Outflows and Black Hole Feedback

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Feedback

mechanical effects opposing gravity
outflows, jets, radiation pressure from stars, and SMBH
SMBH affects galaxy bulge

outflow energy $\sim 0.1 M_{BH} c^2$ is $\sim 10^{61}$ erg for $10^8 M_\odot$ black hole
binding energy of bulge of mass $10^{11} M_\odot$ and $\sigma = 200$ km s$^{-1}$ is $10^{58}$ erg

more than enough energy to unbind bulge – only a fraction used

galaxy must notice presence of hole
Super-Eddington Accretion

most photons eventually escape along cones near axis

most mass expelled as outflow - quasi-spherical

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

\[ \dot{M}v = \frac{L_{\text{Edd}}}{c} \]
Eddington outflows

momentum outflow rate
\[ \dot{M}v = \frac{L_{\text{Edd}}}{c} = \eta \dot{M}_{\text{Edd}} c \quad \text{so} \quad v = \frac{\eta}{\dot{m}_{\text{Edd}}} c \simeq 0.1c \]

mass outflow rate
\[ \dot{M}_{\text{out}} \propto NR^2 v \Rightarrow \xi \Rightarrow \text{X-rays, UV} \]
P Cygni profile of iron K- alpha: outflow with $v \sim 0.1c$
Eddington outflows

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mass outflow rate
\[ \dot{M}_{\text{out}} \propto NR^2v \implies \xi \implies X - \text{rays, UV} \]
Eddington outflows

momentum outflow rate

$$\dot{M}v = \frac{L_{\text{Edd}}}{c} = \eta \dot{M}_{\text{Edd}} c$$

so

$$v = \frac{\eta}{\dot{m}_{\text{Edd}}} c \simeq 0.1c$$

mass outflow rate

$$\dot{M}_{\text{out}} \propto NR^2 v \implies \xi \implies \text{X-rays, UV}$$

energy outflow rate

$$\frac{1}{2} \dot{M}_{\text{out}} v^2 = \frac{\eta}{2} c^2 \dot{M}_{\text{out}} = \frac{\eta}{2} L_{\text{Edd}} \simeq 0.05 L_{\text{Edd}}$$

this is the rate found by iterating cosmological simulations to get $M - \sigma$
outflow shock
outflow must collide with bulge gas, and shock – what happens?

either

(a) shocked gas cools: ‘momentum–driven flow’
   negligible thermal pressure

or

(b) shocked gas does not cool: ‘energy–driven flow’
   thermal pressure > ram pressure

Compton cooling by quasar radiation field very effective out to large bulge radii (cf Ciotti & Ostriker, 1997, 2001)

expansion into bulge gas is driven by momentum \( \frac{L_{\text{Edd}}}{c} \)
swept-up ambient gas, mildly shocked

outer shock driven into ambient gas

ambient gas

Eddington wind, \( v \sim 0.1c \)

wind shock
wind from SMBH
cooling shocked wind
snowplough
interstellar gas

inner (wind) shock
contact discontinuity
outer (ISM) shock

$u \simeq 0.1c$
temperature $T$
density $\rho$
velocity $u$

(King, 2010)
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.
motion of swept-up shell

total mass (dark, stars, gas) inside radius $R$ of unperturbed bulge is

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

but swept-up gas mass $M(R) = \frac{2f_g\sigma^2 R}{G}$

forces on shell are gravity of mass within $R$, and wind ram pressure:

since gas fraction $f_g$ is small, gravitating mass inside $R$ is $\simeq M_{\text{tot}}(R)$: equation of motion of shell is

$$\frac{d}{dt}[M(R)\dot{R}] + \frac{GM(R)[M + M_{\text{tot}}(R)]}{R^2} = 4\pi R^2 \rho v^2 = \dot{M}_{\text{out}} v = \frac{L_{\text{Edd}}}{c}$$

where $M$ is the black hole mass
using \( M(R), M_{\text{tot}}(R) \) this reduces to

\[
\frac{\text{d}}{\text{d}t}(R\dot{R}) + \frac{GM}{R} = -2\sigma^2 \left[ 1 - \frac{M}{M_\sigma} \right]
\]

where

\[
M_\sigma = \frac{f_\sigma \kappa}{\pi G^2 \sigma^4}
\]

integrate equation of motion by multiplying through by \( R\dot{R} \): then

\[
R^2 \ddot{R}^2 = -2GM - 2\sigma^2 \left[ 1 - \frac{M}{M_\sigma} \right] R^2 + \text{constant}
\]
using $\mathcal{M}(R), \mathcal{M}_{\text{tot}}(R)$ this reduces to

$$\frac{d}{dt}(R\dot{R}) + \frac{GM}{R} = -2\sigma^2 \left[ 1 - \frac{M}{M_\sigma} \right]$$

where

$$M_\sigma = \frac{\int_\sigma^\infty \kappa \sigma^A}{\pi G^2 \sigma}$$

integrate equation of motion by multiplying through by $R\dot{R}$: then

$$R^2 \ddot{R}^2 = -2GM\dot{R} - 2\sigma^2 \left[ 1 - \frac{M}{M_\sigma} \right] R^2 + \text{constant}$$

if $M < M_\sigma$, no solution at large $R$ (rhs < 0)

*Eddington thrust too small to lift swept-up shell*
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*Eddington thrust too small to lift swept-up shell*

but if $M > M_\sigma$, $\ddot{R}^2 \to 2\sigma^2$, and shell can be expelled completely
critical value

\[ M_\sigma = \frac{f_g \kappa}{\pi G^2} \sigma^4 \sim 2 \times 10^8 M_\odot \sigma_{200}^4 \]

remarkably close to observed \( M - \sigma \) relation despite effectively no free parameter \( (f_g \sim 0.1) \) (King, 2003; 2005)

SMBH mass grows until Eddington thrust expels gas feeding it
Jets probably cannot produce $M - \sigma$

need *momentum driving* for $M$-sigma relation, i.e.
shocks cool, ram pressure only

ram pressure acts only radially: narrow-angle ram pressure
outflow (jet) just makes a hole
Growing to $M - \sigma$

repeated outflow events, sweeping up shells of matter

all of these fail and fall back until $M$ reaches $M - \sigma$

then momentum-driven outflows can reach large radii

repeated outflow-fallback events can remove dark matter cusp
cf Pontzen & Governato, 2012
energy—driven outflows for $M_\sigma$?

Energy—driven flows (e.g. Silk & Rees, 1998) equate rate of working vs gravity, i.e.

$$\frac{GM_{\text{tot}} M_{\text{gas}}}{R^2} \frac{1}{\sigma}$$

to Eddington luminosity, so

$$M_{\text{BH}} = \frac{f \kappa}{\pi G^2 c} \sigma^5$$

and

$$M_{\text{BH}}(\text{energy}) = \frac{\sigma}{c} M_{\text{BH}}(\text{momentum}) \simeq 1.3 \times 10^5 M_\odot \sigma_{200}^5$$

i.e. far too small, and $\sigma^5$, not $\sigma^4$
energy—driven outflows for \( M_\sigma \)?

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\[
M_{\text{BH(energy)}} = \frac{\sigma}{c} M_{\text{BH(momentum)}} \approx 1.3 \times 10^5 M_\odot \sigma^5_{200}
\]

i.e. far too small, and \( \sigma^5 \), not \( \sigma^4 \)

this results because for observed SMBH masses, BH binding energy >> bulge binding energy – outflow must cool!
transition to energy-driven flow after $M_\sigma$ reached
close to quasar shocked gas cooled by inverse Compton effect
(momentum-driven flow)

but once $M > M_\sigma$, $R$ can exceed $R_C$: wind shock no longer cools
wind shock is adiabatic: hot postshock gas does $P dV$ work
on surroundings
eqn of motion now contains total postshock pressure $P$ (gas plus ram)

wind shock always stays near cooling radius: high sound speed ensures
near-constant pressure in extended region from here to contact
discontinuity (radius $R$) with swept-up host gas

energy-driven outflows are Rayleigh-Taylor unstable (heavy fluid on
top of a light one, so cool (molecular) gas get mixed into the outflow
Zubovas & King, 2012a

Momentum-driven outflow

SMBH

Energy-driven outflow

Wind shock (energy conserved)

Shock from (momentum and pressure conserved)

Fast wind

ISM

Contact discontinuity (momentum and pressure conserved)

ISM shock (energy conserved, but rapidly cooling)

Shock, adiabatically expanding wind ($E_I = 0.5 m v^2$)

Shock, adiabatically expanding ISM ($E = 4m v^2 = E_v$)

ISM shock (energy conserved)
once BH grows to $M > M_\sigma$, shock passes cooling radius

$\Rightarrow$ large-scale energy-driven flow
outer shock runs ahead of contact discontinuity into ambient ISM: velocity jump across it is a factor \((\gamma + 1)/(\gamma - 1)\): fixes velocity as

\[
v_{\text{out}} = \frac{\gamma + 1}{2} \dot{R} \simeq 1230 \sigma_{200}^{2/3} \left( \frac{f_c}{f_g} \right)^{1/3} \text{ km s}^{-1}
\]

and radius as

\[
R_{\text{out}} = \frac{\gamma + 1}{2} R
\]

outflow rate of shocked interstellar gas is

\[
\dot{M}_{\text{out}} = \frac{dM(R_{\text{out}})}{dt} = \frac{(\gamma + 1)f_g \sigma^2}{G} \dot{R}
\]

\[
\dot{M}_{\text{out}} \simeq 3700 \sigma_{200}^{8/3} \dot{R}^{1/3} \text{ M}_\odot \text{ yr}^{-1}
\]
approximate equality

$$\frac{1}{2} M_w v_w^2 \simeq \frac{1}{2} M_{\text{out}} v_{\text{out}}^2$$

means swept-up gas must have momentum rate $> \frac{L_{\text{Edd}}}{c}$, since can rewrite it as

$$\frac{\dot{P}_w^2}{2 M_w} \simeq \frac{\dot{P}_{\text{out}}^2}{2 M_{\text{out}}}$$

$$\dot{P}_{\text{out}} = \dot{P}_w \left( \frac{M_{\text{out}}}{M_w} \right)^{1/2} \sim 20 \sigma_{200}^{-1/3} \frac{L_{\text{Edd}}}{c}$$

all molecular outflows have super-Eddington thrust!

(Zubovas & King, 2012a)
galaxy becomes red and dead
Defects of this picture

accretion not self-consistently treated
must be very small-scale (< 0.1 parsec!)
why is this stopped by large-scale outflow?
Rapid accretion: Nixon, King et al. (2012)