DEEP2 Galaxy Mergers and X-ray Selected AGN to $z=1.4$

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Galaxy Mergers: Simulations and Observations

Understand the amount of star formation due to galaxy mergers TJ Cox PhD Sept 2004, Cox+2006

Study properties of merger remnants TJ Cox+2005,06
  → DM/stellar/gas distributions Matt Covington
  → Angular momenta and kinematics Greg Novak

Predict appearance of interacting galaxies throughout merger, including dust scattering, absorption, and reradiation Patrik Jonsson PhD 2004, Jonsson+2006

Statistically compare to observations (DEEP2 and GOODS: ACS, Chandra, Spitzer, etc.) Jennifer Lotz, Piero Madau, and Primack 2004; Lotz+2005, 2006; Pierce+2006, Nandra+2006, Georgakakis+2006
Galaxy Merger Simulations

In order to investigate galaxy mergers (and interactions) we build observationally motivated N-body realizations of compound galaxies and simulate their merger using the SPH code GADGET (Springel, Yoshida & White 2000, Springel 2005). These simulations include:

- An improved version of smooth particle hydrodynamics (SPH) which explicitly conserves both energy and entropy (Springel & Hernquist 2002).
- The radiative cooling of gas
- Star formation: $\rho_{\text{sfr}} \sim \rho_{\text{gas}}/\tau_{\text{dyn}}$ for ($\rho_{\text{gas}} > \rho_{\text{threshold}}$)
- Metal Enrichment
- Stellar Feedback

* Our simulations contain $\geq 170,000$ particles per galaxy and the resolution is typically $\sim 100$ pc. (Tested up to $1.7 \times 10^6$ particles.)
Disk Galaxy Models

• **The Milky Way + Mass Excursions** (40+ Major Mergers)
  A large, low gas fraction galaxy has been the starting point for the majority of all merger simulations to-date (MH94-96, Springel 2000, and our early work). The mass excursions have a higher gas fraction.

• **Sbc/Sc models** (50+ Major Mergers)
  Built to model the observed properties (Roberts & Haynes 1994) of local Sbc/Sc galaxies. While (roughly) the same size as the Milky way these models have a large amount of extended gas. Model Sc has no bulge and Model Sbc has a small bulge.

• **G models** (13 Major Mergers, 88+ Minor Mergers)
  There are 4 G galaxies (G3,G2,G1,G0, ordered by mass) which are statistically average galaxies whose properties are extracted from SDSS plus other local, early-type galaxy surveys. The dark mass and concentration are constrained to match the baryonic TF relation.
Lots of minor mergers...

**Merger Mass Ratios**

<table>
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<th>Primary</th>
<th>Satellite</th>
<th>Total</th>
<th>Stellar</th>
<th>Baryonic</th>
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<td>1:1</td>
<td>1:1</td>
</tr>
<tr>
<td>G3</td>
<td>G2</td>
<td>2.3:1</td>
<td>3.3:1</td>
<td>3.1:1</td>
</tr>
<tr>
<td>G3</td>
<td>G1</td>
<td>5.8:1</td>
<td>10.0:1</td>
<td>8.9:1</td>
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<tr>
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<td>G0</td>
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<td>50.0:1</td>
<td>38.9:1</td>
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<td>1:1</td>
<td>1:1</td>
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<tr>
<td>G2</td>
<td>G1</td>
<td>2.6:1</td>
<td>3.0:1</td>
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<td>1:1</td>
<td>1:1</td>
</tr>
<tr>
<td>G1</td>
<td>G0</td>
<td>3.9:1</td>
<td>5.0:1</td>
<td>4.4:1</td>
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<td>G0</td>
<td>G0</td>
<td>1:1</td>
<td>1:1</td>
<td>1:1</td>
</tr>
</tbody>
</table>
Merging Two Disks

Orbit, $\epsilon$, $r_{\text{peri}}$

$\phi_1, \theta_1$

$\phi_2, \theta_2$
We find that the short (rotation) axis of the visible elliptical galaxy aligns with the long axis of its dark matter halo. The long axis of the halo is along the merger axis, while the angular momentum axis is perpendicular to that axis.

The stellar ellipsoids are mostly oblate but the dark matter halo is usually triaxial or prolate.

The stellar minor axis usually aligns with the angular momentum axis, which aligns with the dark matter smallest axis, perpendicular to the dark matter major axis.

Comparison with SAURON data in progress by UCSC grad student Greg Novak working with Cox, Jonsson, Faber, and Primack.

NGC 474

Views of G3G3 merger, plotted like SAURON data.

\( I \)

\( V \)

\( \sigma \)

\( h_3 \)

\( h_4 \)
The **conclusions** so far from the SAURON comparison are:

1) Binary hydrodynamic major mergers form qualitatively convincing replicas of the SAURON "fast rotators" (~80%).

2) Binary gas-poor major-mergers spiral galaxy and binary gas poor elliptical-elliptical mergers **cannot** form the SAURON "fast rotators." They have too little rotation and get the V-H3 correlation wrong.

3) Binary gas-poor major-mergers spiral galaxy and binary gas poor elliptical-elliptical mergers **probably can’t** form the SAURON slow rotators (~20%), **unless** slow rotators are significantly more elliptical on average than is indicated by the SAURON survey. Greg Novak is running various types of multiple mergers to try to form galaxies like the SAURON slow rotators, and modeling NGC 6240 with its close SMBH binary.
Simulations of Dust in Interacting Galaxies

HST image of “The Antennae”
Our Approach

For every simulation snapshot:
• SED calculation
• Adaptive grid construction
• Monte Carlo radiative transfer

“Photons” are emitted and scattered/absorbed stochastically
Spectral Energy Distribution

![Graph showing spectral energy distribution with different lines representing 'w/o dust', 'face on', and 'edge on'.](image)
Star-formation history
Luminosities

UV/visual luminosity is practically constant over time.

Attenuation increases with luminosity.
This and the following images show a merger between two Sbc galaxies, each simulated with 3x the mass resolution of the previous ones. The images are color composites of $u$, $r$, and $z$-band images.
Comparing to IRX-Beta relation

- $\text{IRX}_{1600} = \frac{F_{\text{FIR}}}{F_{1600}}$
- UV spectral slope $\beta$

Determined by fitting $f_\lambda \propto \lambda^\beta$

- Observed sample is starbursts observed with IUE (Meurer, Heckman, Calzetti 99)
- Also ULIRGS (Goldader 02)
Split by Luminosity

- Simulated lower-luminosity galaxies follow an IRX-β relation similar to the observed MHC99 galaxies
- Higher-luminosity galaxies occupy the UIRG region
- Note that these were predictions: no parameter fitting!
Quantifying Galaxy Morphology and Identifying Mergers

see Lotz, Primack & Madau 2004, AJ, 128, 163 and subsequent papers

ULIRGS Borne et al. (2000)
Measuring Galaxy Morphology

- by “eye” - Hubble tuning fork E-Sa-Sb-Sc-Sd-(Irr)

- parametric
  1-D profile fit ( r^{1/4}, exponential, Sersic )
  2-D profile fit ( bulge+disk; GIM2D, GALFIT)
  → doesn’t work for irregular/merging galaxies

- non-parametric
  “CAS” - concentration, asymmetry, clumpiness
  neural-net training
  shaplet decomposition

new: Gini Coefficient (Abraham et al. 2003)
M20 2nd order moment of brightest regions
The Gini Coefficient

used in economics to measure distribution of wealth in population
→ distribution of flux in galaxy’s pixels (Abraham et al. 2003)

G=0  for completely egalitarian society (uniform surf brightness)
G=1  for absolute monarchy (all flux in single pixel)
      (G = 0.445 for US in 1999)
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G is independent of large-scale spatial distribution
2nd order moment of light

\[ M_{\text{total}} = \sum f_i r_i^2 \] (minimize to find center)

this depends on size + luminosity
→ find relative moment of brightest regions

\[ M_{20} = \log_{10} \frac{1}{M_{\text{total}}} \sum_{i=1}^{n} f_i r_i^2 \]

where \[ \sum f_i = 0.2 \sum_{i=1}^{n} f_i \]

- very similar to \( C = \log (r_{80\%}/r_{20\%}) \)
  but does NOT assume particular geometry

- more sensitive to merger signatures (double nuclei)
Local Galaxy G-M20 relation

G, Gini coefficient, and $M_{20}$ characterize galaxy morphology, see Lotz, Primack & Madau (2004)

- tight sequence for “normal” galaxies
- most ULIRGs lie above this sequence

ULIRGs

mergers?

Light in a few pixels

Uniform surface brightness

Extended

Concentrated

$G (R)$

-0.8

-0.6

-0.4

-0.2

0.0

0.2

0.4

0.6

0.8

$M_{20} (R)$

$E/S0$

$Sa/Sab$

$Sb/Sbc$

$Sc/Scd$
Nonparametric Morphology Measures
Gini and M20

flux in fewer pixels

Gini

more uniform flux distribution

M20

extended

compact

E/S0/Sa

Sb/Sbc

Sc/Sd/Irr

Mergers

Jennifer Lotz
Modeling Merger Morphologies

Light in a few pixels

Uniform surface brightness

\( C (R) \)

\( M_{20} (R) \)

Extended

Concentrated

no dust

w/ dust
Modeling Merger Morphologies

Light in a few pixels

no dust

w/ dust

Uniform surface brightness

Extended

$M_{200} (\mathcal{R})$

g (\mathcal{R})
Modeling Merger Morphologies

- Light in a few pixels
- Uniform surface brightness

Graph showing data points for 'no dust' and 'w/ dust' with two distinct lines indicating 'Extended' and 'Uniform surface brightness.'
Light in a few pixels

Uniform surface brightness

Concentrated

Extended

Modeling Merger Morphologies
Modeling Merger Morphologies

- our mergers occupy the same region as local ULIRGs

ULIRGs
E/S0
Sa/Sab
Sb/Sbc
Sc/Scd

Light in a few pixels
no dust
w/ dust

Uniform surface brightness

- Extended
- Concentrated

\( C(R) \)
Using morphology and IR - optical color, it’s possible to determine the merger stage of simulated galaxies (senior thesis of Seth Cottrell, supervised by Lotz and Primack). We’re now applying these techniques to a larger sample of simulations, and to observations. This will enable accurate measurement of merger rates.
Comparison with Observational Data

Extended Groth Strip (EGS)

All-wavelength Extended Groth strip International Survey

AEGIS

- EGS: \(\sim0.5\ \text{deg}^2\) (green area)
- ACS: \(\sim0.33\ \text{deg}^2\) (red area)
- IRAC: \(\sim0.5\ \text{deg}^2\) (full EGS)
- Chandra: \(\sim3.75\ \text{sq. arcmin.}\) (Groth Westphal Strip; extra pointings now available)
- Canada-France-Hawaii Telescope Legacy Survey: photometric redshifts
- DEEP2 spectroscopic redshifts

X-ray data now: GWS: 200ks, EGS-5,6,7: 100ks
The highest fraction of EGS galaxies hosting AGN are early-types, not mergers. This suggests that the AGN activity is delayed, rather than occurring mainly during and immediately following mergers. Consistent with Hopkins et al. simulations? (Christy Pierce et al., for DEEP2 AEGIS special issue of ApJ Letters).
EGS X-ray Selected AGN and Close Kinematic Pairs

Close kinematic pairs have
5-50 $h^{-1}$ kpc projected separation,
$\Delta v<500$ km s$^{-1}$, and
magnitude difference $<2$ mag (using $V$ for $0.2<z<0.6$, $I$ for $0.6<z<1.2$)

We find that 7/49 (14%) X-ray selected AGN in the spectroscopic sample are in kinematic pairs, compared to 4.5% of field galaxies. Thus X-ray selected AGN are $3.1\pm1.4$ times more likely to be in kinematic pairs.

This is higher than found by Grogin et al. 2005 in GOODS-N, but we find results consistent with theirs if we use angular separation (as they did) rather than kinematic pairing. Concentration-Asymmetry statistics for EGS X-ray AGN are consistent with those found by Grogin et al. for GOODS-N, but Gini-$M_{20}$ can be used to classify about twice as many galaxies and are more efficient at morphological classification (Lotz, P, and Madau 2004).
AGN in GOODS-N follow same pattern as in EGS

Fig. 1.— *Chandra* sources from GOODS-North (black symbols) and the EGS (grey symbols). Symbol size indicates $L_{2-10\,\text{keV}}$ of the AGN. Host galaxies meet the following criteria: $I < 23.5$, $0.2 \leq z < 1.2$, $\langle S/N \rangle$ per pixel $\geq 2.5$, $r_P \geq 0.3$, and not flagged as a star by SExtractor. Spectroscopic and photometric redshifts are used. Morphologies are measured from the $V$ band for $0.2 \leq z < 0.6$ and from the $I$ band for $0.6 \leq z < 1.2$. The lines are as defined by Lotz et al. (2006).
Mean overdensity estimator $\log(1 + \delta_3)$ against $M_B$ (left) and $U - B$ (right). In both plots the mean $\log(1 + \delta_3)$ is estimated in different $M_B$ and $U - B$ bins. The errorbars correspond to the standard error in each bin. We only plot systems brighter than $M_B = -22$ mag because more luminous galaxies are affected by small number statistics. For the X-ray sample we only plot bins with more than 4 sources. (From A. Georgakakis et al. 2006, for AEGIS special issue of ApJ Letters.)

X-ray AGN at $z \sim 1$ are in higher density regions, unlike at $z \sim 0$
Rest-frame $U-B$ color is plotted against the $B$-band absolute magnitude for DEEP2 comparison galaxies (small blue dots) and X-ray sources (filled red circles) in the EGS in the range $0.7 < z < 1.4$. Squares around the symbols indicate hard X-ray sources, and more luminous systems ($L_X > 10^{43}$ erg s$^{-1}$) are plotted with larger symbols. (Kirpal Nandra et al., for AEGIS special issue of ApJ Letters.)
Conclusions on EGS X-ray Selected AGN

We find that most X-ray selected AGN are hosted by early-type galaxies, based both on G-M$_{20}$ and on visual classification. Mergers and Sb/bc galaxies are represented at the same rate as the field population, and Sc/d/Irr galaxies are greatly underrepresented. Close kinematic pairs are 3 times as likely to host X-ray AGN.

Most X-ray AGN are in the red sequence, in the top half of the blue cloud, or in the transition region between them. This supports the idea that AGN terminate star formation. But many transition galaxies do not have AGN.

Many X-ray AGN are bright ($>10^{42}$ erg/s) for 1 Gyr or more after a starburst. Many hard AGN are on the red sequence, disfavoring star-forming gas as a main source of obscuration.

Much more AEGIS data (including all 8 200 ks Chandra pointings) now being analyzed. Make predictions!