“Fueling Nuclear Activity in Disk Galaxies: Starbursts and Monsters”

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Centers of Disk Galaxies

- Some disk galaxies exhibit strong activity in their central regions, thought to be due to
  - accretion of material onto a central supermassive black hole (BH)
    - active galactic nuclei (AGNs)
  - formation of lots of massive stars in a short period of time
    - starburst galaxies

How can material get to the center?

- Both AGNs and starbursts require the processing of huge amounts of material in order to achieve the observed luminosities.
  - a few percent of the total mass of the galaxy
  - a significant fraction of the total ISM

- How does the ISM get past the angular momentum barrier in order to fuel the central activity?
  - Shlosman, Begelman, & Frank (1990): global nonaxisymmetric instabilities
  - Simkin, Su, & Schwarz (1980): stellar bars channel gas toward center

Gas Dynamics

- Following Simkin, Su, & Schwarz (1980), much of the focus of past simulations was to model the flow of gas in a barred stellar potential, but...
- "there are indications that the *gas* plays an important if not dominant role in the dynamics of the central few hundred parcecs"
  - gas not only affected by gravity, but also by
    - stellar winds
    - supernovae ejecta

Limitations of Past Simulations

- Lack of resolution
  - weren't able to follow gas flows for more than a decade in radius
- Two-dimensional
- Most studies have ignored
  - self-gravity of the gas
  - imposition of an oval or spiral distortion to the gravitational potential
  - “back reaction” of the gas

Goal of this Paper

- To simulate the dynamics of a two component galactic disk (gas+stars) in a responsive halo, including the effects of
  - massive star formation
  - supernovae
- Concentration on the inner disk, as close in as ~50 pc from the center.
- "We aim at understanding the physical processes which lead to nuclear starbursts and to the rapid growth of the central BH."

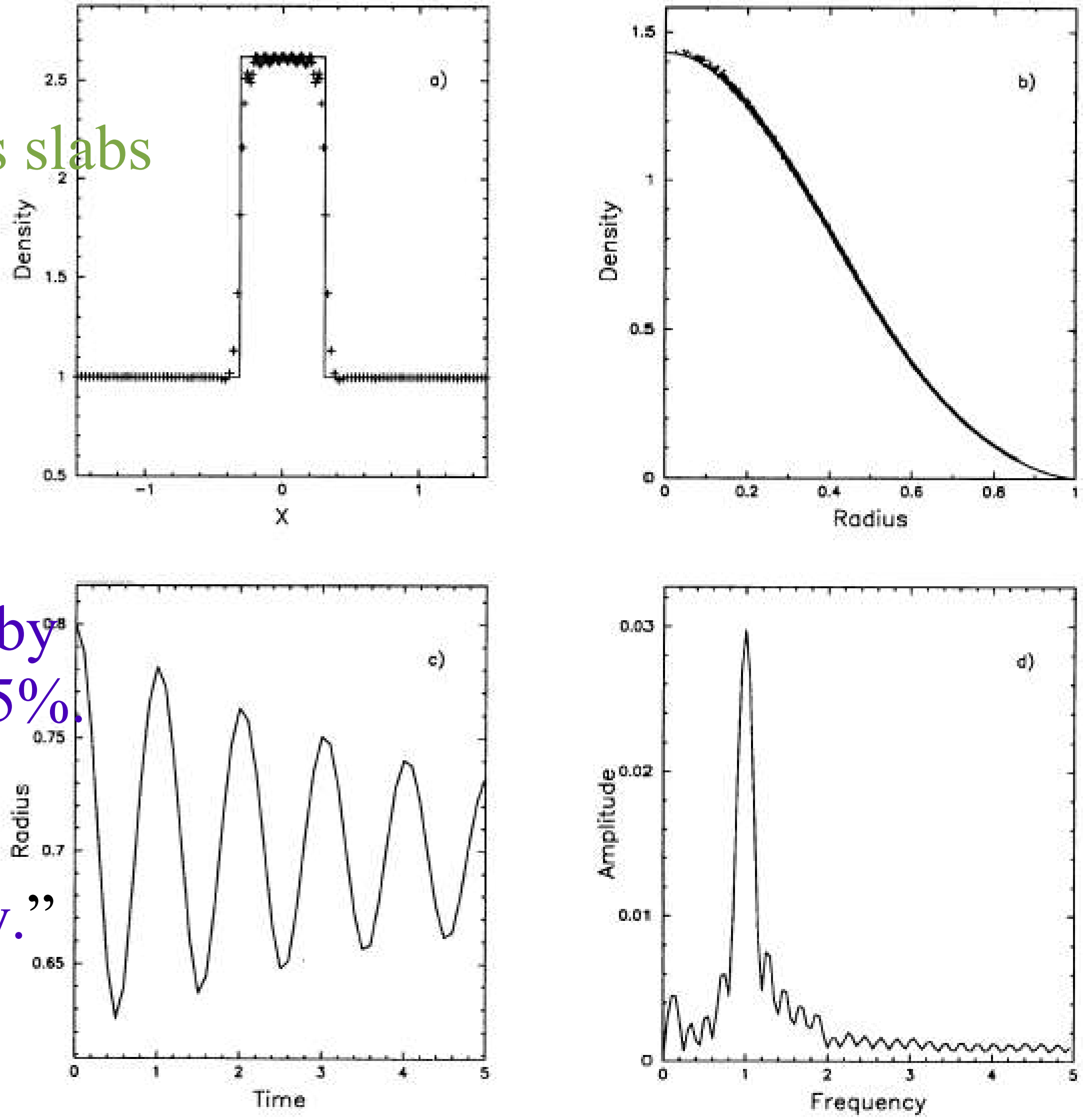
Observational Evidence/Motivation

- Although the observations suffer from low angular resolution, observations of CO, CN, & other molecules tell us that gas in the central kpc often forms "molecular bars" or nuclear rings.
- These bars of molecular gas don't necessarily have to coexist with a stellar bar.
- Central concentrations of molecular gas are associated with high star formation and black hole accretion.
- Supports the idea of large-scale rearrangement of molecular gas.

Numerical Method

- Smooth Particle Hydrodynamics (SPH) is used to evolve the gas.
  - A finite set of "particles" are used to model the gas.
  - Not just treated as point particles; they are smoothed out according to a spherically symmetric function.
- Gravity
  - Force acting on each mass is calculated by dividing all other masses into groupings of appropriate size.
  - "hierarchical TREE method": $N \log N$ computing time
- Multiple time step sizes (necessary to get the desired dynamic range in radius, density)

Fig. 1: Testing the Code



Colliding gas slabs
(no gravity)

Polytropic gas sphere in hydrostatic equilibrium

Induced pulsation by expanding b) by 15%.

Damping is due to “artificial viscosity.”

Simulation correctly produced the expected pulsation frequency.

Galaxy Simulations: Initial Conditions

- Exponential disk (in both radius *r* and height *z*)
  - stars
    - scale lengths 2.85 kpc in *r*, 0.5 kpc in *z*
    - 16,384 collisionless SPH particles
  - gas
    - scale length 0.25 kpc in *z*
    - 8,192 collisional SPH particles
- Spherical halo with 10,240 collisionless particles
- Mass ratio (halo/disk) = 1
- Relaxation to “virial equilibrium”

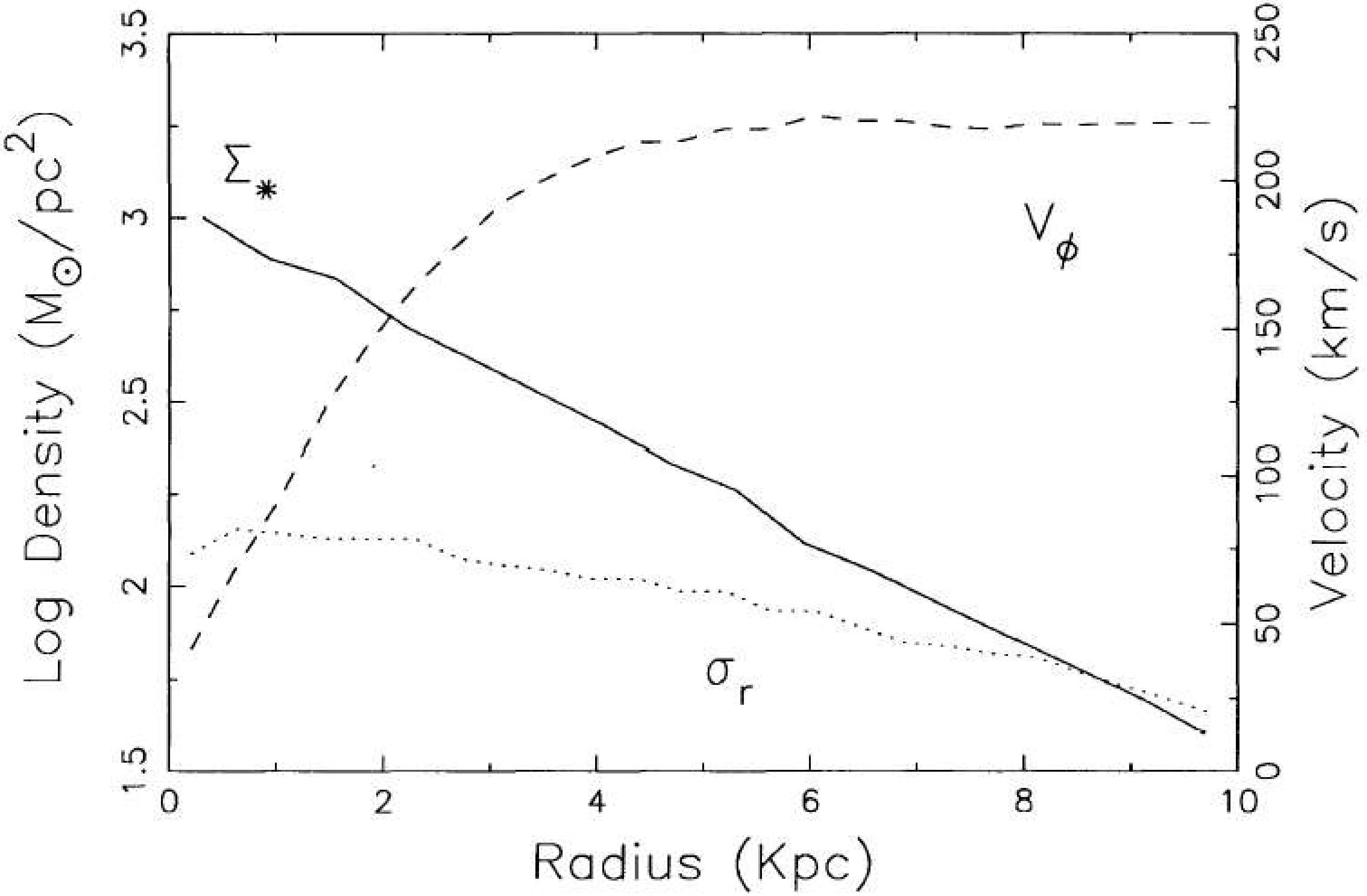


FIG. 2.—Initial conditions for a generic model (A0). Profiles of stellar surface density (*solid line*), rotation velocity (*dashed line*), and radial dispersion velocity (*dotted line*) in the disk.

Simple Model for Stellar Evolution

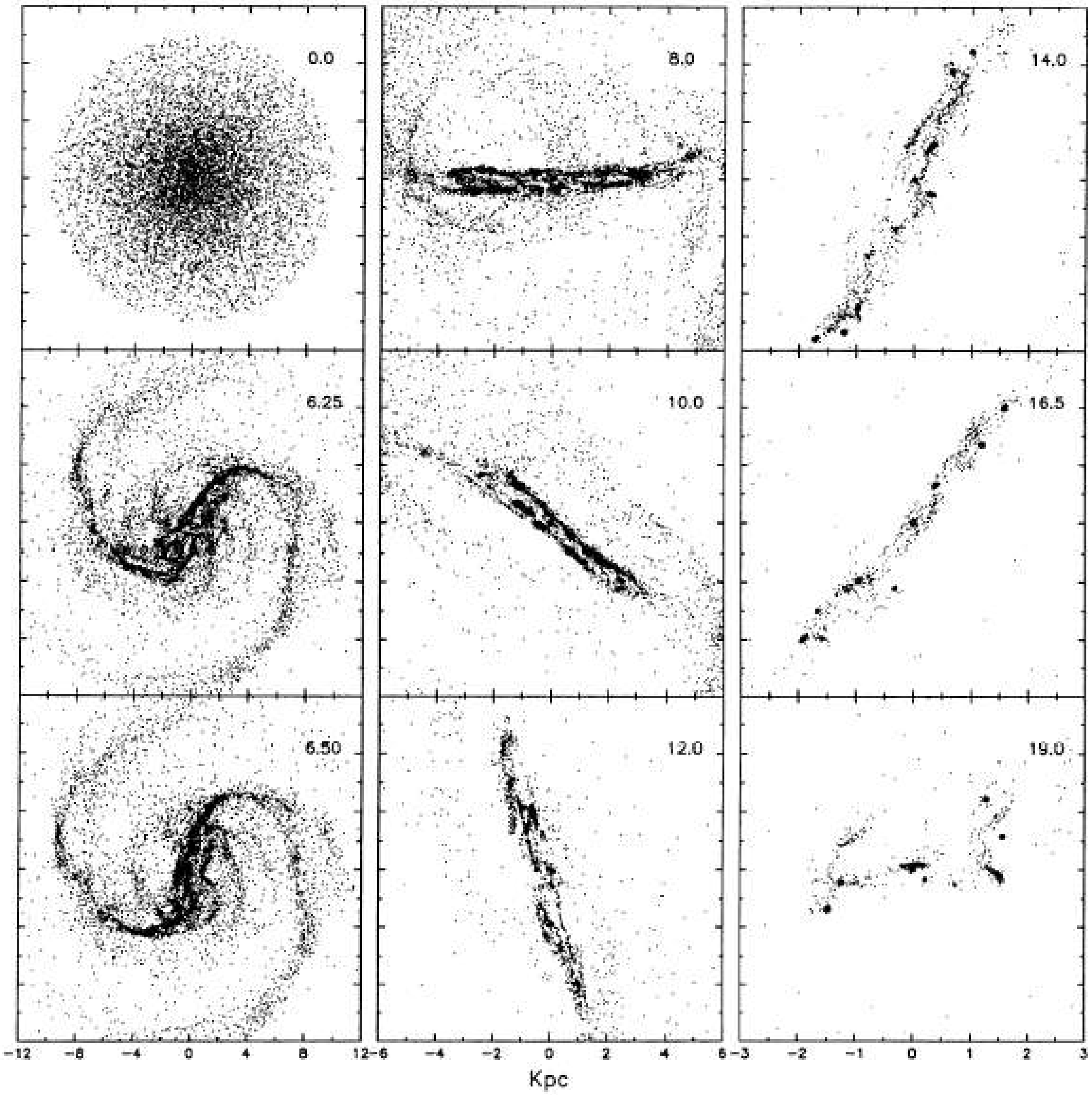
- When the local density of unstable gas exceeds ~100 M_{Sun}/pc^3, the SPH gas particle becomes an OB star.
  - Its stellar wind deposits a specified fraction (say 5%) of $3x10^{51}$ ergs to the surrounding ISM (manifest as an increase in local gas pressure) spread out evenly over its 10^6 yr main sequence lifetime.
  - Supernova! At the end of the MS lifetime, an equivalent amount of energy is released again, but this time over 10^4 yr. No remnant.
- This "IMF" has only very massive stars & may overestimate energy deposition. Compensate by keeping efficiency low.

Simple Model for Black Hole

- Single SPH particle starts with “seed” mass of $5 \times 10^7\ M_{Sun}$.
  - Accretes any *gas* particles within a radius of 20 pc.
  - Absorbed particle's momentum considered to be lost, and radiation from accretion process is not taken into account.

Fig. 3   1% gas   seed BH? Yes   star formation? No

evolution of gas

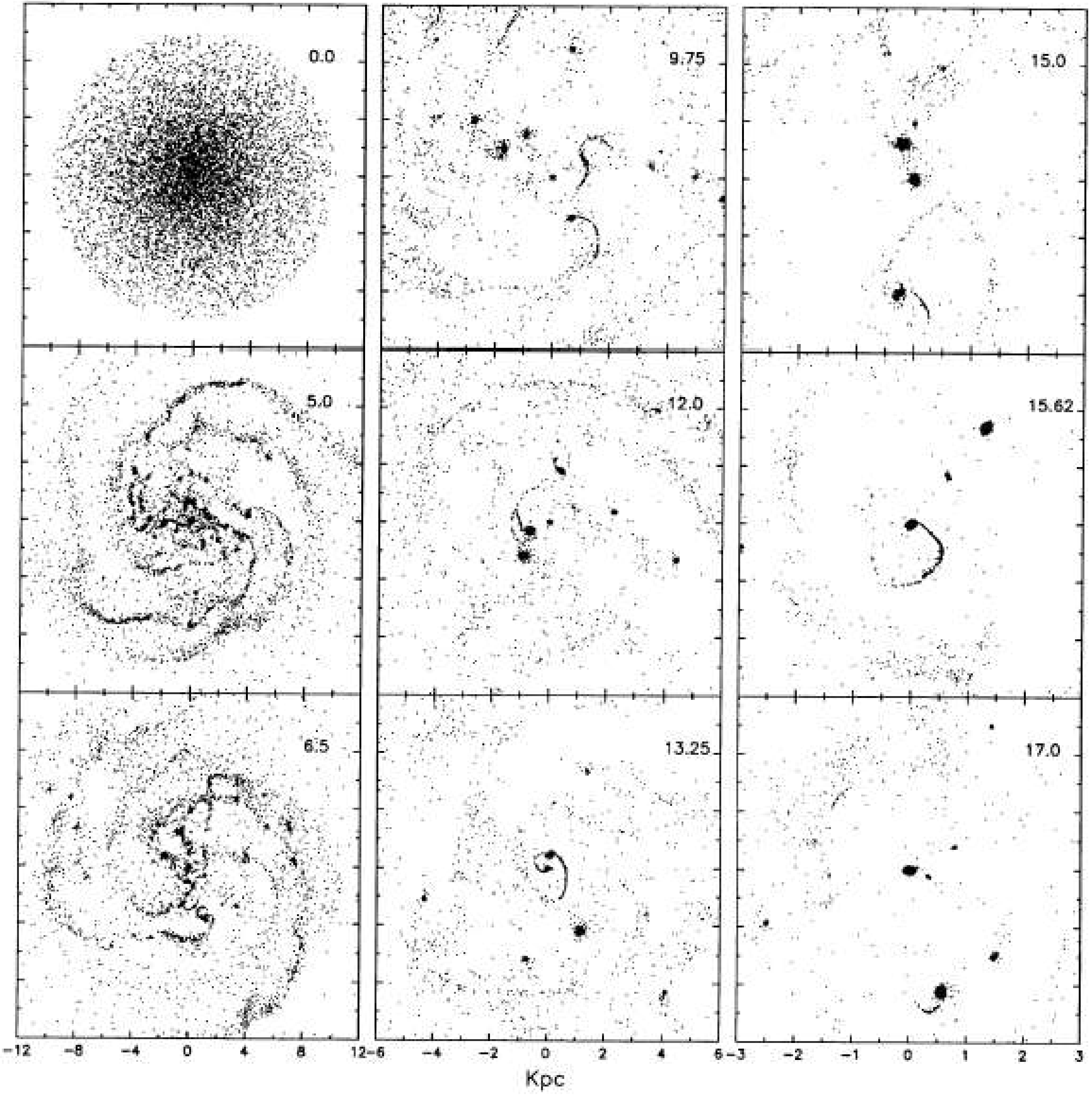


final BH mass = $6x10^8$ solar

1 time unit = $4.7x10^7$ yr

Fig. 4 10% gas seed BH? Yes star formation? No

evolution of gas

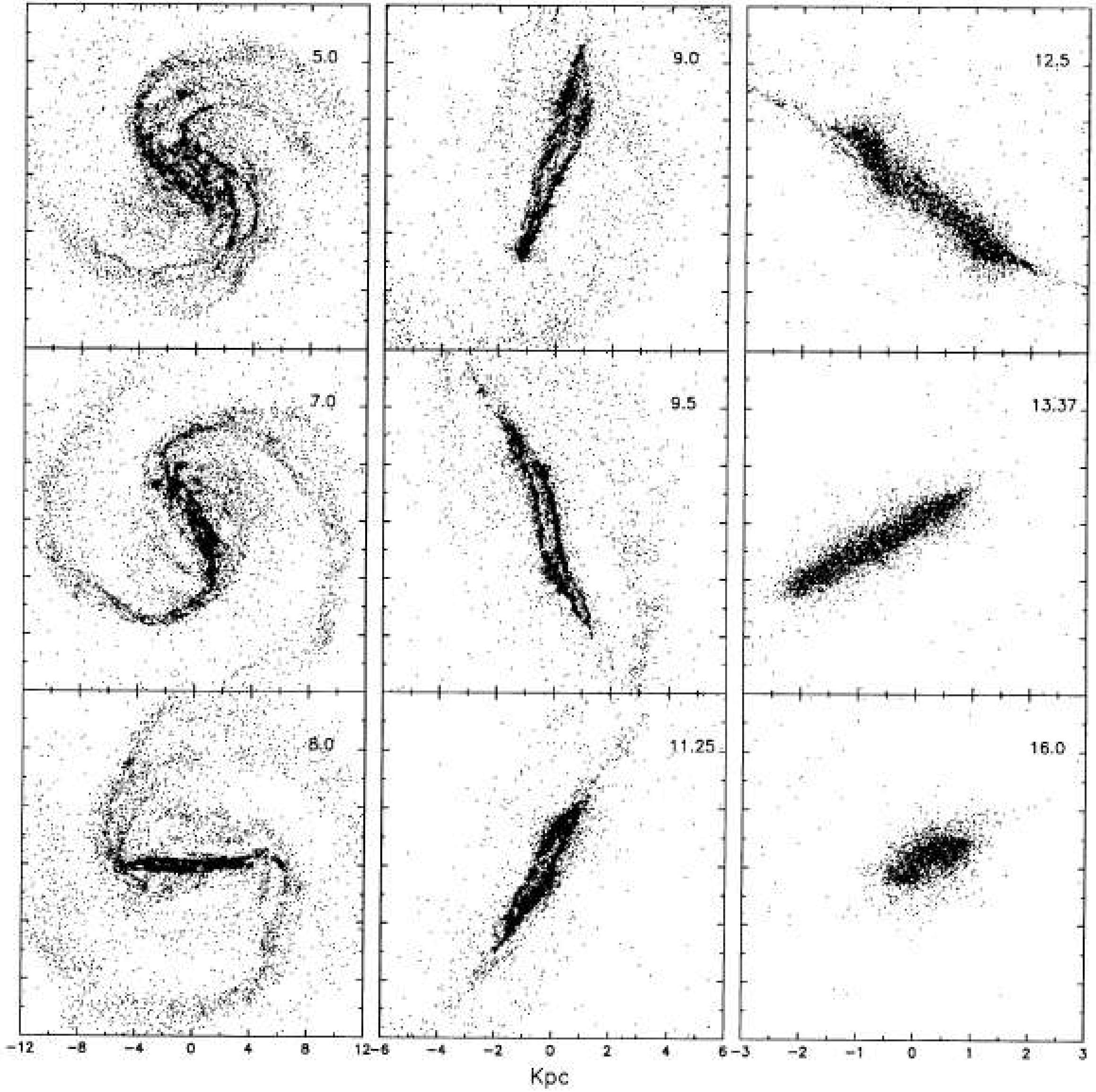


final BH mass = 2.5x10^9 solar

1 time unit = 4.7x10^7 yr

Fig. 5 1% gas seed BH? Yes star formation? Yes

evolution of gas



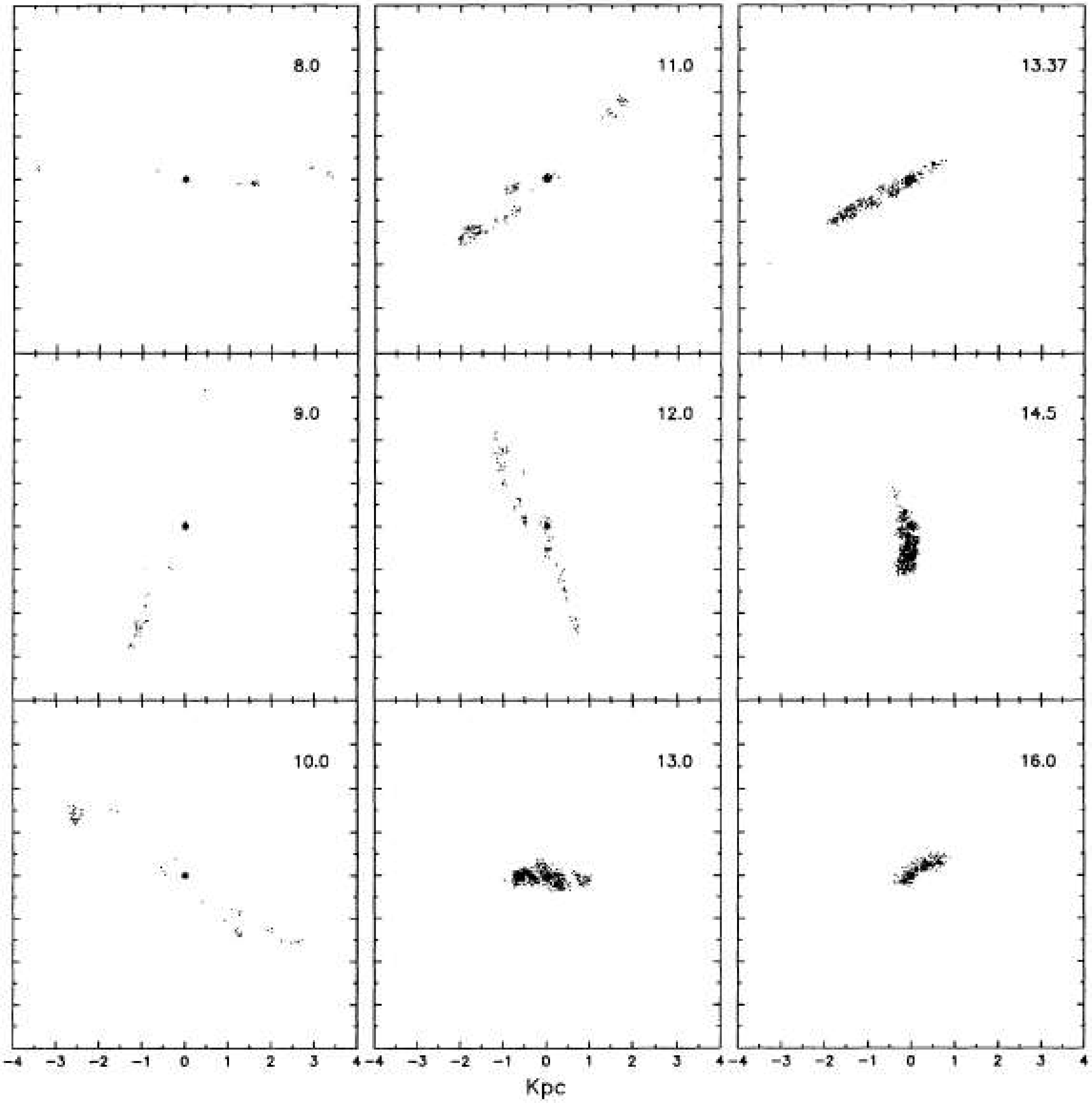
final BH mass = 6×10^8 solar

1 time unit = 4.7×10^7 yr

Fig. 6a 1% gas seed BH? Yes star formation? Yes

same scenario as in Fig. 5

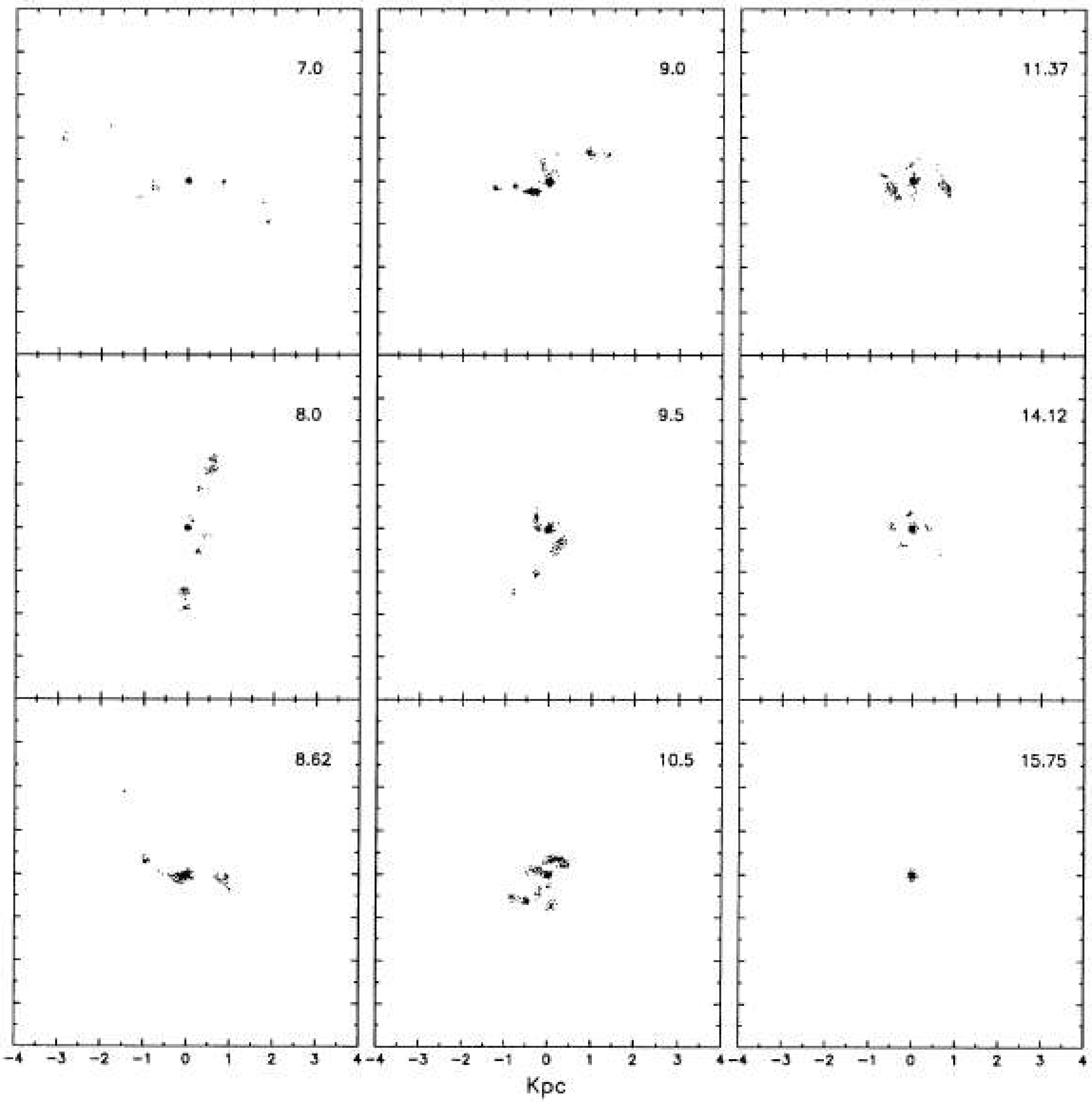
highlights new stars only



1 time unit = 4.7×10^7 yr

Fig. 6b 10% gas seed BH? Yes star formation? Yes

highlights
new stars
only



1 time unit = 4.7×10^7 yr

Fig. 7

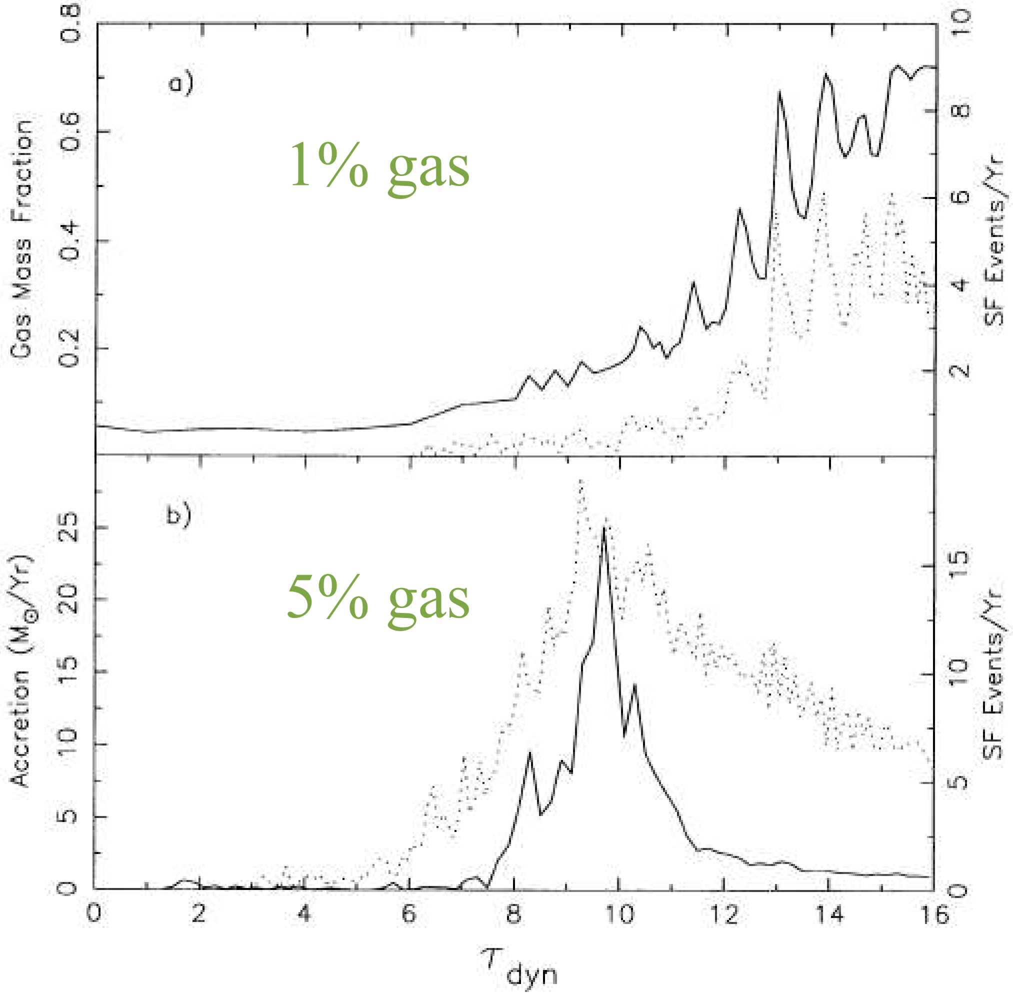
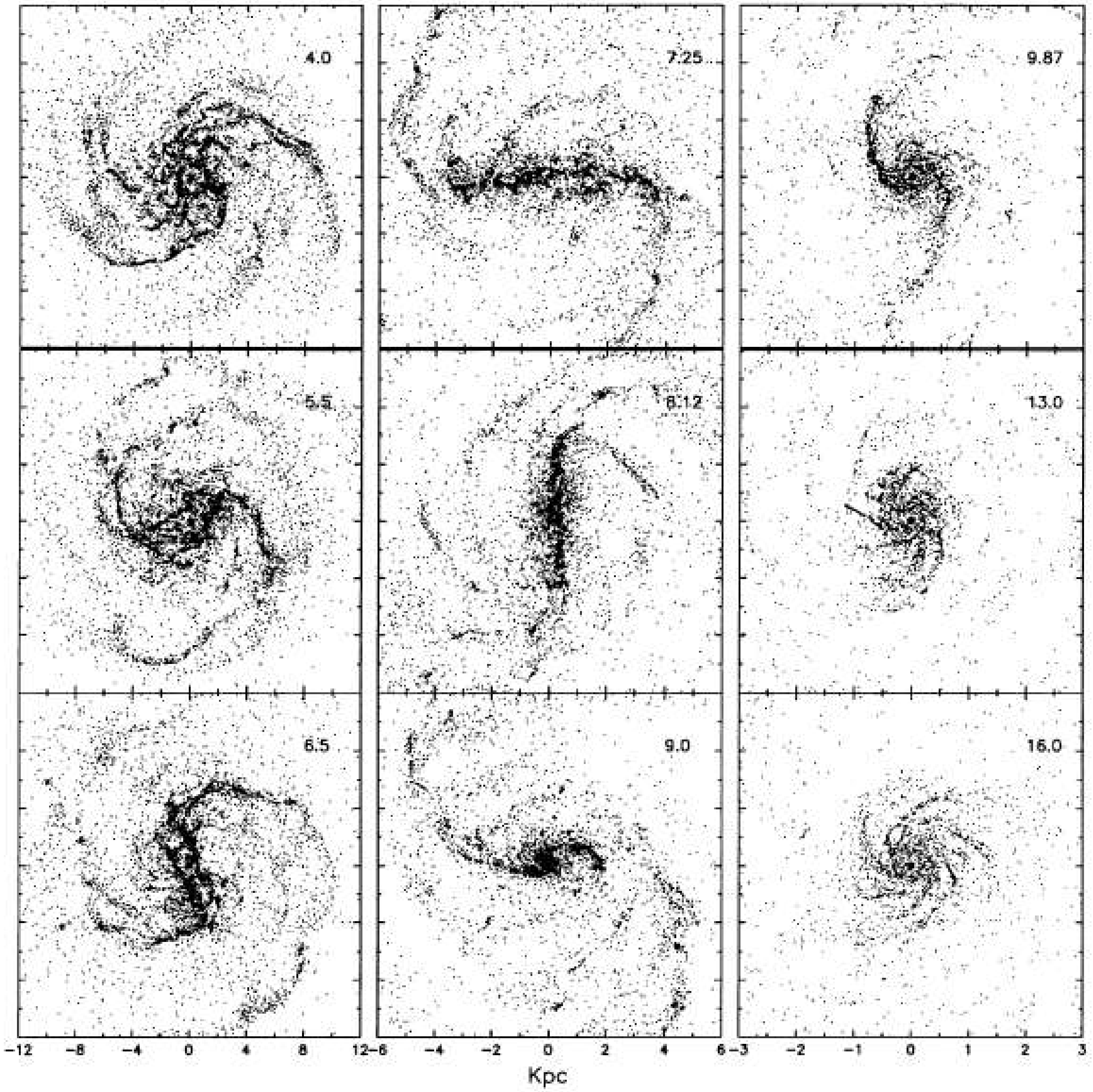


FIG. 7.—(*a*) Correlation between star formation rate (*dotted line*) and the fraction of the gas (*solid line*) in the inner 1 kpc for model B1. The right vertical axis gives the rate of massive star formation per year. The shape of the inflow rate curve (omitted) closely follows the solid line. (*b*) Correlation between star formation rate (*dotted line*) and accretion rate onto the BH (*solid line*) for the model B5.

1 time unit = 4.7×10^7 yr

Fig. 8 10% gas seed BH? Yes star formation? Yes

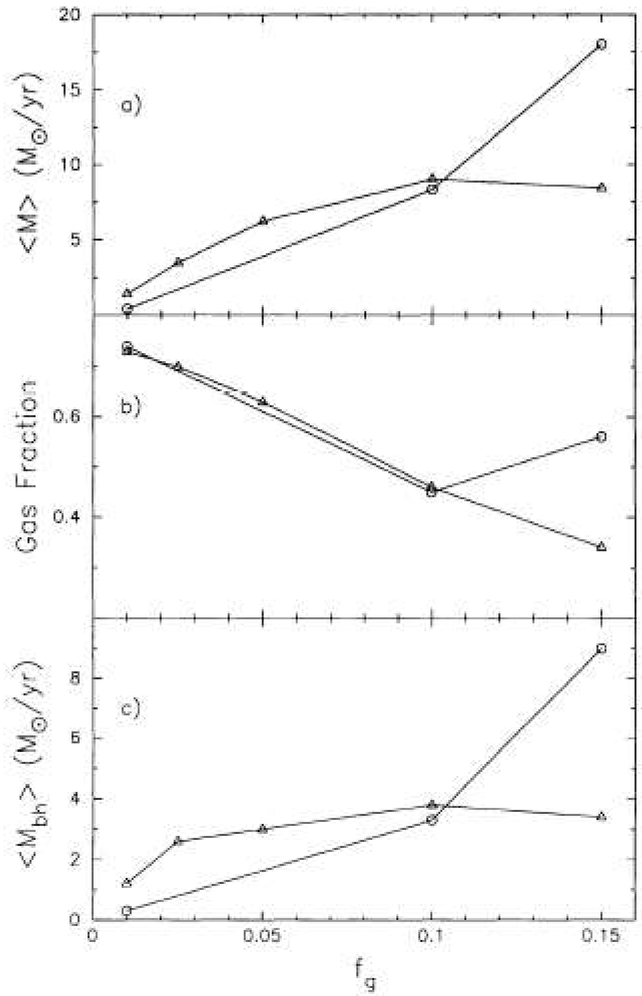
evolution of gas



final BH mass = 2.5×10^9 solar

1 time unit = 4.7×10^7 yr

Fig. 9



inflow rates at $r = 1$ kpc

fraction of total gas within inner 1 kpc at the end of the simulation

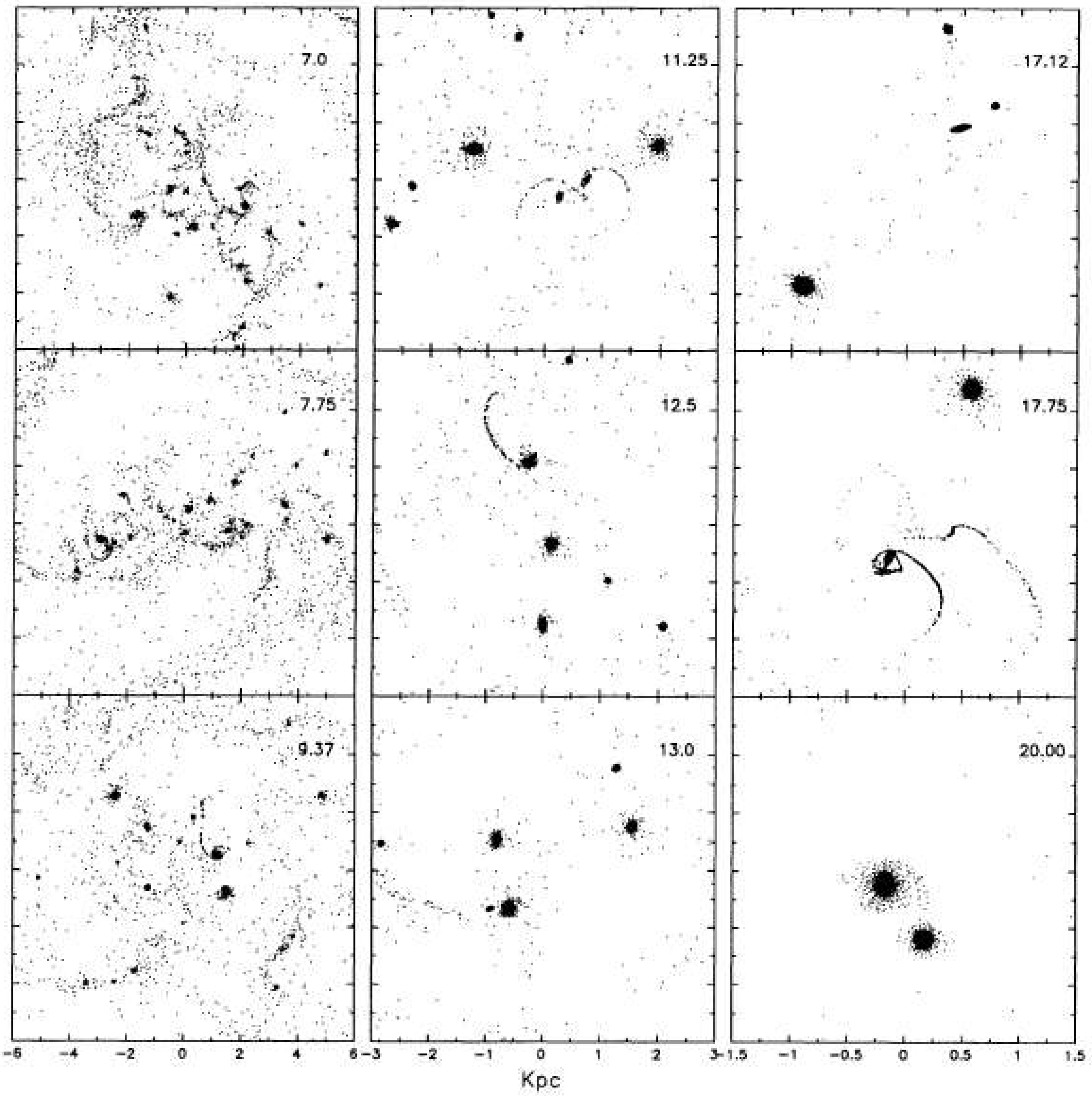
median BH accretion rate

circles: no star formation
triangles: star formation

FIG. 9.—(*a*) Median inflow rates measured at $r = 1$ kpc for A (*circles*) and B (*triangles*) series as a function of gas fraction f_g. (*b*) Fraction of the total gas residing within the inner 1 kpc at the end of the simulation of A (*circles*) and B (*triangles*) series as a function of f_g. Mass of the BH is *included* in the gas mass. (*c*) Median accretion rates onto the BH for A (*circles*) and B (*triangles*) series as a function of f_g.

Fig. 10 10% gas seed BH? No star formation? No

evolution of gas

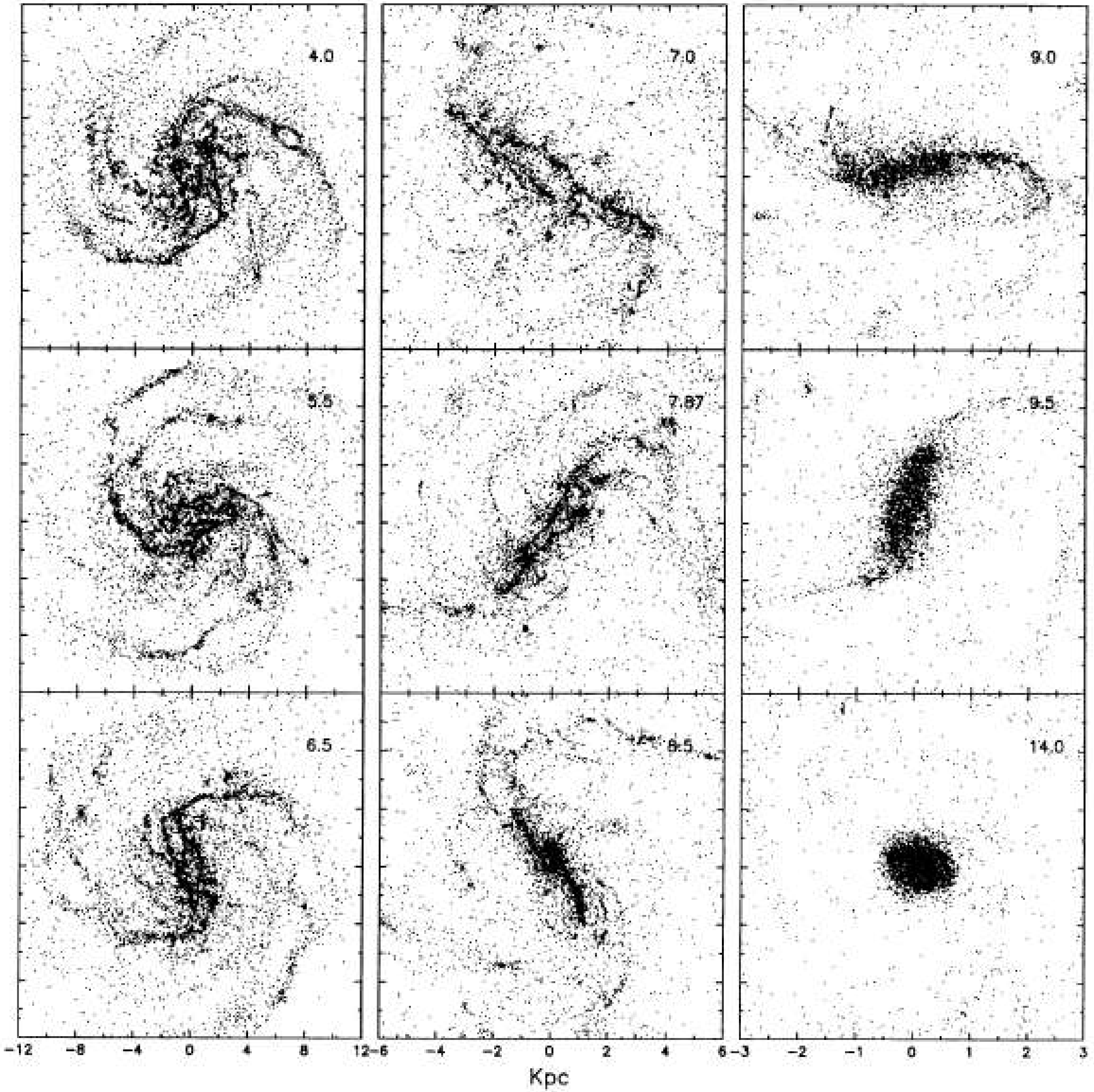


final central cloud mass = 4×10^9 solar

1 time unit = 4.7×10^7 yr

Fig. 11 10% gas seed BH? No star formation? Yes

evolution of gas



1 time unit = 4.7×10^7 yr

Overall Trends

- Models *without* star formation
  - Whether or not you start with a seed BH, the inner 1 kpc becomes dominated by a few large clouds which eventually merge into a single massive object.
  - The accretion onto the central BH is sporadic in nature.
  - The capture and processing of clouds by the central BH results in remnant disks of radius 60-80 kpc (?).

Trends, cont'd

- Models *with* star formation
  - More mixing of gases within the stellar bar.
  - "Star formation which is concentrated at the apocenters of the gaseous circulation in the stellar bar and in the nuclear region."
  - Very luminous (~10^{45}-10^{46} erg/s) central starburst phase which lasts 10^7 yr
  - "The starburst phase coincides with both the gas becoming dynamically important and the catastrophic growth of the BH."

Thanks for Listening