Galaxies & Cosmology (HEAC II)
5 points, ht-2006
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Lecture 8

Contents:
- Active Galactic Nuclei
- Galaxy formation theory
Active galaxies / Active galactic nuclei (AGN)

Central engine
variability put limit on size: \( R \leq c \tau_{\text{var}} \)
Schwarzschild radius: \( R_s = \frac{2 \, G \, M}{c^2} \)
\( R_s = \) size approx Uranus orbit for \( 10^9 M_\odot \)
Accretion allows conversion of \( 0.1mc^2 \)
(fusion only 0.7%)
Radiation pressure will larger than gravity if \( L > L_{\text{EDD}} \)

Accretion disk very hot continuum source => X-rays
Broad line region, dense ionised clouds, rapid moving
Narrow line region, dilute ionised clouds, slower
reverbration mapping
Obscuring torus with dust and molecular gas,
sublimation evacuate central part => torus
Relativistic (superluminal) Jets, and radio Lobes
Unified AGN models

Idea: all AGN are basically the same phenomena
Differing due to different viewing angle and scale:

Face on view: see all components: Sy1, QSO
if looking into jet: Bl Lac (Blazar)

Edge on view: see only hot torus and NLR, Sy2

Why some radio loud while others not?

Unified BH model not perfect, but nothing else works
Unified Model

(a) radio-quiet AGNs
- obscurng torus
- broad-line region
- narrow-line region
- engine
- rotation axis
- observer sees type 2 Seyfert (type 2 quasar?)
- observer sees type 1 Seyfert or quasar (QSO)

(b) radio-loud AGNs
- jet
- observer sees a quasar
- observer sees a blazar
- dusty torus
- observer sees narrow-line radio galaxy
- observer sees broad-line radio galaxy
- radio jet
- broad line clouds
- Sy 1
- narrow line clouds
Spiral seyfert2 with radio jets

Seyfert1
QSO evolution - where are they now?

Debate if fall off at $z>3$ is real

There must be many dead QSOs around in the local universe!
Kinematical evidence for BH in M87

+ Grav redshifted X-ray em-lines detected in Sy1’s
Relation between black hole mass and sigma of host galaxy: a relation between BH and Spheroid Mass
-- Black Hole doesn’t care about disk
-- Co-evolves with spheroid/bulge!
Intergalactic matter
QSO used as lamps
3C 273 $z=0.158$

Q1422+2309 $z=3.62$
Figure 5: Zn abundances in DLAs, from the compilation by Kulkarni et al. 2005 (black), which brings together the results of several surveys for DLAs in optically selected QSO samples, and from the recent survey of CORALS (radio-selected) QSOs by Akerman et al. 2005 (blue). Triangles denote upper limits in DLAs whose Zn II λλ2026, 2062 lines remain undetected.
Metallicity vs "scale"

Figure 11: Snapshot of the metallicity of different components of the high redshift universe. The logarithm of the metallicity is plotted relative to solar (indicated by the long-dash line at 0.0) against the typical linear scale of the structures to which it refers. The term "Lyman break galaxies" (LBGs) is used as a shorthand here to refer to a more general class of actively star-forming galaxies.
Evolution of the neutral hydrogen density

![Graph showing the evolution of neutral hydrogen density](image)

**Figure 2.** Mass density of neutral gas in DLAs from SDSS (points shown as a function of redshift) and radio-selected surveys (cross). Figure adapted from Jørgensen et al. (2006).
Gunn-Peterson effect
Galaxy Formation Theory

Fluid dynamics in a gravitational field
(see e.g. Longair: Galaxy formation, Springer)

The equation of continuity: \[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0
\]

Euler's equation: \[
\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\frac{1}{\rho} \nabla p - \nabla \Phi
\]

Poisson's equation: \[
\nabla^2 \Phi = 4\pi G \rho
\]
From Eulerian (fixed point in space) to Lagrangian (follow the particle) coordinates

\[
\frac{d}{dt} \frac{\partial}{\partial t} = (\mathbf{v} \cdot \nabla)
\]

\[
\dot{\rho} = -\rho \nabla \cdot \mathbf{v}
\]

\[
\dot{\mathbf{v}} = -\frac{1}{\rho} \nabla p - \nabla \Phi
\]

\[
\nabla^2 \Phi = 4\pi G \rho
\]
Introduce a small perturbation

\[ \mathbf{v} = \mathbf{v}_0 + \delta \mathbf{v} \]

\[ \rho = \rho_0 + \delta \rho \]

\[ p = p_0 + \delta p \]

\[ \Phi = \Phi_0 + \delta \Phi \]
Expand to first order:

\[
\frac{d}{dt} \left( \frac{\delta \rho}{\rho_0} \right) = \dot{\Delta} = -\nabla \cdot \delta \mathbf{v}
\]

\[
\frac{d(\delta \mathbf{v})}{dt} + (\delta \mathbf{v} \cdot \nabla) \mathbf{v}_0 = -\frac{1}{\rho} \nabla \delta \rho - \nabla \delta \Phi
\]

\[
\nabla^2 \delta \Phi = 4\pi G \delta \rho
\]

\[
\Delta = \frac{\delta \rho}{\rho_0}
\]

is the density contrast:
Expanding universe $\rightarrow$ use comoving coordinates

$x = a(t)r$. $a$ is the cosmic scalefactor and $r$ is the radial comoving coordinate. $v = \frac{\delta x}{\delta t}$ is the velocity.

Assume adiabatic fluctuations (supported by the positions of the 2d and 3d acoustic peak in the CMB power spectrum)

The adiabatic sound speed $c_s^2 = \frac{\partial p}{\partial \rho}$
After some algebraic exercise we obtain:

\[
\ddot{\Delta} + 2\frac{\dot{a}}{a} \dot{\Delta} = \frac{c_s^2}{\rho_0 a^2} \nabla_c^2 \delta \rho + 4\pi G \delta \rho
\]

We now seek wave solutions of the form

\[
\Delta \propto e^{ik_c \cdot x - \omega t}
\]

and derive the wave equation

\[
\ddot{\Delta} + 2\frac{\dot{a}}{a} \dot{\Delta} = \Delta(4\pi G \rho_0 - k^2 c_s^2)
\]

\(k_c\) is the comoving wavevector: \(k_c = a(t)k\)
Jeans instability in a static medium
\[ \Delta \propto e^{i k_c \cdot x - \omega t} \quad k_c = a \cdot k \quad \dot{a} = 0 \]

The dispersion relation:

\[ \omega^2 = c_s^2 k^2 - 4\pi G \rho_0 \]

If \( c_s^2 k^2 > 4\pi G \rho_0 \) the perturbation is oscillatory

The transition stable \( \leftrightarrow \) unstable happens at

The Jeans wavelength:

\[ \lambda_J = \frac{2\pi}{k_J} = c_s \left( \frac{\pi}{G \rho} \right)^{1/2} \]
\[ c_s^2 k^2 < 4\pi G \rho_0 \]

Growing mode:

\[ \Delta = \Delta_0 e^{(\Gamma t + ik \cdot r)} \]

where

\[ \Gamma = \left[ 4\pi G \rho_0 \left(1 - \frac{\lambda_j^2}{\lambda^2}\right) \right]^{1/2} \]
If

\[ \lambda \gg \lambda_j \]

\[ \Rightarrow \]

Growth at timescale

\[ \tau = \Gamma^{-1} = (4\pi G \rho_0)^{-1/2} \approx (G \rho_0)^{-1/2} \]
Jeans instability in an expanding medium
Einstein - de Sitter ($\Omega = 1, \Lambda=0$)

$$\ddot{\Delta} + 2\frac{\dot{a}}{a} \dot{\Delta} = \Delta(4\pi G \rho_0 - k^2 c_s^2)$$

"Dust": $p=0$, so $c_s = 0$

$$a \propto t^{2/3} \quad \frac{\dot{a}}{a} = \frac{2}{3t}$$

Ansatz: $\Delta \propto t^n$ Insert into eq. $\Rightarrow$ $n = 2/3$ and $-1$

$n=-1$ is a decaying mode, the other slowly growing

$$\Delta = \propto t^{2/3}$$
Open (empty) model ($\Omega = 0, \Lambda = 0$)

\[ a \propto t \]
\[ \Delta \propto t^n \quad \Rightarrow \quad n = 0 \text{ and } -1 \]
No growing mode

If $\Omega < 1$, and $\Omega \neq 0$, then $\Omega$ rapidly approaches unity for small scale factors, so $\Delta$ can grow until $z \approx 1/\Omega_0 - 1$
During the *radiation dominated* era, the matter is relativistic and thus

\[ p = \frac{1}{3} \rho c^2 \]

\[ c_s = c / \sqrt{3} \]

Then it can be shown (Coles and Luccin 1995) that

\[ \ddot{\Delta} + 2 \frac{\dot{a}}{a} \dot{\Delta} = \Delta \left( \frac{32\pi G \rho}{3} - k^2 c_s^2 \right) \]
\[ \lambda_j = 2\pi / k_j = c_s \left( \frac{3\pi}{8G\rho} \right)^{1/2} \]

If we neglect the pressure gradient we obtain

\[ \dddot{\Delta} + 2\frac{\dot{a}}{a} \ddot{\Delta} - \frac{32\pi G\rho}{3} \Delta = 0 \]

From the Fridman equations we obtain

\[ a \propto t^{1/2} \quad \frac{32\pi G\rho}{3} = 1/t^2 \]
Ansatz: $\Delta$ is a power law function of $t$.

$$\Delta \propto t \propto a^2 \propto (1+z)^{-2}$$

Correspondingly in the matter dominated epoch

$$\Delta \propto a \propto \frac{1}{(1+z)}$$
On what mass scales can the perturbations start to grow during the radiation dominated era?

\[ r_H = 2ct = c\left(\frac{3}{8\pi G\rho}\right)^{1/2} \]

\[ \lambda_J = c\left(\frac{3\pi}{24G\rho}\right)^{1/2} \]

Jeans length only slightly smaller than the size of the horizon
No growth of baryonic component during the radiation dominated era
\[ c_s^2 = \frac{c^2}{3} \frac{4 \rho_{rad}}{4 \rho_{rad} + 3 \rho_m} \]

The Jeans mass will stop growing at the transition between radiation dominated and matter dominated era and remain constant until recombination:

\[ M_J = \frac{3.75 \cdot 10^{15}}{(\Omega_B h^2)^2} M_\odot \]
After recombination the sound velocity drops drastically:

\[ c_s = \left( \frac{5kT}{3m_H} \right)^{1/2} \]

Jean's mass = globular cluster size
Baryon inhomogeneities of galaxy size cannot start growing until after recombination. But fluctuations at this level and less have been wiped out before recombination due to photon diffusion from the density peaks, so called Silk damping. The minimum mass of ’survival’ is the Silk mass:

\[ M_{Silk} = 2 \times 10^{26} (\Omega_B h^2)^{-1/2} (1 + z)^{-9/2} M_\odot \]

If structures form from pure baryon inhomogeneities, those with masses below \(10^{12} M_\odot\) have to form from fragmentation of larger units.
The Evolution of the Jeans Mass
Problems with galaxy formation in a baryon dominated universe

- CMB fluctuations too small – many protogalactic clouds will disperse as the universe expands
- The timescale for galaxy formation is too long – galaxies will form late
- Dark matter can do the trick – baryons rapidly assemble in their potential wells

But what kind of dark matter – hot or cold?
Damping of Fluctuations

The primordial (H-Z) spectrum

Sound waves diminish the strength of small scale fluctuations for the CDM case

Relativistic streaming and photon diffusion erase them completely for the HDM case
Damping of Fluctuations

The primordial (H-Z) spectrum

- Sound waves diminish the strength of small scale fluctuates for the CDM case.
- Relativistic streaming and photon diffusion erase them completely for the HDM case.

![Graph showing damping of fluctuations with a log-log scale for P(k) vs. k (Mpc^-1)]
Hot DM will not allow galaxy sized structure to form at high $z$
- vote for CDM!
DM can start to grow when the universe becomes matter dominated. The baryons have to wait until recombination. Then baryons start to fall into the DM potential wells. In a CDM dominated universe the density contrast will increase according to:

$$\Delta = \frac{\delta \rho_B}{\rho_B} \approx \frac{\delta \rho_{CDM}}{\rho_{CDM}} \left(1 - \frac{z}{z_0}\right) \propto M^{-\frac{1}{3}} \left(1 - \frac{z}{z_0}\right)$$

$z_0$ is the redshift when the baryons start to grow and $M$ is the mass of the structure.
The Evolution of Fluctuations

Coles and Lucchin 1990
The Power Spectra

- Primordial H-Z spectrum
- CDM
- Galaxy clustering
- Baryons
- CMB normalization

Graph showing the power spectrum with logarithmic scales.
Post recombination - basic ideas
The nonlinear spherical model

A spherical overdense 'blob' behaves like a closed 'mini-universe'

$$r_p = A(1 - \cos \Theta)$$

$$t = B(\Theta - \sin \Theta)$$

$$A = \frac{\Omega}{2(\Omega - 1)}$$

$$B = \frac{\Omega}{2H(\Omega - 1)^{3/2}}$$

It is convenient to use a parametric description of the evolution. $r_p$ is the proper radius of the blob. We will assume $\Omega_0 = 1$. 
We obtain

\[ t_{\text{max}} = \pi B = \pi \Omega / \left[ 2H(\Omega - 1)^{3/2} \right] \]

\[ r_{\text{max}} = 2A = \Omega / (\Omega - 1) \]

\[ a = \left( \frac{3H_0t}{2} \right)^{2/3} \text{ from the Friedmann equation} \]

\[ \frac{\rho_{\text{max}}}{\rho_0} = \left( \frac{r}{r_{\text{max}}} \right)^3 \approx \frac{9\pi^2}{16} = 5.55 \]
Final collapse:

Assume that the protocloud fragments during the collapse and then virializes:

Virial theorem:  \( V + 2K = 0 \)

\( V \) is the potential energy and \( K \) is the kinetic energy. The virial theorem will be fulfilled when the region has collapsed to *half its maximum radius of expansion*.

This happens at

\[
t = (1.5 + 1/\pi) t_{\text{max}} = 1.81 \ t_{\text{max}}
\]
\[
\rho_0 = \rho_{0,\text{max}} (t/t_{\text{max}}) = \rho_{0,\text{max}}/3.3
\]

The density enhancement is thus

\[
5.55 \times 8 \times 3.3 = 150 \text{ times the background density.}
\]
\[
\frac{1 + z_{\text{collapse}}}{1 + z_{\text{turnover}}} = 2^{-\frac{2}{3}} \approx 0.63
\]

\[
\rho_{\text{virial}} \geq 100 \cdot \frac{3H_0^2}{8\pi G}(1 + z_{\text{formation}})^3
\]

\[
\rho_{\text{virial}} \approx \frac{\sigma_v^6}{\frac{4\pi}{3} G^3 M^2}
\]

$z_{\text{formation}} \leq 10$ for galaxies with $\sigma_v \sim 300$ km/s

$z_{\text{formation}} \leq 1$ for large clusters
The role of dissipation

Cooling processes during the early stages:

- $z > 10$ Compton
- $z < 10$ H-He free-free, free-bound

The cooling time:

$$t_{cool} = \frac{3}{2} nkT/(n^2 \Lambda(T))$$

The dynamical collapse time

$$t_{dyn} \approx \left(\frac{3}{2\pi G \rho}\right)^{\frac{1}{2}}$$

The cooling rate
The 'cooling diagram' (Blumenthal et al 1984, Nature 311, 517) The bottom line is: Galaxies (stars) can form if $t_{\text{cool}} < t_{\text{Hubble}}$. 

![Diagram showing the cooling diagram with various lines and labels indicating cooling timescale ($t_{\text{cool}}$) and dynamical timescale ($t_{\text{dyn}}$).]
Basic scenarios

A. Monolithic collapse. Case 1.

\[ t_{\text{cool}} < t_{\text{dyn}} \]

Fragmentation and collapse to ellipsoidal system

Cooling, dissipation, contraction, fragmentation, star formation, virialisation
Basic scenarios

A. Monolithic collapse. Case 2.

- $t_{\text{cool}} > t_{\text{dyn}}$  
  Disk formation

The halo and (at least part of) the bulge may form stars during collapse. The gaseous disk forms during quasi-static contraction and dissipation.
Basic scenarios

B. Hierarchical buildup

Mergers

- Smaller galaxies merge into larger
- Wet mergers - star formation rate increases when gas mass increases
- Dry mergers – mass and luminosity increases but not metallicity.
- Ellipticals with similar luminosities but with different metallicity distributions, SF histories, stellar kinematics may coexist.

Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the width of the branches of the tree represent the mass of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the merging population of that mass. The formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.
Additional important processes

Feedback and quenching

• Shock heating from infalling gas, heating and outflows from SF regions and AGNs stops the star formation

• Ram pressure removes the gas as the galaxy falls into a cluster or into the gaseous halo of a larger galaxy
Measuring Clustering

- Count in cells
- 2-point correlation function

\[ dP = \rho_0^2 \left[ 1 + \xi(r) \right] dV_1 dV_2 \]

\[ \xi = (r/r_0)^{-\gamma} \]
Cosmic shear

- Effect on each individual galaxy tiny only visible through large and deep samples