Interaction of the AGN and X-ray Emitting Gas

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Significance of AGN heating

Conductive heating may be able to balance radiative cooling in some cooling flow clusters, but not in all (Zakamska & Narayan, *ApJ*, **582**, 162, 2003)

Thermal conduction is unlikely to be significant in elliptical galaxies (groups?):

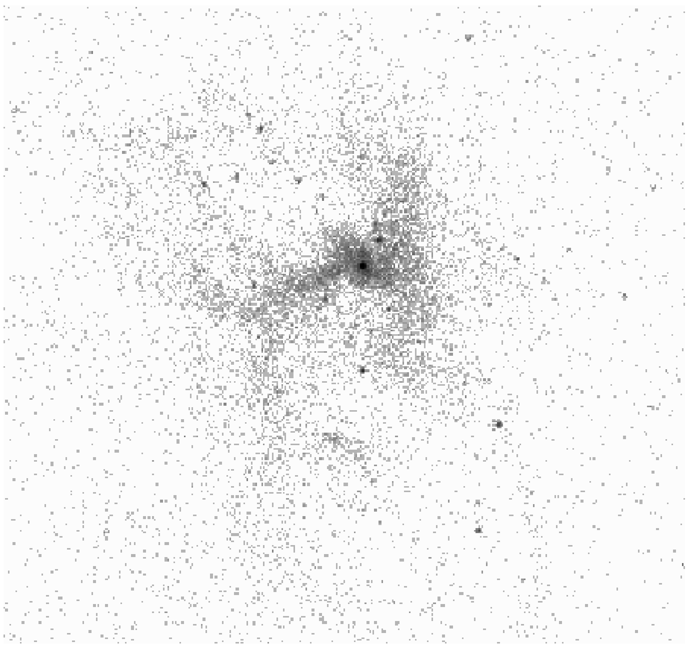
- Thermal conductivity $\kappa \propto T^{5/2}$ — similar cooling times to clusters
- No reservoir of hot gas to supply the heat

AGN outbursts are significant for energetics of cluster cooling flows, dominant for ellipticals (e.g. M84 — Finoguenov & Jones, *ApJ*, **547**, L107, 2001)

If AGN outburst is powered by Bondi accretion of cooling hot gas, what sized outburst should we expect?

Chandra Image of M84

Finoguenov & Jones, *ApJ*, **547**, L107, 2001



Feeding the Outburst

Bondi accretion rate ($\gamma = 5/3$)

$$\dot{M}_{\rm B} = \frac{\pi \rho_0 (G M_{\rm h})^2}{s_0^3} = \frac{\pi (G M_{\rm h})^2}{\Sigma_0^{3/2}}$$
$$= 0.012\ n_{\rm e} T^{-\frac{3}{2}} M_9^2\ {\rm M_\odot\,y^{-1}},$$

sound speed $s_0 = 519\, T^{1/2}$ km s^{-1},
temperature T (keV),
electron density $n_{\rm e}$ (cm^{-3}),
black hole mass $M_{\rm h} = 10^9 M_9\ {\rm M_\odot}$,
"entropy" $\Sigma_0 = 5 p_0 / (3 \rho_0^{5/3}) = 5 k T_0 / (3 \mu m_{\rm H} \rho_0^{2/3}) = s_0^2 \rho_0^{-2/3}$.

Cooling reduces the entropy, boosting accretion rate:

$$\rho T \frac{dS}{dt} = -n_{\rm e} n_{\rm H} \Lambda(T)$$

gives

$$\frac{d \log \Sigma}{dt} = - \frac{1}{t_{\rm cool}}.$$

While the cooling gas is hydrostatic, it remains close to the "virial temperature" $kT/(\mu m_{\rm H}) \simeq GM(r)/r$.

Hydrostatic equilibrium is lost when $t_{\rm cool} \lesssim t_{\rm sc} = r/s$.

Bondi flow ceases to be "hot" when

$$\left.\frac{t_{\rm cool}}{t_{\rm sc}}\right|_{r_{\rm B}} = \beta \simeq \frac{2kT_0 s_0^3}{n_{\rm e,0}\mu G M_{\rm h} \Lambda(T_0)} \simeq 1.$$

Putting $n_{\rm e,0}$ in terms of β, the Bondi accretion rate is

$$\dot m_{\rm B} = \frac{\dot M_{\rm B}}{\dot M_{\rm Edd}} \simeq \frac{\eta \sigma_{\rm T} c k T_0}{\beta \Lambda(T_0)} \simeq 0.3 \frac{\eta_{-1} T}{\beta \Lambda_{-23}},$$

where the "Eddington" accretion rate, $\dot M_{\rm Edd}$ is defined by

$$\eta \dot M_{\rm Edd} c^2 = L_{\rm Edd} = \frac{4\pi G M_{\rm h} m_{\rm H} c}{\sigma_{\rm T}},$$

and $L_{\rm Edd}$ is the Eddington limit.

Assume outburst occurs when $\beta \simeq 1$.

Mass accreted before $\beta \simeq 1$

$$\begin{aligned}
M_{\rm a} &= \int_{t_{\rm i}}^{t_{\rm f}} \dot{M}_{\rm B}\, dt \\
&\simeq \int_{\Sigma_{\rm f}}^{\Sigma_{\rm i}} \dot{M}_{\rm B} t_{\rm cool} \frac{d\Sigma_0}{\Sigma_0} && \text{(uniform gas)} \\
&= \int_{\Sigma_{\rm f}}^{\Sigma_{\rm i}} \frac{\pi \rho_0 (G M_{\rm h})^2}{s_0^3} \times \frac{2kT_0}{n_{\rm e,0}\mu\Lambda(T_0)} \frac{d\Sigma_0}{\Sigma_0} \\
&= \dot{M}_{\rm B,i} t_{\rm cool,i} \ln \frac{\Sigma_{\rm i}}{\Sigma_{\rm f}} && (T_0 \text{ constant})
\end{aligned}$$

Putting $M_{\rm a} = \chi \dot{M}_{\rm B,i} t_{\rm cool,i}$, the mass accreted is

$$M_{\rm a} \simeq \frac{48\pi\chi(G M_{\rm h} m_{\rm H})^2}{35 s_0 \Lambda(T_0)} \simeq 2 \times 10^5 \frac{\chi M_9^2}{T^{1/2}\Lambda_{-23}}\ {\rm M}_\odot.$$

The mechanical energy generated is

$$E_{\rm a} = \eta_{\rm mech} M_{\rm a} c^2 \simeq 3.7 \times 10^{58}\, \frac{\eta_{{\rm m},-1}\chi M_9^2}{T^{1/2}\Lambda_{-23}}\ {\rm erg}.$$

Hydra A:

(David *et al.*, *ApJ*, **557**, 546, 2001) $kT \simeq 3$ keV; $\Lambda_{-23} \simeq 1.8$ $(Z = 1)$; $M_{\rm h} \simeq 4 \times 10^9$ $\mathrm{M}_\odot$ (estimated; Sambruna *et al.*, *ApJ*, **532**, L91, 2000)

$$\longrightarrow E_{\rm a} \simeq 2 \times 10^{59} \chi \eta_{{\rm m},-1} \text{ erg}.$$

For SW cavity $pV \simeq 2 \times 10^{59}$ erg. Thermal energy 3 – 4 times greater if cavity filled with relativistic plasma; double again for NE cavity.

Continuing jet may "top up" outburst.

Summary

- Effect of cooling on Bondi accretion provides a mechanism for AGN feedback.

- Outburst occurs as $t_{\rm cool} \to t_{\rm flow}$ at the Bondi radius.

- Outburst energy is insensitive to gas density and details of when outburst occurs

- — determined chiefly by black hole mass and virial temperature of host.