Merger-Driven Co-Evolution of Quasars, Supermassive Black Holes & Elliptical Galaxies

Lars Hernquist
Harvard University

Spitzer Science Symposium
October 27, 2009

with: TJ Cox (Carnegie) & Phil Hopkins (Berkeley)
How are Quasars, Supermassive Black Holes, Elliptical Galaxies Connected?

- Black holes, spheroids correlated $\Rightarrow$ formation related
- Most black hole mass in quasar phases (Soltan)
- Simplest picture: originate primarily in one event
- Is this sensible?

Barth, Greene & Ho (2004)
Requirements on Single “Event”

- Fast, violent
- Blend of gas & stellar dynamics
- Why?
  * Soltan (1982): bulk of SMBH mass density grown through radiatively efficient accretion in quasars
    → gas dynamics; rapid (~ few $10^7$ years)
  * Lynden-Bell (1967): orbits of stars redistributed in phase space by large, rapid potential fluctuations
    → stellar dynamics; freefall timescale
- Need galaxy’s supply of each: BH / host relations; structure of ellipticals
Candidate Process: Gas-Rich, Major Merger

- Locally, related to:
  - growth of spheroids
  - causing starbursts
  - fueling SMBH growth, quasar activity

NGC 7252
Schweizer (1982)
Candidate Process: Gas-Rich, Major Merger

- Locally seen related to:
  - growth of spheroids
  - causing starbursts (ULIRGs)
  - fueling SMBH growth, quasar activity

Yun & Hibbard (2001)
Candidate Process: Gas-Rich, Major Merger

- Locally, seen related to:
  - growth of spheroids
  - causing starbursts (ULIRGs)
  - fueling SMBH growth, quasar activity

Komossa et al. (2003)
Plausible Physical Mechanism

- Tidal torques ⇒ large, rapid gas inflows (e.g. Barnes & LH 1991)
- Triggers starburst (e.g. Mihos & LH 1996)
- Feeds BH growth (e.g. Di Matteo et al. 2005)
- Merging stellar disks grow spheroid

**Requirements:**
- major merger
- supply of cold gas
  (“cold” = rotationally supported)

Barnes & LH (1996)
Testing the Hypothesis

- Simulations: 3-D, time-dependence
- Consider:
  - single, multiple mergers
  - varying mass ratios
  - star formation, supernova feedback & winds (sub-resolution)
  - black hole growth, feedback (sub-resolution)
  - large gas fractions: made possible by SN feedback

Li et al. (2006)
Stars

QuickTime™ and a decompressor are needed to see this picture.
Gas

QuickTime™ and a decompressor are needed to see this picture.
Generic Outcome of Gas-Rich Mergers

- Gas inflow $\rightarrow$ starburst
  - BH mainly buried in optical by gas & dust: obscured growth
- AGN feedback $\rightarrow$ dispersal
  - black hole briefly visible as optical quasar: blowout phase
- Remnant relaxes
  - quasar dies when gas supply runs out
  - spheroid satisfies $M_{\text{BH}} - \sigma$
  - little residual star formation (quickly reddens)

Hopkins et al., astro-ph/0506398
Relics: Black Hole - Host Correlations

- BH mass determined by feedback, gas cooling, potential well, gas dynamics
- BH growth self-regulated, fixing feedback efficiency $E_{\text{feed}} = \varepsilon_f M_{\text{BH}} c^2$ with $\varepsilon_f \sim 0.005$
- Match observed slope of $M-\sigma$ relation
- Interpretation motivates more refined correlations

Di Matteo, Springel & LH (2005)
Self-Regulated Black Hole Growth

• “BH fundamental plane” (Hopkins et al. arXiv:0707.4005, 0701351):
  – energy input $\propto \frac{dM_{BH}}{dt} \sim M_{BH}$
  – gas binding $\sim M_\ast \sigma^2$
  – data: $M_{BH} \sim (M_\ast \sigma^2)^{0.7}$ or $M_{BH} \sim \sigma^3 R_e^{0.5}$
  – pressure-driven outflow unbinds gas (Hopkins & LH 2006)
Self-Regulated Black Hole Growth
(Hopkins et al., arXiv / 0701351 & 070.4005)

- Resolves outliers in $M_{BH} - \sigma$ and $M_{BH} - M_*$ relations
- Predicts BHs more massive for fixed $M_*$ at high $z$ (deeper potentials):
  
  $M_{BH} \sim M_*^{1.5} R_e^{-1.0}$

  Trujillo et al.: $R_e \sim (1+z)^{-0.4}$

  expect: $M_{BH} / M_* \sim (1+z)^{0.5}$ (similar to e.g. Peng et al. 2006)
Relics: Two - Component Spheroids

- predicted theoretically:
  - outer “envelope” from pre-existing stars
  - inner relic “starburst” component
- verified by more general, more accurate simulations

Mihos & LH (1994)
Hopkins et al. (2008), arXiv:0802.0508
Relics: Two - Component Spheroids

Fraction of starburst component determined by gas content

Hopkins et al. (2008), arXiv:0802.0508
Theoretical / Observational Analysis
(Hopkins et al., arXiv:0802.0508v2, 0805.3533v2, 0806.2325v2)

• Observations (span \(\approx 0.01 \, L* - 10 \, L*\)):
  – \(\approx 50\) gas-rich mergers (Rothberg & Joseph)
  – \(\approx 80\) cusp ellipticals (Kormendy et al., Bender et al., Lauer et al.)
  – \(\approx 110\) core ellipticals (ibid.)

• Simulations - many hundreds:
  – vary: orbit, structure/masses of progenitors, gas content, star formation/feedback, black hole accretion/feedback, resolution

• Analysis:
  – best matching simulation
  – two-component Sersic fits: \(I \propto \exp[-(r/r_0)^{1/n}]\) for \(n_{in}\) & \(n_{out}\)
    (note: \(n=1 \rightarrow\) exponential; \(n=4 \rightarrow r^{1/4}\) law)
Theoretical / Observational Analysis
(Tabulated in arXiv: 0802.0508v2, 0805.3533v2, 0806.2325v2)

- two-component matches to all ellipticals (but at $L \approx 0.01 L_*$)
- exclude dwarf spheroidals, S0s
- top: parameter fit
- middle: 3 best matching sims. (starburst = dash)
Theoretical / Observational Analysis
(Tabulated in arXiv: 0802.0508v2, 0805.3533v2, 0806.2325v2)

- starburst component declines with $M$: progenitor gas-richness $\rightarrow$ star formation more efficient in high mass disks (higher $\Sigma_{\text{gas}}$)
Inferring Starburst History of Universe

• Central component from starbursts; know $\Sigma_{\text{burst}}(R)$

• Assume:
  – gas collapses to center, forms stars in situ
  – Kennicutt-Schmidt Law

• $\Sigma_{\text{burst}}(R) \Rightarrow \Sigma_{\text{gas}}(R, t_0) \Rightarrow$
  $d \Sigma_*(R, t_0)/dt$ (KS Law)

  $d \Sigma_*/dt = -d \Sigma_{\text{gas}}/dt \propto \Sigma_{\text{gas}}^{nK}$

• Start at $t=t_0$, integrate forward in time

Hopkins & Hernquist (2009)
Inferring Starburst History of Universe

- Characterize starbursts in individual systems:
  - burst mass
  - peak burst SFR
  - burst timescale
  - spatial size
- Use empirical constraints on ages to assign (Monte Carlo) burst redshifts
- Use empirical relations between SFR and IR

Hopkins & Hernquist (2009)
Inferring Starburst History of Universe

- Characterize starbursts in individual systems:
  - burst mass
  - peak burst SFR
  - burst timescale
  - spatial size
- Use empirical constraints on ages to assign (Monte Carlo) burst redshifts, construct mock populations
- Use empirical relations between SFR and IR to get IR burst luminosity

Hopkins & Hernquist (2009)
Inferring Starburst History of Universe

• Total (8 - 1000 μm) IR LFs:
  - reasonable agreement at bright end
  - bursts unimportant at faint end
  - transition: ULIRGs (z=0), HyLIRGs (z =2)
• At all z, bursts small fraction (∼ 5 - 10 %) of total SFR or IR density

Hopkins & Hernquist (2009)
Inferring Starburst History of Universe  

- Total (8 - 1000 µm) IR LFs:
  - good agreement at bright end
  - bursts unimportant at faint end
  - transition: ULIRGs (z=0), HyLIRGs (z =2)

- At all z, bursts small fraction (~ 5 - 10 %) of total SFR or IR density

Hopkins & Hernquist (2009)
Inferring Starburst History of Universe

• Complementary approach: forward modeling from theory:
  – populate halos with galaxies using empirical constraints
  – track quiescent star formation
  – use simulations (light curves) for burst, quasars in mergers

• can estimate contribution from obscured AGN: smaller than bursts

Hopkins et al. (2009)
Unified Picture for Galaxy Evolution

(c) Interaction/“Merger”
- now within one halo, galaxies interact & lose angular momentum
- SFR starts to increase
- stellar winds dominate feedback
- rarely excite QSOs (only special orbits)

(d) Coalescence/(U)LIRG
- galaxies coalesce: violent relaxation in core
- gas inflows to center
- starburst & buried (X-ray) AGN
- starburst dominates luminosity/feedback, but total stellar mass formed is small

(e) “Blowout”
- BH grows rapidly; briefly dominates luminosity/feedback
- remaining dust/gas expelled
- get reddened (but not Type II) QSO: recent/ongoing SF in host high Eddington ratios merger signatures still visible

(f) Quasar
- dust removed: now a “traditional” QSO
- host morphology difficult to observe: tidal features fade rapidly
- characteristically blue/young spheroid

(g) Decay/K+A
- QSO luminosity fades rapidly
- tidal features visible only with very deep observations
- remnant redens rapidly (E+A/K+A)
- “hot halo” from feedback
- sets up quasi-static cooling

(h) “Dead” Elliptical
- star formation terminated
- large BH/spheroid - efficient feedback
- halo grows to “large group” scales
- mergers become inefficient
- growth by “dry” mergers

Hopkins et al., astro-ph/0706.1243v2
Remnant Structure: Central Light Excess

- Remnant surface density like elliptical galaxies
- Gas-rich mergers → starbursts → ellipticals ⇒ multiple stellar populations
- Predict central light excess from starburst (Mihos & LH 1994; Springel & LH 2005)

Mihos & LH (1994)
Remnant Structure: Central Light Excess

- Remnant surface density like elliptical galaxies
- Gas-rich mergers $\rightarrow$ starbursts $\rightarrow$ ellipticals $\Rightarrow$ multiple stellar populations
- Predict central light excess from starburst (Mihos & LH 1994; Springel & LH 2005)
Remnant Structure: Central Light Excess

• New observational evidence:
  – Kormendy et al. (2007): relaxed ellipticals

• Amount $\sim 10^{10} \, L_{\text{sun}}$ (e.g. Rothberg & Joseph); similar to gas content of ULIRGs

• Relic starburst?

Central Light Excess: Theoretical / Observational Analysis

(Hopkins et al. 2007)

Observations:
- Relaxed ellipticals: Kormendy et al. (2007), Bender et al. (1998), Lauer et al. (2006)
  - ≈ 100 “cusp” ellipticals
  - ≈ 100 “core” ellipticals
- Multiple observations of each object in various wavebands with different instruments

Simulations:
- Many hundreds: vary orbit, structure/masses of progenitors, gas content, star formation/feedback, black hole accretion/feedback, resolution, etc.
Two Families of Ellipticals?

- “Coreless”: steep central profiles (lower mass Es)
- “Core”: shallow central profiles (higher mass Es)
- “Coreless”: direct remnant of gas-rich merger
- “Core”: modified by subsequent gas-free merger; core from binary black hole?

Kormendy et al. (2007)
Two Families of Ellipticals?

• “Coreless” vs. “core”: distinction on scales << relic starbursts
• Focus here on coreless ellipticals (analysis of core ellipticals in progress)
• Hypothesis: ellipticals, black holes originate via gas-rich mergers, some only later modified by gas-free mergers

Kormendy et al. (2007)
Two Component Luminosity Profiles

- **Sersic profile:**
  \[ I \propto \exp \left[ - \left( \frac{r}{r_0} \right)^{1/n} \right] \]
  exponential: \( n = 1 \)
  \( r^{1/4} \) - law: \( n = 4 \)

- Simulations motivate multi-component fits:
  - inner starburst (\( n=1 \))
  - outer profile (\( n_s \))

- Single component fits less accurate; physically misleading

Hopkins et al. (2007)
Two Component Profiles: Observations

- Apply 2-component fits to observations: ≈ 50 gas-rich mergers (Rothberg & Joseph);
- ≈ 100 cusp ellipticals (Kormendy, Lauer, Bender)
- Superior matches to data in nearly each case
- Simulation analogs often provide even better fits
- For some objects, classification altered

Hopkins et al. (2007); from Kormendy et al. (2007)
Two Component Profiles: Merger Properties

- Dependence on nature of merger; e.g. gas fraction (all else equal): more extra light, similar outer profiles
- Depends also on galaxy mass, orbit; e.g. fixed initial gas fraction: \( f_{sb} \propto M_*^{-0.15} \) (explains elliptical FP tilt)
- Extra light correlated with gas mass at end of merger
- Observed systems occupy similar location in e.g. extra light fraction vs. \( M_* \)

Hopkins et al. (2007)
Two Component Profiles: Merger Properties

- Dependence on nature of merger; e.g. gas fraction (all else equal): more extra light, similar outer profiles
- Depends also on galaxy mass, orbit; e.g. fixed initial gas fraction: $f_{sb} \propto M_*^{-0.15}$ (explains elliptical FP tilt)
- Extra light correlated with gas mass at end of merger
- Observed systems occupy similar location in e.g. extra light fraction vs. $M_*$: extra light $\sim 3 - 30 \%$; need gas fractions $\sim 10 - 40\%$

Hopkins et al. (2007)
Two Component Profiles: Merger Properties

- Dependence on nature of merger; e.g. gas fraction (all else equal): more extra light, similar outer profiles
- Depends also on galaxy mass, orbit; e.g. fixed initial gas fraction: $f_{sb} \propto M_\ast^{-0.15}$ (explains elliptical FP tilt)
- Extra light correlated with gas mass at end of merger
- Observed systems occupy similar location in e.g. extra light fraction vs. $M_\ast$: extra light $\sim 3 - 30\%$; need gas fractions $\sim 10 - 40\%$

Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)
Outer Sersic Indices

- Match observations with fits, simulation analogs
- Compare statistically
- E.g. outer Sersic index: no strong dependence on mass
- Different from e.g. Graham (2001), Ferrarese et al. (2006), but with single component fits
- Expect similar outer profiles (violent relaxation/gravity)
- Slight offset ($\Delta n \sim 0.25$) may be resolution artifact in data

Hopkins et al. (2007); solid: simulations; open: observed; data from Kormendy et al. (2007)
Outer Sersic Indices

- Match observations with fits, simulation analogs
- Compare statistically
- E.g. outer Sersic index: no strong dependence on mass
- Different from e.g. Graham (2001), Ferrarese et al. (2006), but with single component fits
- Expect similar outer profiles (violent relaxation/gravity)
- Slight offset ($\Delta n \sim 0.25$) may be resolution artifact

Hopkins et al. (2007); black: simulations; red: observed; data from Kormendy et al. (2007)
Spatial Extent of Extra Light

- Measure effective radii of inner, outer components
- Fractionally smaller in higher mass galaxies
- More massive galaxies have fractionally less extra light
- $R_{\text{extra}} \propto M_{\text{extra}}^{0.33}$

Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)
Spatial Extent of Extra Light

- **Spatial extent**: gas self-gravity
- **Scenario (Mihos & LH 1996)**:
  - gas loses angular momentum
  - gas enters free-fall
  - becomes self-gravitating
  - no longer free-falling, shocks
  - quasi-equilibrium: cooling offset by feedback from star formation
  - gas stalls, rapidly forms stars

Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)
Spatial Extent of Extra Light

- Spatial extent: gas self-gravity
- Self-gravity condition:
  \[ \frac{G M_{\text{extra}}}{R_{\text{extra}}} = \alpha \frac{G M_*}{R_e} \]  
  \( (\alpha \sim 1) \)
- Describes simulations, data
- Independent of treatment of ISM, star formation, feedback
- Numerically converged spatially

Hopkins et al. (2007); data (magenta) from Rothberg & Joseph (2004)
Other Properties

• Time evolution of profiles in various bands
• Stellar population gradients
• Age, metallicity gradients
• Color gradients:
  – early on, cores blue: young stars, age gradients dominate
  – later, cores red: metallicity gradients dominate
• Kinematic subsystems, embedded disks
Metallicity & Gradients in Ellipticals

- Long-standing objection: metallicity, gradients in ellipticals too strong compared to present-day spirals (Ostriker 1980)
- Ignores dissipation: boosts central metallicity, gradients
- In fact, simulations, observations consistent (bottom left)
- N.B.: Z measured in $R_e / 8 \Rightarrow$ not much self-enriched material

Hopkins et al. (2007)
red = 0.1 gas
orange = 0.2 gas
green = 0.4 gas
Gas-Rich Merger Origin of Ellipticals

- Explains structure: multi-component systems
- Provides physical basis for structure:
  - outer profile from violent relaxation (roughly self-similar)
  - inner component from dissipation, star formation (non-homology)
- Supports view that blend of stellar & gas dynamics required, with galaxy’s supply of each
- Needed gas fractions ~ 10 - 30 %, similar to phase-space constraints (Hernquist, Spergel & Heyl 1993)
- Eliminates objections to (generalized) merger hypothesis
- Explains observed correlations (fundamental plane)
- Accounts for metallicity, gradients in ellipticals
Gas-Rich Merger Origin of Ellipticals

- Preliminary analysis: merger of cusp ellipticals $\rightarrow$ cores
- Basic properties of ellipticals, black holes set by gas-rich mergers
- Cusp/core dichotomy set on scales $\ll$ inner component
- Kinematic anomalies, fine structure destroyed in secondary, gas-free mergers
- Predict presence of these features correlated with family type

Kormendy et al. (2007)
Remnants Properties: Fine Structure

- Shells in ellipticals: phase-wrapping of “cold” stellar material (Quinn 1984; Quinn & LH 1986)
- From debris in tidal tails (LH & Spergel 1992)
- NOT signature of major mergers of spheroids, just the opposite!

NGC 3923
Remnant Properties: Kinematics

- Measure $\tan \Psi = \frac{V_{\text{min}}}{V_{\text{maj}}}$
- Match elliptical kinematic misalignments if gas fraction > 25 - 30 % (little minor axis rotation)

Cox et al. (2005)
Black Hole - Host Correlations

- BH mass determined by feedback, gas cooling, potential well, gas dynamics
- BH growth self-regulated, fixing feedback efficiency $E_{\text{feed}} = \varepsilon_f M_{\text{BH}} c^2$ with $\varepsilon_f \sim 0.005$
- Match observed slope of $M-\sigma$ relation
- Interpretation motivates more refined correlations

Di Matteo, Springel & LH (2005)
Black Hole Fundamental Plane
(Hopkins et al., astro-ph / 0701351 & 070.4005)

- Elliptical galaxy FP:
  \( R_e \sim \sigma^{1.5} I^{-0.8} \) (K-band)
- Try: \( M_{BH} \sim M_*^{\alpha} \sigma^\beta \)
- From data: \( M_{BH} \sim (M_* \sigma^2)^{0.5} \)
- Condition for pressure-driven outflow to unbind gas (Hopkins & LH 2006)
- No evidence for curvature
Black Hole Fundamental Plane
(Hopkins et al., astro-ph / 0701351 & 070.4005)

- Resolves outliers in \( M_{\text{BH}} - \sigma \) and \( M_{\text{BH}} - M_* \) relations

- Predicts BHs more massive for fixed \( M_* \) at high \( z \) (deeper potentials):
  \[ M_{\text{BH}} \sim M_*^{1.5} R_e^{-1.0} \]
  Trujillo et al.: \( R_e \sim (1+z)^{-0.45} \)
  so, expect:
  \[ \frac{M_{\text{BH}}}{M_*} \sim (1+z)^{0.5} \]
  (similar to e.g. Peng et al. 2006)
Quasars

• new picture for quasar evolution:
  – complex, evolving light-curves, lifetimes
  – evolving pattern of obscuration: increases with luminosity, drops during blowout

• new interpretation of quasar luminosity function

• self-consistent model for quasar population, cosmic X-ray background, supermassive black hole & galaxy spheroid population

• analytic model for low-luminosity AGN not fueled by mergers

• new description of quasar clustering

• explanation for “universal” quasar host halo mass
Quasar Evolution

Hopkins et al. (2005)
Quasars: Light-curves & Lifetimes

- Luminosity evolves:
  - Extended dim phases
  - Short peak phases (< $10^8$ yrs)
- "Lifetime" depends on both peak and instantaneous luminosities
- Unlike "light bulb," pure exponential growth
- More time at faint L (e.g. Adelberger & Steidel 2005)

Hopkins et al. (2005)
Quasars: Absorbing Columns

- absorbing column evolves with time:
  - large spread in $N_H$ with time
  - smaller spread at given time
- quasar phenomena mainly evolutionary?

Hopkins et al. (2005)
Cosmological Context
(Hopkins et al. astro-ph / 0706.1243 & 0706.1246)

• Combine:
  – halo/sub-halo mass functions
  – halo occupation models
  – dynamical friction estimates

• Predict abundance, biasing of major gas-rich mergers vs. z

• Use quasar light curves from merger simulations

• Predict e.g. quasar LF, excess small-scale clustering, bias of quasars

bolometric QLF: points from data in various bands (Hopkins et al. 2007); red lines allow “dry” mergers to trigger quasars
Cosmological Context
(Hopkins et al. astro-ph / 0706.1243 & 0706.1246)

- Combine:
  - halo/sub-halo mass functions
  - halo occupation models
  - dynamical friction estimates
- Predict abundance, biasing of major gas-rich mergers vs. z
- Use quasar light curves from merger simulations
- Predict e.g. quasar LF, excess small-scale clustering, bias of quasars

Observed points: Myers et al. (2006), Hennawi et al. (2006)
Origin of Quasars, Supermassive Black Holes & Elliptical Galaxies in Gas-Rich Mergers

Cox et al. (2006)
Origin of Quasars, Supermassive Black Holes & Elliptical Galaxies in Gas-Rich Mergers

• Explains:
  – Clustering, abundance, evolution of quasars
  – Growth, demographics of supermassive black hole population
  – Abundance, clustering, structure (profiles, kinematics, correlations) of elliptical galaxies
  – Properties of cosmic X-ray background
  – Nature of starburst galaxies (ULIRGs, SMGs)
  – Blue → red galaxy transition