Galaxy Mergers through Cosmic Time

Jennifer Lotz
Space Telescope Science Institute
The Role of Mergers in Galaxy Assembly

galaxy mergers vs. gas accretion
how to galaxies grow in mass?

Lacey & Cole 1993

Ceverino et al. 2009
The Role of Mergers in shaping galaxy properties
How To Find a Galaxy Merger

- close galaxy pairs (pre-mergers)
- morphology (pre- and post-mergers)

not the same!

- kinematics (pre- and post-mergers)
Galaxy Merger Fractions disagree!

$M_{\text{star}} > 10^{10} \, M_\odot$

or $L_B > 0.4 \, L_*$

Lotz et al. 2008
Lin et al. 2008
Bundy et al. 2009
de Ravel et al. 2009
Darg et al. 2009
Conselice et al. 2009
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How to Calculate the Galaxy Merger Rate

the ‘merger’ rate is defined as

$$R_{\text{merg}} \ [\text{Gyr}^{-1}] = \frac{f_{\text{merg}}}{T_{\text{merg}}}$$

or

$$\Gamma_{\text{merg}} \ [\text{Mpc}^{-3} \text{Gyr}^{-1}] = \frac{\phi_{\text{merg}}}{T_{\text{merg}}}$$

where

- $f_{\text{merg}}$ is fraction of galaxies in a merger
- $\phi_{\text{merg}}$ is number density of merger events ($f_{\text{merg}} \times n_{\text{gal}}$)
- $T_{\text{merg}}$ is time for merger to complete (few Gyr)
How to Calculate the Galaxy Merger Rate

but we observe merger events at particular stages (depending on method) with a range of merger parameters (mass ratio, gas fraction...)

\[ R_{\text{merg}} \, [\text{Gyr}^{-1}] = \frac{f'_{\text{merg}}(z)}{\langle T_{\text{obs}}(z) \rangle} \]

\[ \Gamma_{\text{merg}} \, [\text{Gyr}^{-1} \, \text{Mpc}^{-3}] = \frac{f'_{\text{merg}}(z) \, n_{\text{gal}}(z)}{\langle T_{\text{obs}}(z) \rangle} \]

\( T_{\text{obs}} \) depends on merger parameters... and

\( \langle T_{\text{obs}}(z) \rangle \) depends on distribution of parameters with \( z \)
GADGET N-Body/SPH galaxy merger simulations
initial galaxies: gas-rich disks (5 models)

(Cox et al. 2006, 2008)

Disk-disk mergers:
- orientation
- orbits (pericentric distance, eccentricity)
- gas fraction (20%, 40%, 50% of baryons)
- total mass ($10^9 - 10^{12}$ Msun)
- mass ratio (1:1 -- 1:10)
- supernova feedback prescription (No AGN!)
- nparticles 1x, 10x

with T.J. Cox, P. Jonsson, J. Primack, R. Somerville
Galaxy Merger Simulations

Particles (stars, gas) $\Rightarrow$ Light (dust, $\lambda$)

SUNRISE: Monte-Carlo radiative transfer code (Jonsson 2006)

http://archive.stsci.edu/prepds/diggss
Merger Timescales - Mass Ratio

G-M$_{20}$ finds major and minor mergers

Lotz, Jonsson, Cox, & Primack, 2010a
Asymmetry timescales depend on gas fraction

Lotz, Jonsson, Cox, & Primack, 2010b
Cosmological Weighting

\[ \langle T(z) \rangle = \sum n_i(z) T_i \]

to compute \( \Gamma_{\text{merger}}(z) \) need \( \langle T(z) \rangle \)

weighted by \( n(\text{mass ratio, gas fraction...}) \)

\Rightarrow \text{use distributions of merger properties}

from cosmological models
(Somerville et al. 2008; Croton et al. 2006; Stewart et al. 2008)
Cosmological Weighting

Gas fraction v. z

Somerville 08
Cosmological Weighting

Timescale v. z

\[ T(\text{pair}), \ T(G-M_{20}) \]

independent of \( f_{\text{gas}} \)

\[ T(\text{Asym}) \sim f_{\text{gas}}(z) \]

Lotz et al., in prep
Galaxy Merger Rate at $z<1$

Lotz et al., in prep
How to Measure the Galaxy Merger Rate

\[ f_{\text{merg}}(z) \quad \langle T_{\text{obs}}(z) \rangle \quad R_{\text{merg}}(z) \quad n_{\text{gal}}(z) \quad \Gamma_{\text{merg}}(z) \]

- \( f_{\text{merg}}(z) \) for major mergers: \( R_{\text{merg}} \sim (1+z)^2 \) \( \Gamma_{\text{merg}} \sim \text{flat} \)
- \( f_{\text{merg}}(z) \) for major+minor mergers: 3-5 x major merger; weaker evolution?
Galaxy Merger Rate at $z<1$

\[ \Gamma_{\text{minor}} \sim (\Gamma_{\text{G-M20}} - \Gamma_{\text{pairs}}) \]
\[ \Rightarrow \sim 1-3 \text{ minor mergers} \]
\[ \text{per } >0.5 \text{ L}^* \text{ galaxy since } z\sim 1 \]

\[ \Gamma_{\text{major}} \sim \Gamma_{\text{pairs}} \sim \Gamma_{\text{asym}} \]
\[ \Rightarrow \sim 0.5 - 1 \text{ major merger} \]
\[ \text{per } >0.5 \text{ L}^* \text{ galaxy since } z\sim 1 \]
Connecting to Dark Matter Halos

Dark Matter Halos: $R_{\text{merg}} \sim (1+z)^{2-3}$ for FIXED halo mass
merger rate depends on halo mass
(see also Hopkins et al. 2010)
Connecting to Dark Matter Halos

$n_{\text{gal}}$-selected

Galaxy Merger Rate evolution depends on how galaxy sample is selected (because merger rate depends on halo mass, halo $\leftrightarrow$ galaxy mapping?)

$\alpha \sim 3.0 \pm 0.2$

$\sim 2.9 \pm 1.1$
Peak Epoch of Star-Formation at $2<z<5$

Bouwens et al. 2009

redshift  

Bouwens et al. 2009
Merger $\rightarrow$ Starburst $\rightarrow$ AGN $\rightarrow$ Spheroid

e.g. Sanders & Mirabel 1996
HST WFC3 NIR needed at $z \sim 2$

need high resolution NIR imaging to probe rest-frame optical structures of $z \sim 2.5$ galaxies

Cosmic Assembly Near-IR
Deep Extragalactic Legacy Survey
HST MCT program
Galaxy Structures at $z \sim 2$

Approximately 35% disturbed, 20% spheroids, and 45% disks
(30 galaxies, $1.5 < z < 2.5$, $M_{\text{star}} > 10^{10} \, \text{M}_{\odot}$)
Merger v. Clumpy Star-Forming Disk?

⇒ need simulations of z~2 unstable disk galaxies and gas-rich mergers to interpret HST structures (+ALMA + Herschel + ground-based IFU)

Bournaud & Elmegreen 2009

F_{24} = 628. \mu Jy

T=0.72 \text{ Gyr} \quad 24/R=1377

Narayanan et al. 2009

[24\mu - R - B]
Galaxy Mergers at $z<1$

- merger ‘fractions’ disagree (not surprising!)
- theoretical timescales needed to compute ‘rate’
- fractional merger rate $R(z) \sim (1+z)^2$
  \hspace{1cm} volume-averaged merger rate $\Gamma(z) \sim \text{flat}$
  \hspace{1cm} (for constant stellar mass selection)
- need halo $\leftrightarrow$ galaxy to compare to halo merger rate

- Merger-driven SF accounts for $<12\%$ total $\rho_{SFR}$
The Role of Mergers at $z \sim 2$

- peak epoch of SF, AGN activity; also mergers?
- need high-res NIR imaging
  CANDELS (+ JWST)
- mergers v. clumpy disk??
  need simulations + kinematics (ALMA?)