Cooling, dynamics and fragmentation of massive gas clouds: clues to the masses and radii of galaxies and clusters

M. Rees, J. Ostriker 1977

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Talk contents:

- The global picture
- The relevant theory
- Implications of the theory
- Conclusions

The global picture

- Galaxies and clusters have characteristic masses and scales
- This can't be from gravity alone; several physical processes can play a role
- These physical processes have varying degrees of effectiveness depending on the parameters
- We will explore the effects some of these processes may have

The relevant theory

- The article focuses on the epoch where the primordial density fluctuations enter the nonlinear regime, i.e. when $\delta\rho/\rho \gg 1$
- Two expansion processes are going on: Hubble expansion and internal cloud expansion
- The "turn-around" redshift z_{turn} is that redshift when Hubble expansion equals the internal cloud expansion, and expansion "stops"
- After this time the cloud can collapse

The first (non-dissipative) model

- Uniform, pressure-free, spherical density enhancement in a Friedmann universe
  $r = (270/h^{2/3}) M_{12}^{1/3} (t_{turn}/t_0)^{2/3}$ kpc
  $\rho = M/\frac{4}{3}\pi r^3$
- Can then show that $\rho \propto (1 + z_{turn})^2$, this implies that low-density bound systems can't have formed too early
  $\sigma \simeq 127 M_{12}^{1/3} (t_{turn}/h t_0)^{-1/3}$
- σ is the velocity dispersion, for clusters this implies that the outer parts of clusters are still in their early evolutionary stages
- This also keeps the possibility open that we may see galaxies that have recently formed

Flaws of this model

- Real density perturbations have a smooth profile
- Perfectly spherical perturbations don't happen
- Dynamical processes during virialization can modify the density distribution

Including dissipational effects

- Intuitively one will expect that gas dynamical and radiative processes will change the evolutionary process of collapsing gas clouds
  $p \propto \rho T$ (from the ideal gas law)
  $M_J \simeq 10^8 T_4^{3/2} n^{-1/2} M_\odot$
- Gas pressure is important on scales $\leq M_J$
  $T_{virial} \simeq (GMm_p/k_B r)$
- T_{virial} is the "temperature" of a bound particle, gas pressure is negligible if T $< T_{virial}$

Timescales

- Comparison of gravitational collapse timescale and cooling timescale is the key part of the analysis
  $t_{cool} \simeq (3kT/\Lambda(T))n^{-1}$
  $t_{grav} \simeq 2 \times 10^7 n^{-1/2}$ yr
- Contraction happens when energy is radiated away, increasing T and ρ
- The volume cooling rate $\Lambda(T)$ has been computed numerically, includes bremsstrahlung and H, He recombination. It has a sharp cutoff below 10^4 K where H becomes predominantly neutral

First evolution

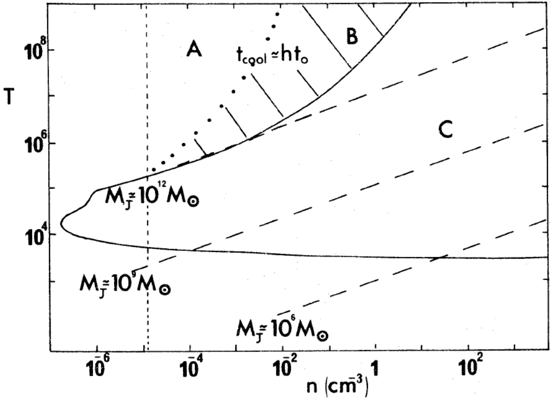

Figure: Region A: $t_{cool} \geq t_0$; region B: $t_0 \geq t_{cool} \geq t_{grav}$; region C: $t_{grav} \geq t_{cool}$; solid line: $t_{grav} = t_{cool}$; dashed line: 5.5 times ρ_c, never collapses

More of the same, but different

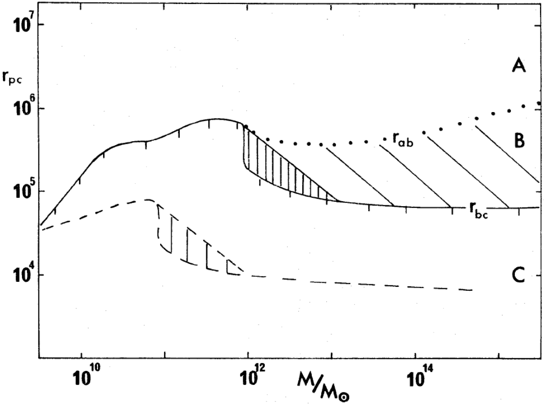

Figure: $r_{pc} = (3M/4\pi\rho)^{1/3}$; dashed line: when a fraction $x = 0.9$ of the gas has been converted into stars; vertical solid line: shift in r_{bc} when T_{virial} is such that the cloud can radiate *more* energy at a *lower* temperature due to $\Lambda(T)$ form

Almost done? Let's change everything!

- We have cooling contributions from bremsstrahlung and H, He recombination
- At higher redshifts one should consider Compton scattering $t_{Comp} \simeq 3 \times 10^{12}(1+z)^{-4}$ yr
- With this, *all* clouds can cool in a Hubble time! Region A entirely disappears.
- Past figures have shown that mass-dependent physical processes can influence the evolution of collapsing gas clouds
- The most interesting parts: *scales* of galaxies and clusters of galaxies emerge naturally!
- But is our analysis accurate?

The formation picture

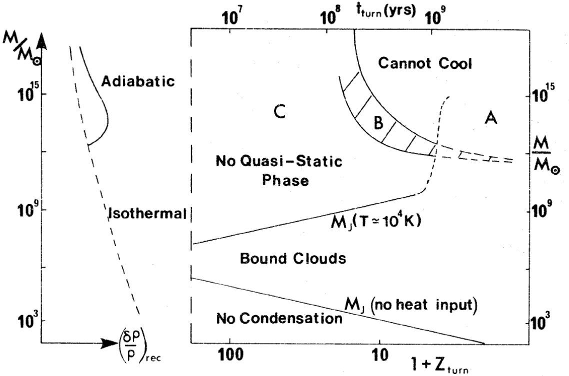

Figure: Solid lines: Jeans masses M_J depending on initial fluctuations; dashed line: change in M_J from reheating the gas

Primordial fluctuations indepth

- The evolution of M_J depends on $\delta\rho/\rho$
- Isentropic, isothermal or entropy fluctuations are the only possibilities for $\delta\rho/\rho$
- Rees & Ostriker show that *stellar* systems with a mass M must have radii $r \leq \min[\mathrm{r_{turn}(M)/2, r_{bc}(M)/2}]$
- These are approximately equal if star formation is efficient $r_{turn} \leq 2r_{ab}$
- This has to hold or else the gas cloud will come into pressure equilibrium in region A and would not be able to cool

Other effects on evolution

- Supernova ejecta, galactic winds and other heat input mechanisms can inhibit further gas condensation
- These have the effect of applying external pressure on the gas cloud, which can cause gravitational collapse despite $M < M_J$

Star formation effects on evolution

- After a fraction x of the gas is converted into stars, the evolution is changed in the following ways:
- The cooling rate drops by $(1-x)^2$, the heat input by $(1-x)$, so the gas is pressure-supported down to a lower critical radius
- Contamination of the gas with heavier elements would enhance the cooling rate
- The gas will become more inhomogeneous, this enhances the cooling rate as well
- Supernova ejecta can heat the gas above T_{virial}, ejecting gas from the galaxy. There are many unknowns with this though.

Radiation trapping and pressure

- Cloud collapse and fragmentation histories may be affected by radiation trapping and pressure
- Two opacities are important: Thomson scattering by free electrons and scattering of trapped Lyman α
- $\tau_{es} \leq 1$ and therefore negligible. $\tau_{Ly\alpha}$ however becomes enormous near $T \sim 10^4$ K
- Radiation pressure modifies the Jeans mass, Lyman α can never stop collapse entirely but it can inhibit fragmentation
- However, the trapping efficiency factor is mostly unknown

Results of the theory

- For masses $10^{12} M_{\odot}$ we have an upper limit on t_{turn}
- Final radii ($\sim r_{bc}$) are comparable with those observed
- Collapse is not purely gravitational, radiative cooling enhances the gravitational binding energy by $\beta = r_{turn}/r_{bc}$
- A cloud of mass $10^{14} M_{\odot}$ which turned around at $z \leq 3$ could have remained unchanged for 10^{10} yr and would be detectable as thermal X-ray sources only. This could explain Coma Cluster observations

Radiative effects

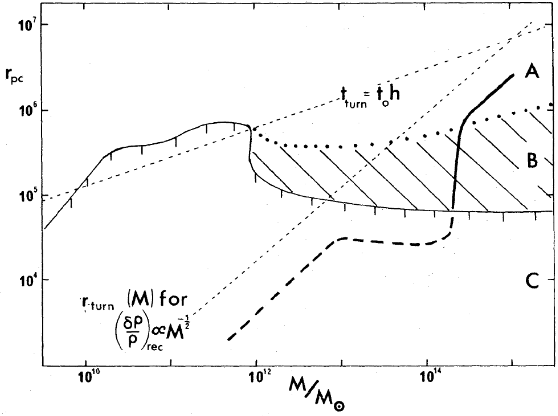

Figure: Thick line: the final mass-radius relation, dashed portion indicates fragmentation; the "glitch" is due to dissipation increasing the gravitational binding energy

Questions?