Astro 358/Spring 2012

Galaxies and the Universe

Figures + Tables for Lecture on May 1

Impact of Galaxy Interactions/Mergers on Galaxy Evolution

Nearby Interacting and Merging Galaxies

NGC 4736 / The Mice

Cartwheel galaxy
Head-on collision

(Credit: NASA/STScI/Hubble Heritage)

Nearby Interacting and Merging Galaxies

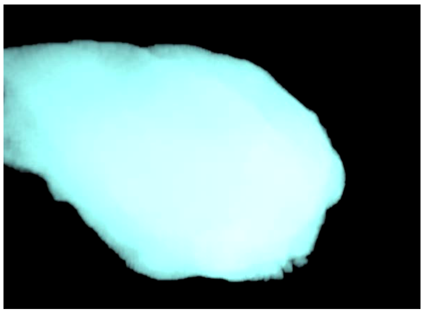
The Antennae

Credit: NASA/STScI/Hubble Heritage)

Outline of Topics

- Why are galaxy interactions and galaxy mergers important?
- When do interactions lead to mergers?
- What factors determine the impact of galaxy mergers?
- Type of mergers: Major and Minor mergers
- Basic Physics: Impact of Mergers on gas (gravitational torques and shocks)
- Basic Physics: Impact of Mergers on stars (tidal heating, violent relaxation)
  Fate of Stellar Disks in Major vs Minor Mergers : Old view vs New Paradigm
- Impact of Mergers on Star formation Activity
- Impact of Mergers on Black hole activity
- Interactions of the Milky Way

Why is it important to study Galaxy Mergers ?



Courtesy: Frank Governato

Above is a toy Simulation of how a Milky Way Type galaxy is built over 13.7 Gyr. Assembling a galaxy (made of gas, stars, dark matter) is a complex process involving smooth gas accretion along filaments as well as mergers of galaxies.
Galaxy mergers are one of the fundamental ways in which galaxies grow their total mass, form new stars and change their structure over time

When do interactions result into mergers?

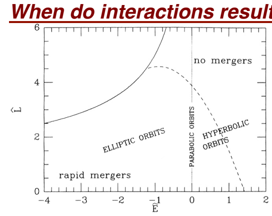


Figure 7-9. The time required for two galaxies to merge is a function of the initial position of the binary orbit in the $(\tilde{E}, \tilde{L})$ plane defined by equations (7-85). Orbits are only possible below and to the right of the full curve formed by the circular orbits. In principle all elliptic orbits ($\tilde{E} < 0$) will eventually lead to a merger, but the time to merging increases rapidly toward the upper right portion of the diagram. For typical galactic parameters, orbits below and to the left of the dashed line evolve to mergers in about a Hubble time.

(GD= Galactic Dynamics, Binney & Tremaine)

Mergers occur for bound orbits where total energy E<0 :
Merger timescale = f (E, relative orbital angular momentum L)

What factors determine the impact of galaxy mergers?

Impact of a galaxy merger on the star formation, structure, and AGN activity of the galaxies depends on many factors, including

1) The mass ratio M1/M2 of progenitors (e.g., major vs minor mergers)

2) The gas content of progenitors

3) The structure (e.g. Bulge to disk ratio)

4) The orbital geometry of the encounter
prograde (orbital and spin angular momentum are parallel)
retrograde (orbital and spin angular momentum are anti-parallel)

5) orbital parameters
(e.g., eccentriciity of orbits, radial vs non-radial orbits)

Types of Mergers: Major and Minor Galaxy Mergers

Major Merger
- Merger of 2 galaxies of mass ratio M1/M2 < 1/4 (e.g., 1:1, 1:2, 1:3)
- Different studies use halo mass (theory) or baryonic mass (Mgas + Mstars) or stellar mass to get M1/M2. These different criteria are not equivalent

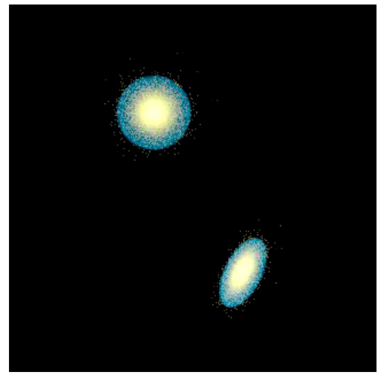
Fig. 9.15. The Antenna galaxies. On the left, the "true" op-

Example of ongoing major merger

NGC 4736 / The Mice (Credit: NASA/STScI/Hubble Heritage)

HST image shows details of a collision between 2 spiral galaxies 30 kpc apart.
Example of a nearby ongoing major merger

Simulation of a major merger of 2 spirals of moderate gas fraction



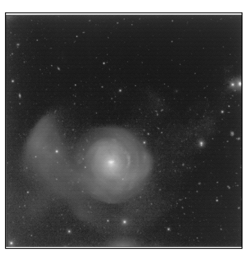
A first look!

(Mihos & Hernquist; DM halo + Stars =yellow, gas= blue, Duration = 1 Gyr)
Major Merger of 2 spirals of low/moderate gas fraction

Types of Mergers: Major and Minor Galaxy Mergers

Minor merger
- Merger of 2 galaxies of mass ratio 1/10 <M1/M2 <= 1/4 (e.g., 1:4, 1:5, 1:6)

Cartwheel galaxy ; Head-on collision
(Credit: NASA/STScI/Hubble Heritage)



NGC 2782 (Jogee +1999; Smith+ 1999)

What drives the radical transformations you saw in the movies?

Basic Physics: Impact of galaxy mergers on gas and stars

Basic Physics: Impact of Galaxy Mergers on Gas
(gravitational torques and shocks)

Gas inflows/ouflows during a merger are driven by shocks and gravitational torques

1) Shocks (sometimes called 'hydrodynamic torques')

When 2 galaxies merge, their stars do not collide but their gas does. When gas at very different velocities collide, they are shocked, lose energy and move inward deeper in the gravitational potential

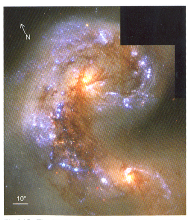


Fig. 9.15. The Antenna galaxies. On the left, the "true" op-

Impact of Galaxy Mergers on Gas
(gravitational torques and shocks)

2) Gravitational torque : see fig 2 handed in class

- Let **F** be the force exerted by galaxy G1 at position r in galaxy G2
- The gravitational torque $\boldsymbol{\tau}$ exerted by galaxy G1 at position r in galaxy G2

  $\boldsymbol{\tau} = \mathbf{r} \times \mathbf{F}$

- Angular momentum **L** of star or gas of mass m at position r in G2 moving at velocity v

  $\mathbf{L} = m\,(\mathbf{r} \times \mathbf{v})$

- If τ and L are parallel, then gas or star in G2 gains angular momentum and is driven out

  If τ and L are anti-parallel, then gas or star in G2 loses angular momentum and is driven in

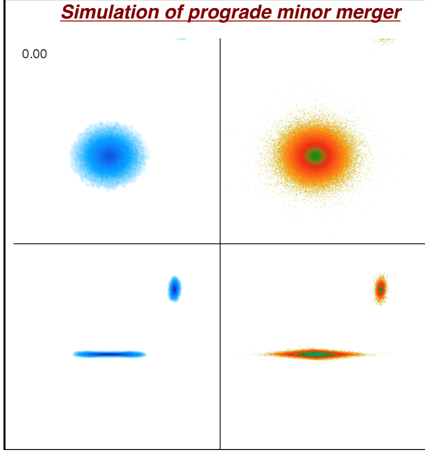
- The gravitational torque on galaxy G2 during an interaction can often be split into two parts

  i) the torque τ_1 exerted on galaxy G2 by companion G1 (this is called tidal torque)

  ii) the torque τ_2 exerted by a stellar bar, which may be induced in the plane of galaxy G2 by G1

  -> During prograde minor mergers, the torque $\tau_2 >> \tau_1$! (Mihos & Hernquist 1995

Simulation of prograde minor merger



Gas (blue) & stars (yellow) are shown in 2 projections: face-on and edge-on

(Credit = T. J. Cox)

1) A strong stellar bar or bar-like feature is induced in the disk of the main galaxy G1

2) Gravitational torques from this bar and the companion drives gas inflows in the main galaxy, leading to central starbursts

3) The stellar disk survives, but is tidally heated and disrupted

Basic Physics: Impact of Galaxy Mergers on Gas
(gravitational torques and shocks)

Tidal tails : To conserve angular momentum during the mergers of 2 disk galaxies, gas is often flung out in tidal tails

NGC 4736 / The Mice (Credit: NASA/STScI/Hubble Heritage)

Basic Physics: Impact of Galaxy Mergers on Stars
(tidal heating and violent relaxation)

- Tidal heating in major and minor mergers

The concept of tidal heating of stars discussed earlier in the context of galaxy interactions also drive the physics of galaxy mergers.
When 2 galaxies merge, all the relative orbital Kinetic energy (KE) of the 2 galaxies is converted into internal random KE of the stars in each galaxy:

-> Severe "tidal heating": large rise in random motion (velocity dispersion) of stars)
-> Any existing stellar disk is thickened by tidal heating

Example: In a minor merger, the disk may be thickened by tidal heating even if it is not destroyed. One outstanding challenge in galaxy evolution is the presence of super-thin bulgeless galaxies

Basic Physics: Impact of Galaxy Mergers on Stars
(tidal heating and violent relaxation)

- Violent relaxation in major mergers

For major mergers, where the gravitational potential undergoes large and rapid changes, a process called violent relaxation occurs.

--> Violent relaxation destroys any existing stellar disk and redistributes the stars into a puffed-up 'spheroidal' distribution supported by velocity dispersion (like some massive ellipticals or massive bulges).

-> The surface brightness profile of the remnant is often a de Vaucouleurs $R^{1/4}$ profile

Fate of Stellar Disks in Major vs Minor Mergers

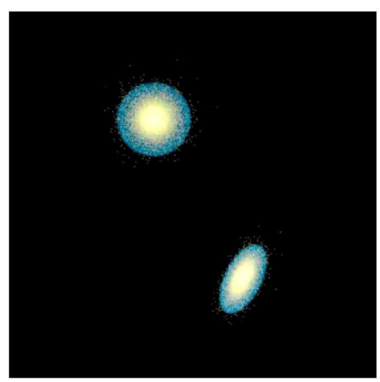
Major merger

- In a major merger involving 1 or 2 spirals, the **existin**g stellar disk of the spiral(s) is/are destroyed by violent relaxation and re-morphed into a puffed-up 'spheroidal' distribution supported by velocity dispersion (like some massive classical ellipticals or classical bulges).
- The new view of major mergers: In the old classical picture, it was assumed the major merger of 2 spirals always built a classical E or bulge. But, it has now been shown that if the galaxies are gas-rich, a new disk can form from residual gas violent relaxation producing 'disky remnants'. This is especially relevant at high redshift (e.g. Robertson 06, Hopkins 09)

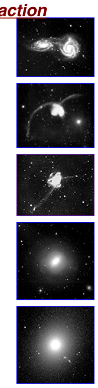
Minor merger

- In a minor merger, if the larger galaxy is a spiral galaxy, then the existing stellar disk is not destroyed because the rate of change in the gravitational potential is not large enough to induce violent relaxation.
- The disk survives, but may be thickened or distorted with ripples, arcs, warps etc.

Simulation of a major merger of 2 spirals of moderate gas fraction



(Mihos & Hernquist; DM halo + Stars =yellow, gas= blue, Duration = 1 Gyr)
Major Merger of 2 spirals of low/moderate gas fraction



Data
The Toomre Sequence

Toomre Sequence is a set of galaxies believed to represent different stages of a major merger of 2 spirals of low/moderate gas fraction. The outcome is a classical elliptical or bulge

Credit: Vera Rubin (CIW/DT NGC 5426/5427

Credit: Francois Schweizer (NGC 4038/4039

Credit: Francois Schweizer (NGC 7252

Credit: Francois Schweizer (NGC 3610

Credit: Digitized Sky Survey

During the major merger two spirals of low/moderate gas fraction

1) Cold molecular gas is driven to central regions, piles up to high density and form stars at a high rate (central starburst)

2) Gravitational forces fling out gas and stars into two extended tails. The stars in the tails fade away, while gas in the tails falls back into the galaxies to form stars

3) Orbital KE and orbital angular momentum of galaxies are converted to internal KE and angular momentum of stars) : tidal heating, velocity dispersion of stars rises

4) The stellar disks are destroyed due to tidal heating and violent relaxation. The stars are redistribute into a puffed-up, component which
a) is supported primarily by random motion rather than rotation (ie has low v/σ)
b) has a surface brightness profile with high Sersic n>3, where n=4 is a de Vaucouleurs profile

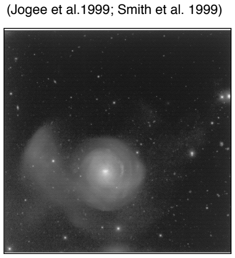
Visualization of major merger phases vs real galaxy snapshots

(Credit = NASA, ESA, STScI, Frank Summers)

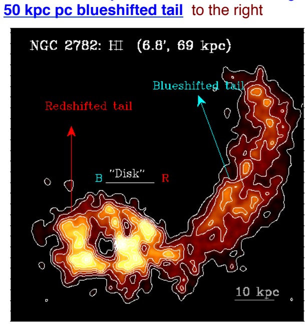
Example of a Minor merger

Optical R image of NGC 2782
- a disk with some ripples
- a 20 kpc pc tail to **the left**

(Jogee et al.1999; Smith et al. 1999)

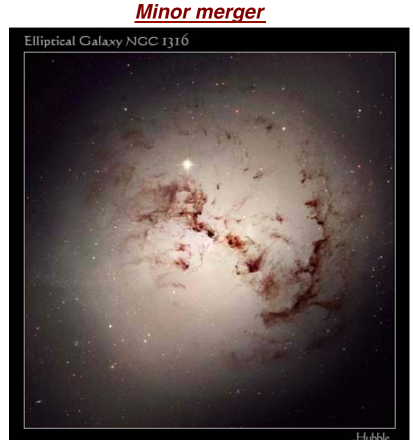


21 cm (atomic H) map shows a disk, a **redshifted 20 kpc tail** to the left and a huge **50 kpc pc blueshifted tail** to the right



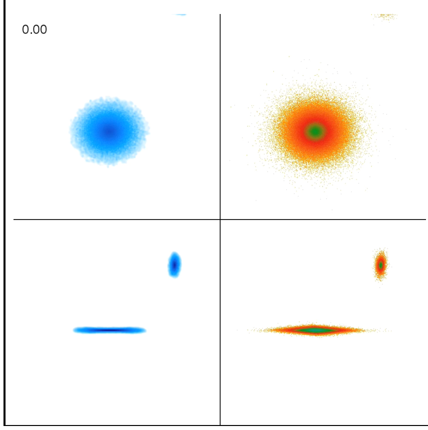
The optical morphology (distribution of stars) & the distribution + kinematics of the HI atomic gas distribution can be modelled with a merger of mass ratio 1:4

Minor merger



The elliptical galaxy (NGC 1316) has recently cannibalized smaller gas-rich spiral galaxies which are 1/10 to 1/100 its mass

Simulation of prograde minor merger



Gas (blue) & stars (yellow) are shown in 2 projections: face-on and edge-on

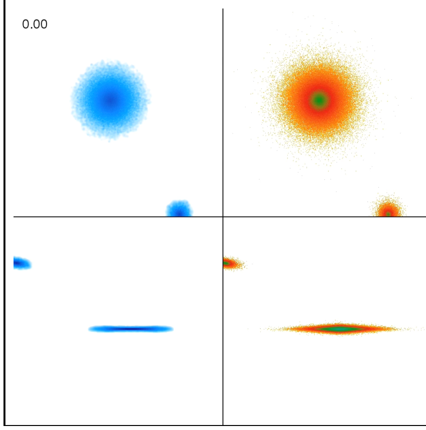
(Credit = T. J. Cox)

1) A strong stellar bar or bar-like feature is induced in the disk of the main galaxy G1

2) Gravitational torques from this bar and the companion drives gas inflows in the main galaxy, leading to central starbursts

3) The stellar disk survives, but is tidally heated and disrupted

Simulation of retrograde minor merger



Gas (blue) & stars (yellow) are shown in 2 projections: face-on and edge-on

(Credit = T. J. Cox)

Galaxy Interactions & Their Impact on Star Formation activity

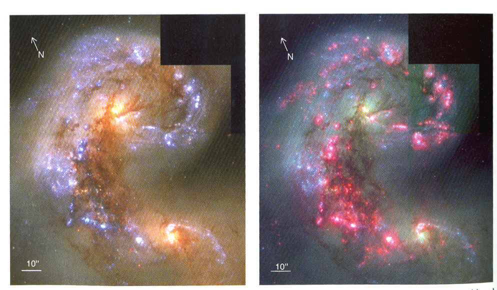
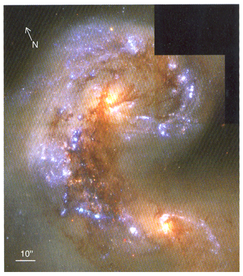


Fig. 9.15. The Antenna galaxies. On the left, the "true" optical colors are shown, whereas in the right-hand image the reddish color shows Hα emission. This pair of merging galaxies (also see Fig. 1.13 and Fig. 3.4 for other examples of merging galaxies) is forming an enormous number of young stars. Both the UV emission (bluish in the left image) and the Hα radiation (reddish in the right image) are considered indicators of star formation. The individual knots of bright emission are not single stars but star clusters with typically $10^5 M_\odot$; however, it is also possible to resolve individual stars (red and blue supergiants) in these galaxies

(EAC)

The Antenna galaxies = ongoing major merger of 2 disk galaxies

Note dust, gas and sites of massive stars (recent star formation) between the 2 disks



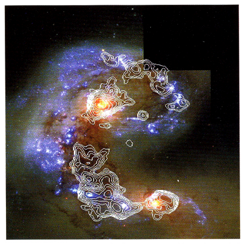


Fig. 9.16. The Antenna galaxies: superposed on the optical HST image are contours of infrared emission at 15 μm, measured by ISO. The strongest IR emission originates in optically dark regions. A large fraction of the star formation in this galaxy pair (and in other galaxies?) is not visible on optical images because it is hidden by dust absorption

(EAC)

Star formation is obscured at optical wavlengths by dust in gas-rich region, but revealed in mid-infrared images

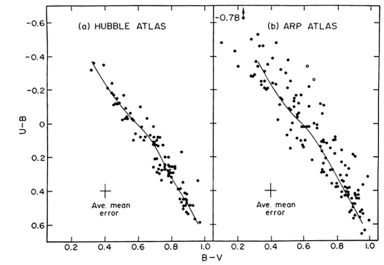


Figure 7-19. Tidally disturbed galaxies often have anomalous colors: the left panel shows the colors of predominantly undisturbed galaxies, while the galaxies of the right panel are all highly disturbed. The full curve is the same in each plot. Reproduced from Larson and Tinsley (1978) by permission of *The Astrophysical Journal.*

(GD)

Interacting galaxies : wider range and more extreme colors

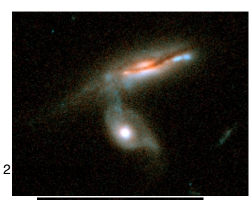
Important questions on galaxy Interactions & Their Impact on Star Formation over the last 7 Billion Years

- What is enhancement in the average SFR of mergers vs non-interacting galaxies, over the last half of the age of the Universe ?

- How much of the total SFR comes from of mergers vs non-interacting galaxies, over the last half of the age of the Universe ?

- Was galaxy evolution still dominated by violent galaxy mergers over this interval?

Example of interacting/merging galaxies at lookback =3 to 8 Gyr



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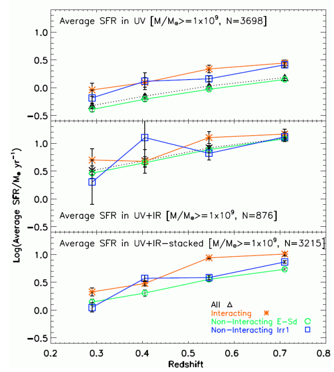
(Jogee, Miller, Penne, et al. & GEMS collaboratiion 2009, Astrophysical Journal)
http://xxx.lanl.gov/abs/0903.3700

Example of interacting/merging galaxies at lookback =3 to 8 Gyr

(Jogee, Miller, Penne, et al. & GEMS collaboratiion 2009, Astrophysical Journal)
http://xxx.lanl.gov/abs/0903.3700

Mean SFR in Interacting vs Normal galaxies over last 7 Gyr



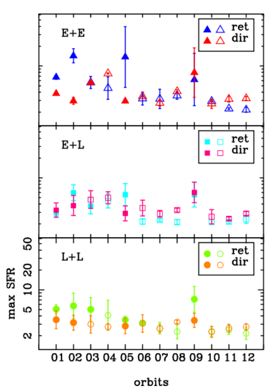
3 4 5 6 7 Lookback time in Gyr

(Jogee, Miller, Penne, & GEMS collaboration, 2009, ApJ, accepted)
(Paper on astrophysics server today)
at http://xxx.lanl.gov/abs/0903.3700

Over the last 7 Gyr: the mean SFR of mergers is enhanced by only a small factor of ~1.5 to 2.0 compared to non-interacting galaxies

Thus, over the last 7 Gyr, while the highest obscured SFRs tend to occur in mergers, the reverse is not true: not all mergers have extreme SFR

Simulations of the enhancement in mean SFR of mergers



(Di Matteo, P. et al. 2007)

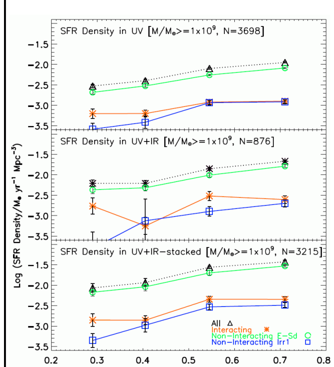
Statistical study of several hundred TREE-SPH simulations of major mergers of different B/D, gas, orbital parameters, etc

- E+E = merger 2 early type spirals e.g. Sa +Sb
- E+L = merger of early type and late type spiral e.g. Sa+Sc
- L+L = merger of 2 late type spirals

Y axis = Max value of the RATIO (SFR of merging systems /SFR of normal undisturbed galaxy)

SFR is enhanced typically by a factor of 2-3 in a merger compared to an isolated undisturbed galaxy

SFR density from mergers over last 7 Gyr



For M*>=1e9 Mo & M*>=2.5e10 visible mergers account for less than 30% of the SFR density over the last 7 Gyr. Most (above 70%) of the SFR density comes frrom normal non-interacting systems !!

Implications

1) the behavior of the SFR density over the last 7 Gyr is shaped by non-interacting galaxies rather than mergers,

2) At half of its present age, the Universe had already transitioned from a violent to a fairly quiescent phase and the evolution of massive galaxies was no longer dominated by mergers

(Jogee, Miller, Penne, et al. & GEMS collaboratiion 2009, ApJ, accepted)

Galaxy Interactions & Their Impact on Black Hole activity

Mass accretion rate to power high and low luminosity AGN

Table 1. Typical L_{bol} and $\dot{M}_{bh}$ for QSOs and local AGN

Type of AGN (1)	L_{bol} [a] (ergs s^{-1}) (2)	Typical L_{bol} (ergs s^{-1}) (3)	Typical $\dot{M}_{bh}$ [b] ($M_\odot$ yr^{-1}) (4)
QSOs	10^{46}–10^{48}	10^{47}–10^{48}	10–100
Seyferts	10^{40}–10^{45}	10^{43}–10^{44}	10^{-3}–10^{-2}
LINERs	10^{39}–$10^{43.5}$	10^{41}–10^{42}	10^{-5}–10^{-4}

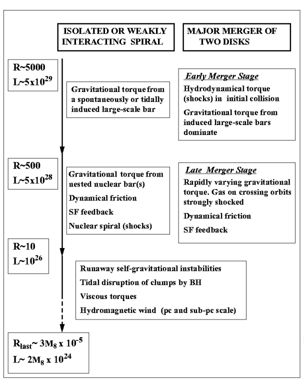
Notes to Table – a. The full range in bolometric luminosity (L_{bol}) for Seyfert and LINERS is taken from Ho, Filippenko, & Sargent 1997a, while for QSOs different sources in the literature are used; b. The typical $\dot{M}_{bh}$ in column (4) is derived from the typical L_{bol} in column (3) assuming a standard radiative efficiency $\epsilon \sim 0.1$

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

Fueling the Central BH :The Angular Momentum Problem

Before gas in the outer disk at a radius R of ~5 kpc can can feed a black hole , its specific angular momentum L must be lowered by a factor of 10^5.

Interactions or mergers can help at least partly



(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

Tight Correlation between BH Mass & Bulge Velocity Dispersion

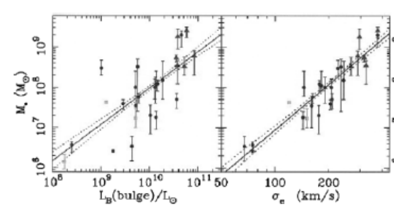
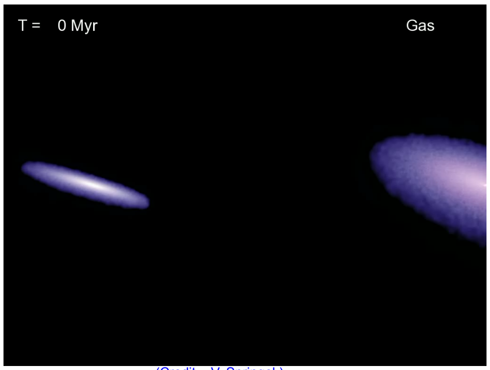


Fig. 1. Correlation between central BH mass and circumnuclear velocity dispersion – Black hole mass versus bulge luminosity (*left*) and the luminosity-weighted aperture dispersion within the effective radius (*right*). Green squares denote galaxies with maser detections, red triangles are from gas kinematics, and blue circles are from stellar kinematics. Solid and dotted lines are the best-fit correlations and their 68% confidence bands. (From Gebhardt et al. 2000)

Do mergers produce large gas inflows which lead to a synchronous growth of central bulge and central black hole?

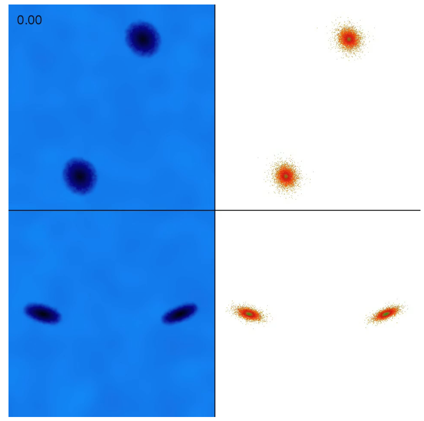
Does feedback from starburst winds and jets+energy from an activie black hole prevent a bulge from growing indefinitely?

Simulation of major mergers with black holes



(Credit = V. Springel)

Simulation of major merger including BH+diffuse IGM



Gas (blue) and stars (yellow) are shown in two projections: face-on and edge-on

Include black hole accretion + feedback, and diffuse IGM (Credit = T. J. Cox;)

Interactions of the Milky Way

Current and Future Interactions of Milky Way (SBbc spiral)

→It is presently 'digesting' the Spr I (dSp?) = accretion or **minor merger**
→ It is interacting w/ SMC (63 kpc)) and LMC (50 kpc) to give Magellanic stream of atomic H.
→ System of SMC and LMC may be sinking via dynamical friction into M Way: **minor merger**
→ It has a warp and thick disk → may be due to a past **minor mergers**

→ Milky Way (Sbc) and M31 (SAb) at separation of 770 kpc are approaching eah other at rel. speed of 120 km/s → **future major merger in 6 Gyr**