Black Hole Outflows

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P Cygni profile of iron K- alpha: *outflow* with $\nu \simeq 0.1c$
Pounds et al., 2003; King & Pounds, 2003: \( v \sim 0.1c - 0.3c, \ \xi \sim 10^4 \)

measured ionization parameter \( \xi = \frac{L_i}{NR^2} \sim 10^4 \)

=> mass outflow rate

\[
\dot{M}_{\text{out}} = 4\pi bm_p NR^2 v \sim 1M_\odot \text{ yr}^{-1} \sim \dot{M}_{\text{Edd}}
\]

=> momentum outflow rate

\[
\dot{M}_{\text{out}} v \sim 0.1\dot{M}_{\text{Edd}} c \sim \eta \dot{M}_{\text{Edd}} c = \frac{L_{\text{Edd}}}{c}
\]

=> photons scatter ~ once before escaping: Eddington outflow has \( \tau \sim 1 \)

Tombesi et al., 2010a,b: > 35% of a sample of 50 AGN show similar outflows: solid angle factor \( b = \Omega/4\pi > 0.6 \)
Super-Eddington Accretion

disc
Super-Eddington Accretion

disc

most mass expelled as outflow
Super-Eddington Accretion

most photons eventually escape along cones near axis

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Super-Eddington Accretion

most photons eventually escape along cones near axis

don average photons give up all momentum to outflow after ~ 1 scattering

most mass expelled as outflow

disc
Super-Eddington Accretion

most photons eventually escape along cones near axis

on average photons give up all momentum to outflow after $\sim 1$ scattering

$$\dot{M} v \approx \frac{L_{\text{Edd}}}{c}$$
conversely if we *assume* Eddington outflow, then mass and momentum conservation =>

\[ v \sim \eta c, \quad \xi \sim 10^4 \]

Eddington outflow \(\leftrightarrow\) X—ray lines with \(v \sim 0.1c\)

*effect on galaxy must be significant*

SMBH binding energy \(\eta M c^2\)

exceeds bulge binding energy \(\eta M_b \sigma^2\)
swept-up ambient gas, mildly shocked

outer shock driven into ambient gas

ambient gas

cooling shocked wind (‘momentum – driven’)

Eddington wind, $v \sim 0.1c$

(single scattering limit)

SMBH

shock pattern near AGN
The image shows a diagram of a wind from a Supermassive Black Hole (SMBH) interacting with interstellar gas. The diagram illustrates the temperature $T$, density $\rho$, and velocity $u$ profiles along the $z$ axis. The wind from the SMBH is marked with a velocity $u \approx 0.1c$. The cooling shocked wind and snowplough regions are indicated with distinct changes in temperature and density profiles. The contact discontinuity is shown as a boundary between the inner wind and the outer interstellar medium (ISM) shock. King, 2010 refers to the source or reference for this diagram.
NGC 4051
Pounds & Vaughan, 2011

evidence for shock structure: other velocity components are present
ionization parameter decreases with outflow velocity as required by mass conservation

\[ \dot{M}_{\text{out}} \propto \frac{L_i v}{\xi} = \text{const} \]
Figure 8. Outflow velocities derived from the Gaussian fitting plotted against the optimum ionization parameter for each parent ion stage. Also shown by asterisks are the parameters of the four photoionized absorbers derived from XSTAR modelling of the RGS absorption spectra, together with a velocity/ high-ionization point to represent the putative pre-shock wind.
Figure 10. Sketch showing the origin of separate absorption spectra, in the continuum by line of sight to the AGN and by self-absorption in the soft X-ray emission from a limb-brightened shell.

Pounds & Vaughan, 2011
self-absorption in limb-brightened shell

blueshifted absorption of continuum

O VIII Lα velocity profile in PG1211+143

Pounds & Vaughan, 2011
effect on galaxy: $M - \sigma$ relation

(simple derivation)

matter originally distributed so that

$$\frac{GM_{\text{tot}}(R)}{R} = 2\sigma^2$$

with

$$\frac{GM_{\text{gas}}(R)}{R} = 2f_g \sigma^2 \quad (f_g \approx 0.16)$$
at radius $R$ total weight of shell is

$$\frac{GM_{\text{tot}} M_{\text{gas}}}{R^2} = \frac{4f_g \sigma^4}{G}$$

BH mass grows until Eddington thrust $\frac{L_{\text{Edd}}}{c}$ matches this weight, i.e.

$$\frac{4\pi GM_{\text{BH}}}{\kappa} = \frac{4f_g \sigma^4}{G}$$

or

$$M_{\text{BH}} = \frac{f_g \kappa}{\pi G^2} \sigma^4$$  (King, 2003; 2005)

NB: no free parameter
\[ M = 2 \times 10^8 \sigma_{200}^4 M_\odot \]

The relation is *upper limit* to \( M \) for given \( \sigma \) (Bacheldor, 2010)

(need to resolve SMBH sphere of influence \( R_{\text{inf}} = 2GM/\sigma^2 \))

AGN black holes should be *below* this limit
SMBH – host connection

SMBH in every large galaxy, grown by luminous accretion (Soltan) but only a small fraction of galaxies are AGN

⇒ SMBH should grow at ~ Eddington rate in AGN

AGN should show outflows

AGN black holes should be underweight
NB: many BH mass estimates assume $M - \sigma$!

-- tendency to overestimate mass and underestimate Eddington factor
frequency of Eddington outflows

Tombesi et al 2010 a, b:

22/42 radio—quiet AGN, 3/5 BLRGs show outflows with

\[ v \sim 0.1c - 0.3c, \quad \xi \sim 10^4 \]

and hence \( \dot{M}_{\text{out}} \sim 1 - 10M_\odot \text{yr}^{-1} \), with very large momentum rates

high frequency \( \Rightarrow \) solid angles large, \( b \sim 0.5 - 1 \): \( \sim 50\% \) of sample have super—Eddington episodes with significant duty cycles
observed X-ray column fixed by inner boundary of flow $R_{\text{in}}$

$$N_H \simeq \frac{10^{24} \dot{m}^3}{b \eta_{0.1}^2 (R_{\text{in}}/100 R_s)} \text{ cm}^{-2}$$

so if outflow stopped a time $t_{\text{off}}$ ago, we have

$$t_{\text{off}} \simeq 0.2 \frac{\dot{m}^3 M_8}{b \eta_{0.1}^2 N_{23}} \text{ yr}$$

recent!
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but only a small fraction of galaxies are AGN

⇒ *SMBH should grow at ~ Eddington rate in AGN*

*AGN should show outflows*

*AGN black holes should be underweight*
SMBH – host connection

SMBH in every large galaxy, grown by luminous accretion (Soltan)

but only a small fraction of galaxies are AGN

⇒ SMBH do grow at \( \sim \) Eddington rate in AGN

AGN do show outflows

AGN black holes are underweight
SMBH – host connection

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X-ray outflows are key to SMBH-galaxy formation link