Quasars, Feedback, (and Galaxy Formation)

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What Might We Learn From BH-Host Correlations?







Simplest Idea: FEEDBACK ENERGY BALANCE (SILK & REES '98)

• Accretion disk radiates:

$$L = \epsilon_r \left(\mathrm{d}M_{\mathrm{BH}} / \mathrm{d}t \right) c^2 \quad (\epsilon_r \sim 0.1)$$

- Total energy radiated (typical ~10⁸ M_{sun} system) ~ $0.1 M_{\rm BH} c^2 \sim 10^{61} \, {\rm ergs}$
- Compare to gravitational binding energy of galaxy:

$$\sim M_{\rm gal} \, \sigma^2 \sim (10^{11} \, M_{\rm sun}) \, (200 \, \rm km/s)^2 \sim 10^{59} \, \rm erg$$

- If only a few percent of the luminous energy coupled, it would unbind the baryons!
- Turn this around: *if* some fraction f ~ 1-5% of the luminosity can couple, then accretion stops when

$$M_{\rm BH} \sim (1/f\epsilon_r) M_{\rm gal} (\sigma/c)^2 \sim 0.002 M_{\rm gal}$$

Implications for Fueling: "Feeding the Monster" WHAT CAN BREAK DEGENERACIES IN FUELING MODELS?

HST • WFPC2

Quasar Host Galaxies PRC96-35a + ST Scl OPO + November 19, 1996

J. Bahcall (Institute for Advanced Study), M. Disney (University of Wales) and NASA

• *If* BHs trace spheroids, then *most* mass added in violent events that also build bulges



Gas

Gas

Tidal torques \Rightarrow large, rapid gas inflows (e.g. Barnes & Hernquist 1991)

Gas

Gas

Triggers Starbursts (e.g. Mihos & Hernquist 1996)

Gas

Gas

Fuels Rapid BH Growth (e.g. Di Matteo et al., PFH et al. 2005)

Gas

Gas

Feedback expels remaining gas, shutting down growth (more later...)

Gas

Gas

Merging stellar disks grow spheroid

Gas



Observations & Simulations Suggest this Simple Picture Works MAKES UNIQUE PREDICTIONS:

- What is the "fundamental" correlation? M_{BH}-E_{binding}: BH "fundamental plane" (PFH et al.)
- Different correlation for "classical" and "pseudobulges"
- Both tentatively observed (Aller & Richstone; Greene et al.; Hu; Gadotti et al.)



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Observations & Simulations Suggest this Simple Picture Works MAKES UNIQUE PREDICTIONS:

• Naturally predicts some evolution in BH-Host correlations:

• Hosts more gas rich/compact at high-z \rightarrow more "work" for the BH before self-regulation



Of Course, Not Every AGN Needs a Merger MORE QUIESCENT GROWTH MODES?

- $z \sim 2$ QSO: 10¹¹ M_{sun} in <10pc in $\sim t_{dyn}$
- Seyfert: only 10^{7-8} M_{sun} ~ GMC
- Minor mergers?

10¹⁰

10⁹

10⁸

107

10'

M_{BH,f} (M_©)

• Secular instabilities/bars?



10¹⁸

Younger et al. 2008

1017

1016

 $(M_{\odot} \text{ km}^2 \text{ s}^{-2})$

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1014

1015

 $M_{bulge}\sigma^2$



• Observed luminosity function: populations at different *evolutionary* stages

Feedback Means that AGN Move Non-Trivially *Along* the Luminosity Function...

Let's look at this in detail





Quasar Lightcurves and Lifetimes

• Feedback determines the decay of the quasar light curve:



- Explosive blowout drives power-law decay in L
- No Feedback:
 - Runaway growth (exponential light curve)
 - "Plateau" as run out of gas but can't expel it (extended step function)

PFH et al. 2006a

This is Very General: (EVEN THOUGH NOT ALL AGN ARE MERGER-DRIVEN)

- Almost any (ex. radio) AGN feedback will share key properties:
 - Point-like
 - Short input (~ t_{Salpeter})
 - E~Ebinding
- Simple, analytic solutions:
 - $L \sim (t / t_Q)^{-1.7(ish)}$
 - Agrees well with simulations!
- Generalize to "Seyferts"
 - Disk-dominated galaxies with bars
 - Minor mergers



So What Is the "Quasar Lifetime"?



• "Quasar Lifetime": a conditional, *luminosity-dependent* distribution



PFH et al. 2009



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• Complimentary constraints from clustering (Meyers, Croom, Porciani, da Angela)

BHs gained their mass in just a couple of "major" events

Where Does the Energy/Momentum Go? QUASAR-DRIVEN OUTFLOWS?

(outflow reaches speeds of up to ~1800 km/sec)



Feedback, you say? What can it do for me?

• Quasars were active/BHs formed when SF shut down...



Quasar Outflows May Be Significant for the ICM & IGM SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



Gas Temperature

Quasar Outflows May Be Significant for the ICM & IGM SHUT DOWN COOLING FOR ~ COUPLE GYR. PRE-HEATING?



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Feedback-Driven Winds METAL ENRICHMENT & BUILDING THE X-RAY HALO





A Caution: THE SCALES AFFECTED BY THE AGN DEPEND ON THE FORM OF FEEDBACK

• New simulations: feedback in form of pure momentum flux coupled on large (100-500pc) scales –not so "point like" or "explosive" injection



A Caution: THE SCALES AFFECTED BY THE AGN DEPEND ON THE FORM OF FEEDBACK

• These are still toy models – almost certainly have "mixed" scenarios:



cross section by factor ~50; now easily "blown out"

- Hot outflow "pre-processes" cold clouds makes them order-of-magnitude more receptive to radiation flux
 - Enhance feedback efficiency by order-of-magnitude (only need ~0.003 L_{OSO} to couple); but will "look like" stellar winds

A Caution: THE AGN DOESN'T ALWAYS WIN!





Expulsion of Gas Turns off Star Formation ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



Expulsion of Gas Turns off Star Formation ENSURES ELLIPTICALS ARE SUFFICIENTLY "RED & DEAD"?



... MOST of the work is still done by star formation/stellar feedback - but over a longer period of time -

PFH, Cox et al. 2007

AGN or Starburst-Driven Winds? WHICH ARE MORE IMPORTANT?



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"Transition"

- Move mass from Blue to Red
- Rapid
- Small scales
- "Quasar" mode (high mdot)
- Morphological Transformation
- Gas-rich/Dissipational Mergers



"Maintenance"

Keep it Red

VS.

- Long-lived (~Hubble time)
- Large (~halo) scales
- "Radio" mode (low mdot)
- Subtle morphological change
- Hot Halos & Dry Mergers





Regulates Galaxy Mass

Maintenance Mode IS IT ALSO "RADIO"-MODE?

- Know that (non-cooling flow) clusters do look "pre-heated"... but we also *see* radio jets doing work:
- What is "typical"?



Fabian (Perseus Cluster)

Allen (X-ray Ellipticals)

Maintenance Mode IS IT ALSO "RADIO"-MODE?

• Know that (non-cooling flow) clusters do look "pre-heated"... but we also *see* radio jets doing work:

Ho: P(radio) versus Eddington ratio:

Allen: P(jet) versus P(accretion):



• Observational constraints on the power involved are leading the way



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Summary

- MBH traces spheroid Ebinding
 - Suggests self-regulated BH growth
 - You CAN'T build very big BHs without making bulges first
 - BHs "know more" about their hosts than the galaxy centers!
 - Which mechanisms dominate BH feedback? When/where?
- If self-regulated, this feedback may be radically important:
 - Heating gas, ejecting metals, shutting down SF
 - Self-regulated decay of QSO luminosity:
 - Why are quasar lifetimes generically self-similar?
 - Where/what is the transition/maintenance mode role?
 - Function of Eddington ratio? What does each "phase" do?
- "Are AGN mergers?" is the wrong question (even in merger-driven models!)
 - Should ask: "Where (as a function of L, z, d) do mergers vs. secular processes vs. relaxing/relaxed systems dominate the AGN population?"
 - Observations of small-scale clustering, host properties (SFH, morphologies, etc)