Clumpy accretion flows in Active Galactic Nuclei

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ABSTRACT

We discuss the fuelling of the central black hole in Active Galactic Nuclei (AGN) within the framework of clumpy accretion flows.
Shocks between elements (clumps) forming the accretion flow are at the origin of the radiation and also provide a mechanism of angular momentum transport.
We expect a cascade of shocks in which optically thick shocks give rise to optical/UV emission, and optically thin shocks give rise to X-ray emission.
We obtain X-ray to UV luminosity ratios (L_X/L_{UV}) always smaller than unity, and lower values in massive objects compared to less massive sources, consistent with the observed α_{OX} - l_{UV} anticorrelation.
We derive a characteristic X-ray variability timescale within our model and compare it with the observed X-ray Power Spectral Density (PSD) break time scale.
The predicted dependence of the X-ray variability time scale on black hole mass and accretion rate agrees remarkably with the observational relation obtained by McHardy et al. (2006). We further discuss X-ray spectral properties, in particular we compare the predicted hard X-ray power law slope with observations.
Model results are able to reproduce the range of photon index typically measured in Seyfert galaxies and quasars. Spectral and variability properties are closely related, with steeper spectra being associated with shorter characteristic timescales. This agrees with the observed « spectral-timing » correlation.

Optically thick shocks and UV emission

We consider clumps of mass $M_C = M_{33} \cdot 10^{33}$g at a distance of ~100 Schwarzschild radii moving at the local free-fall velocity in the gravitational field of the central black hole.

A collision between two such elements leads to an optically thick shock in which a fraction of the kinetic energy of the clumps is radiated at the photosphere $R_{max} = 3 \cdot 10^{15} M_{33}^{1/2} \zeta_{UV}^{-1/4}$ cm.

$$T = \left(\frac{L_{UV}}{4\pi\sigma R^2_{max}} \right)^{1/4} \cong 2.6 \cdot 10^4 \, \eta_{1/3}^{1/4} M_{33}^{-1/8} \zeta_{UV}^{-3/16} \text{ K}$$

photospheric temperature

T is of the order of the blue bump temperature, optically thick shocks may be at the origin of the optical/UV emission in AGN.

Optically thin shocks and X-ray emission

Following the optically thick shocks, expanding envelopes overlap in the central regions leading to further shocks, this time in optically thin conditions.

$$\epsilon = \left(\frac{R_{max}}{R_{\zeta_{UV} Rs}} \right)^3 \cong 10^{-3} M_{33}^{3/2} \zeta_{UV}^{-15/4} \left(\frac{M_{BH}}{10^9 M_\odot} \right)^{-3}$$

volume filling factor of the post-shock configuration

The relative importance of the filling factor defines two classes of objects:

Class S: $\varepsilon \sim 1$, $M_{BH} \leq 10^8 M_0$ — large filling factor → **Seyfert galaxies**

Class Q: $\varepsilon << 1$, $M_{BH} \geq 10^9 M_0$ — small filling factor → **Quasars**

Ions tranfer energy to electrons through Coulomb collisions, while electrons radiate via Compton emission.

Equilibrium: $L_{Coulomb} = L_{Compton}$ → electron energy E_e

The resulting electron temperature is of a few hundred keV:
the Compton cooling of hot electrons gives rise to X-ray emission.

Two cases, **Case A** and **Case B**, are defined according to the time scale condition: radiation time shorter or longer than accretion time: $t_{Compton}$ < or > t_{dyn} ?

Case A: $\langle L_X \rangle \cong 4.9 \cdot 10^{43} E_{p,MeV}^{4/7} \zeta_{UV}^3 M_8^3 u_\gamma^{5/7} n_8^{9/7}$ erg/s

Case B: $\langle L_X \rangle \cong 2.1 \cdot 10^{43} E_{p,MeV}^{4/7} \zeta_{UV}^{3/2} M_8^2 u_\gamma^{-2/7} n_8^{9/7}$ erg/s

X-ray variability properties and power spectral density (PSD)

We derive a characteristic X-ray time scale associated with the heating/cooling process of the electrons responsible for the X-ray emission.

$\tau_X \sim \tau_{heat} \sim \tau_{cool}$ $\quad$ $\tau_X \cong 5 \, \eta_{1/3}^{-1} \zeta_{UV}^3 \dot{M}_0^{-1} M_8^2$ d $\quad$ characteristic X-ray time scale

Comparison of the model time scale (τ_X) with the measured power spectral density break time scale ($T_B = 1/\nu_B$) shows good agreement in both magnitude and trend.

Empirical relation between break time scale, black hole mass, and accretion rate (McHardy et al. 2006):

$$T_B \approx \frac{M_{BH}^{1.12}}{\dot{m}_E^{0.98}} \qquad \dot{m}_E \approx L_{bol}/L_E$$

L_{bol}: bolometric luminosity
L_E: Eddington luminosity

observation $T_B \propto \frac{M_{BH}^{2.1}}{\dot{M}^{0.98}}$ $\quad$ $\tau_X \propto \frac{M_{BH}^2}{\dot{M}}$ **model**

⇒ **The model dependence is in agreement with the observational relation obtained by Mc Hardy et al. (2006), without additional parameters**

Luminosity ratios L_X/L_{UV}

Class S:

Case A : $\frac{\langle L_X \rangle}{\langle L_{UV} \rangle} \cong 0.40 \, f_1^{9/7} \eta_{1/3}^{-2/7} \zeta_{UV}^{-1/14} E_{p,MeV}^{4/7} \dot{M}_0 M_8^{-1}$

Case B : $\frac{\langle L_X \rangle}{\langle L_{UV} \rangle} \cong 0.17 \, f_1^{9/7} \eta_{1/3}^{-9/7} \zeta_{UV}^{10/7} E_{p,MeV}^{4/7}$

Class Q:

Case A : $\frac{\langle L_X \rangle}{\langle L_{UV} \rangle} \cong 0.01 \, f_{1/2}^{9/7} \eta_{1/3}^{-2/7} \zeta_X^{15/14} \zeta_{UV}^{-8/7} E_{p,MeV}^{4/7} \dot{M}_1 M_9^{-1}$

Model results:

- L_X/L_{UV} always smaller than unity
- $0.01 < L_X/L_{UV} < 0.8$
- L_X/L_{UV} smaller in Class Q than in Class S

Observations:

- α_{OX} - l_{UV} anticorrelation
- majority of objects lie within the predicted range
- trend of decreasing L_X/L_{UV} with increasing luminosity
→ in agreement with model results

Sample (number of objects)	$\langle \alpha_{OX} \rangle$	$\langle L_X/L_{UV} \rangle_{obs}$	$\langle L_X/L_{UV} \rangle_{model}$
low-redshift Seyfert 1 (37)	−1.34(1)	0.39	0.40 $\dot{M}_0/M_8$
COMBO (47)	−1.36(2)	0.34	0.40 $\dot{M}_0/M_8$
BQS (45)	−1.46(2)	0.19	0.17
SDSS main (155)	−1.51(1)	0.14	-
high-redshift luminous AGN (36)	−1.72(1)	0.04	0.01 $\dot{M}_1/M_9$
most luminous QSO (33)	−1.80(3)	0.02	0.01 $\dot{M}_1/M_9$

Samples from:
Strateva et al. (2005), Steffen et al. (2006), Just et al. (2007)

X-ray power law spectra as a result of Comptonization

We compute the hard X-ray power law spectral slope as a function of source parameters, using estimates of the electron temperature and optical depth derived within our model.

We follow Titarchuk & Lyubarskij (1995) who give the exact analytical solution for the spectral index without restriction on plasma parameters.

non-relativistic case: $\alpha = \sqrt{9/4 + \beta/\Theta} - 3/2$

relativistic case: $\alpha = \frac{\beta - \ln d_0(\alpha)}{\ln(4\Theta^2)}$

Class S: $\Theta = \frac{kT_e}{m_e c^2} \sim 0.6$

Case A: $\tau \cong 0.2 \, n_S \zeta_{UV} M_8$ ⇒ **Γ ~ 1.9**

Case B: $\tau \cong 0.1 \, n_S \eta_{1/3}^{-1} \zeta_{UV}^{5/2} \dot{M}_0^{-1} M_8^2$ ⇒ **Γ ~ 2.1**

Class Q: $\Theta = \frac{kT_e}{m_e c^2} \sim 1.4$

Case A: $\tau \cong 0.4 \, n_Q \zeta_X M_9$ ⇒ **Γ ~ 1.5**

We obtain photon index values in the range Γ ~ 1.5-2.1, covering the range of spectral slopes typically observed in Seyfert galaxies and quasars.

For a given black hole mass:

⇒ steeper spectra in higher accretion rate systems (B) than in lower accretion rate objects (A)

It may account for the **Γ - L/L_E correlation** observed in different AGN samples.

« Spectral-timing » relation

X-ray spectral and variability properties are closely related.

Combining the above obtained results:
⇒ shorter characteristic timescales are associated with steeper spectra and vice versa

This agrees with the recently discovered **spectral-timing correlation** (Papadakis et al. 2009).

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