accretion luminosity of $L_x = 10^{38}$, observed are $L_x \approx 10^{40}$erg/s $\approx 10 \cdot L_{\rm Edd}$. The high luminosity is clearly not accretion luminosity. We suggest it could be extracted from a spinning black hole.

The total spin energy available is $E_{\rm rot} \leq \frac{1}{2}Mc^2 \approx 10^{54}$erg. If a fraction f goes into L_x (the larger part might go into a jet), the lifetime is t=$fE_{\rm rot}/L_x = f \cdot 10^{6.5}$yr. This points to young objects and agrees with the location in young star forming regions.

But how can the super-Eddington luminosity be possible? Our suggestion is the following: relativistic particles in a strong magnetic field impinge from above onto the innermost accretion disk. Their energy is deposited in the accretion disk and reprocessed into X-rays. Then the super-Eddington radiation pressure can be balanced by the particle impact pressure.

Consistency of the model requires:

- (a) the particles in the corona reach relativistic energies
- (b) the energy extraction gives the high luminosity

- (c) the confinement of the relativistic particles
- (d) the disk surface density is high enough to stop the particle penetration
- (e) the confinement of the magnetic field by the disk below

With obvious assumptions we estimate the following values:

(a) The density ρ of the gas can be estimated from the accretion rate in the hot corona $\dot{M} \approx 4\pi r^2 \rho v_r$, $\quad \rho = nm$ with n, m particle number density and mass, radial drift velocity $v_r \approx \alpha^\star c, \alpha^\star < 1, c$ velocity of light. The luminosity from the reprocessing of the energy of the impinging particles can be written as $L_x = 2\pi r^2 \eta \gamma n m c^3$ (πr^2 disk area, $\gamma m c^2$ energy of particles) if a fraction η reaches the disk surface below. With the assumption $\dot{M} = \frac{1}{10}\dot{M}_{\rm Edd}$ (spectral transitions) n can be deduced from $\dot{M}$. The value of γ follows as $20\alpha^\star/\eta$.

(b) In our scenario the flux tubes connecting the black hole region with the inner disk are twisted due to the differential rotation between black hole and disk. The extracted energy $\dot{E}$ is proportional to the volume, magnetic stress and the twisting rate of the field. The energy extracted near the black hole horizon (Schwarzschild radius $r_{\rm S} = \frac{2GM}{c^2}$) is then of order of magnitude

$$\dot{E} = \frac{4\pi}{3} {r_{\rm S}}^3 \frac{B^2}{4\pi} \Omega_{\rm BH} = \frac{B^2}{3\pi}\sqrt{GM{r_{\rm S}}^3}. \tag{1}$$

Equating $\dot{E}$ to the luminosity L_x with $L_{40} = \frac{L_x}{10^{40}}$erg/s the magnetic field estimate becomes

$$B = 10^{8.5} \frac{{L_{40}}^{1/2}}{M/10M_\odot} \text{gauss}. \tag{2}$$

(c) The relativistic particles require a magnetic energy density for their confinement similar or larger than their own. This leads to a similar estimate for the magnetic field as above.

(d) The strong magnetic field suppresses the (magnetic) friction ("Balbus-Hawley instability"). If the magnetic field energy density becomes comparable to the gas pressure frictional heating is quenched, the disk then is practically isothermal, the disk temperature is determined by the reprocessing of the energy of impinging particles. From the temperature corresponding to the luminosity, the gas pressure equal to the magnetic pressure ($B = 10^{8.5}$ gauss) and surface density equal to density times pressure scaleheight we get $\Sigma_{\rm d} \approx 10^{4.6}(r/r_s)^{5/4}(M/10M_\odot)^{3/4}{L_{40}}^{1/8}$g/cm^3, large enough to stop the penetration of the impinging relativistic particles.

(e) Taking the values for the mass in the disk derived above we see that the gravitational pull exceeds the expansion force of the magnetic field by far, so that the magnetic field can be held by the disk.

From these estimates it appears that this might be a viable model deserving further investigation.

References

1. A. Esin, E. McClintock, R. Narayan et al. ApJ 489, 865 (1997)
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