Introduction to Astronomy and Astrophysics I
Lecture 11

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Ionization in the ISM

- Ionization can occur through various processes:
  - Photoionization by UV radiation from stars
  - Cosmic ray ionization
  - Collisional ionization in hot gas
- The balance between ionization and recombination determines the ionization state of the gas
- This balance is described by the Saha equation

The Saha Equation works in Local Thermodynamic Equilibrium

The Saha equation describes the ionization equilibrium for a gas:

$$\frac{n_{i+1} n_e}{n_i} = \frac{2g_{i+1}}{g_i} \left(\frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-\chi_i/kT}$$

Where:

- n_i, n_{i+1}: number densities of atoms in ith and $(i+1)$th ionization states
- n_e: electron number density
- g_i, g_{i+1}: statistical weights of the ith and $(i+1)$th states
- m_e: electron mass
- k: Boltzmann constant
- T: temperature
- h: Planck constant
- χ_i: ionization energy from ith to $(i+1)$th state

Implications of the Saha Equation

- Ionization increases with temperature
- Ionization decreases with increasing electron density
- Different elements ionize at different temperatures due to varying ionization energies
- The equation assumes Local Thermodynamic Equilibrium (LTE), which may not always hold in the ISM

Equilibrium Conditions in the ISM

The ISM is often in various states of equilibrium:

- **Thermal Equilibrium**: Balance between heating and cooling processes

$$\Gamma_{\text{heating}} = \Lambda_{\text{cooling}}$$

- **Pressure Equilibrium**: Balance of thermal pressure with other pressure sources

$$P_{\text{thermal}} + P_{\text{magnetic}} + P_{\text{cosmic ray}} + P_{\text{turbulence}} \approx \text{constant}$$

- **Ionization Equilibrium**: Balance between ionization and recombination rates

$$R_{\text{ionization}} = R_{\text{recombination}}$$

Thermal Equilibrium in the ISM

Key heating and cooling processes in the ISM:

Heating:

- Photoelectric heating from dust
- Cosmic ray heating
- X-ray heating
- Shock heating

Cooling:

- Line emission (e.g., CII, OI)
- Continuum emission from dust
- Bremsstrahlung radiation
- Adiabatic expansion

The balance between these processes determines the temperature structure of the ISM.

Non-Equilibrium Conditions

While equilibrium conditions are useful for understanding the ISM, it's important to note:

- Many regions of the ISM are not in equilibrium
- Dynamical processes (e.g., turbulence, shocks) can drive the ISM out of equilibrium
- Non-equilibrium conditions are often associated with:
  - Star formation regions
  - Supernova remnants
  - Galactic outflows

No class next Tuesday, makeup on Wednesday

I am out of town on 17 Sep, so no class on that day. Will do a makeup class on Wed 18 Sep at 10 am.

Initial Mass Function IMF

The IMF $\xi(M)$ specifies the distribution in mass of a newly formed stellar population and it is frequently assumed to be a simple power law: $\xi(M) = c\,M^{-(1+x)}$. In general, $\xi(M)$ is assumed to extend from a lower (M_1) to an upper cutoff (M_2).

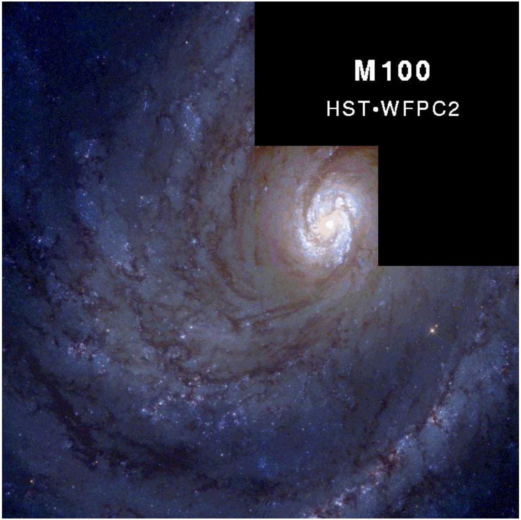
Initial Mass Function

IMF	M_1	M_2	x
Salpeter	0.10	125.	1.35
Scalo	0.10	0.18	-2.60
	0.18	0.42	0.01
	0.42	0.62	1.75
	0.62	1.18	1.08
	1.18	3.50	2.50
	3.50	125.	1.63
Miller & Scalo	0.10	1.00	0.25
	1.00	2.00	1.00
	2.00	10.0	1.30
	10.0	125.	2.30

Homework Question

For a Salpeter IMF, what is the relative number of K and A stars in a cluster that has just formed?

M100 nucleus



Barred galaxies

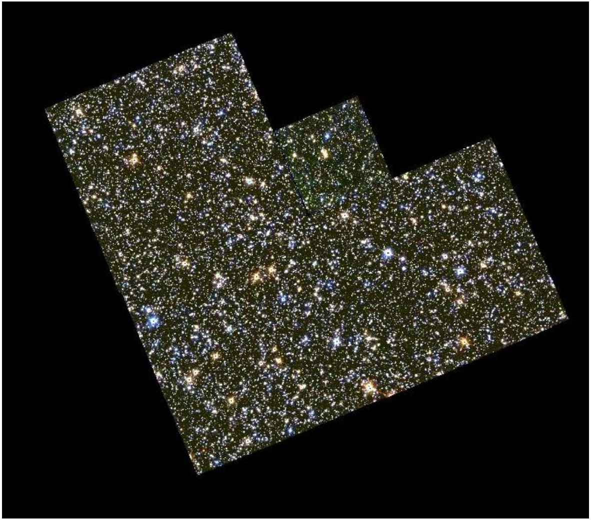
- Half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light.
- S0 galaxies also have bars – a bar can persist in the absence of gas
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar.
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy

Barred Spiral

Lopsided galaxy - unstable disks

Irregular

Large Megallanic Cloud



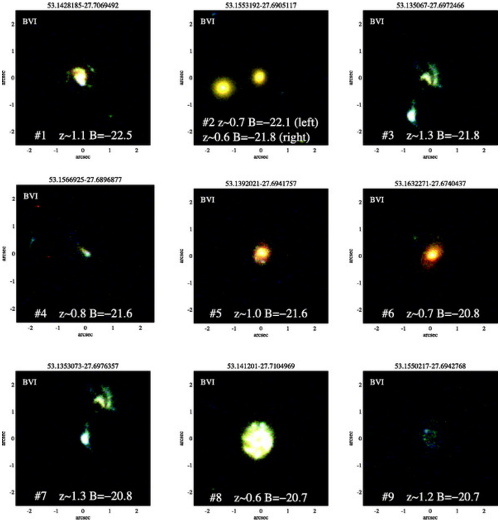
Credit: Wadadekar et al. (2006)

Nomenclature: Early and late type

Objects along the sequence are often referred to as being either an early-type or a late-type. Ellipticals and S0 galaxies are collectively called and early-type and spirals are called late-type. Within spirals, an Sa galaxy is called an early-type spiral, and an Sc galaxy a late-type spiral. *This nomenclature is not a statement of the evolutionary stage of the objects but is merely of purely historical origin.*

$\sim$30% of galaxies at $z \sim 1$ are peculiar in rest frame UV

First, distant galaxies.



Mergers can alter morphology

The Milky Way - Andromeda galaxy merger

Galaxies in the process of transformation, generally from disks to ellipticals
In late stages of a merger, the 2 galaxies are no longer distinguishable.
What does the merger product look like?
Show movie

Major and minor mergers

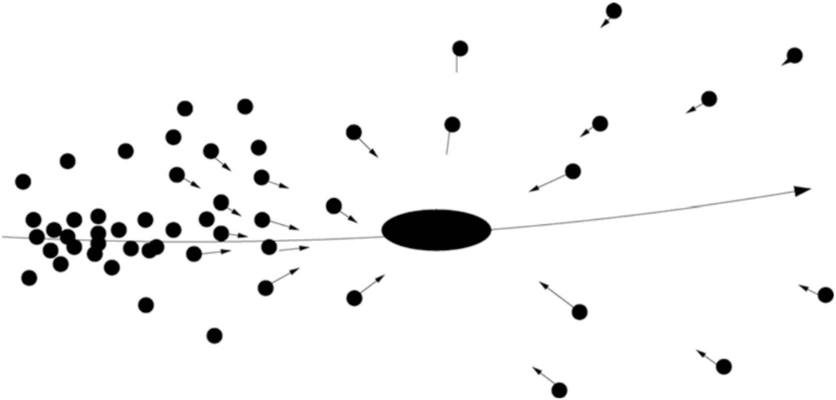
In minor mergers, the mass ratios of halos is large (typically in excess of 3:1), and major mergers where the two masses are similar.
Which type of merger will be more common?

Dry and wet mergers

Dry merger: merger between gas-poor galaxies
Wet merger: merger between gas-rich galaxies
What are the observable differences between these two types of mergers?

NGC 474 - Shells and tidal tails

Dynamical Friction



Questions

- Why are the most massive galaxies in a cluster found near its centre?
- Why do supermassive black holes also merge during a galaxy merger?
- What will happen with the Megallanic Clouds in the distant future?
- Why can’t compact groups be very old?

Dynamical Timescale

Typical time taken to cross a massive structure once. Indicates the time needed to reach equilibrium in the system.
For a MW type galaxy it is 2×10^8 yr. For a cluster, it is 2×10^9. Most clusters have not yet reached equilibrium.
What is the dynamical timescale for the earth?

Questions

If you go look at the night sky most of the stars look white or blue with a few red ones which are all red giants. But the IMF tells us that most stars should be red looking M-dwarfs or G and K type dwarfs? Why are these common stars extremely uncommon in the night sky?

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Malmquist Bias - See Binney & Merrifield (1998) pp. 111-115

Large scale structure of galaxies

So far, we have looked at galaxies and their components from a structural point of view. The physical scale is a few 10s of kiloparsecs.

Large scale structure of galaxies

So far, we have looked at galaxies and their components from a structural point of view. The physical scale is a few 10s of kiloparsecs. Now we look at the large scale structure of baryons in the universe on Mpc scales. Just as stars are the individual building blocks of galaxies, galaxies are building blocks of the *cosmic web* of large scale structure. Remember, however, that galaxies are *biased* tracers of the underlying DM distribution i.e. M/L ratio is not constant!

Why conduct galaxy redshift surveys?

- Density fluctuations evolve into structures we observe: galaxies, clusters, etc.
- On scales $>$ galaxies, we talk about the Large Scale Structure (LSS); groups, clusters, filaments, walls, voids, superclusters are the elements of LSS
- To map and quantify the LSS (and compare with the theoretical predictions of cosmological models), we need redshift surveys: mapping the 3-D distribution of galaxies
- Today we have redshifts measured for $>$ 2 million galaxies
- While the existence of clusters was recognized early on, it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures.

Galaxy imaging surveys

1970	Lick (Shane-Wirtanen)	1 M galaxies

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1990	APM	2 M
1995	DPOSS	50 M
2005	SDSS	200 M
$>$2023	LSST	2000 M

Galaxy redshift surveys

1985	CfA	2500 galaxies

Galaxy redshift surveys

1985	CfA	2500 galaxies
1995	CfA2	20000
1996	LCRS	23000

Galaxy redshift surveys

1985	CfA	2500 galaxies
1995	CfA2	20000
1996	LCRS	23000
2003	2dF	250k
2005	SDSS	800k

Galaxy redshift surveys

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1996	LCRS	23000
2003	2dF	250k
2005	SDSS	800k
2017	SDSS DR14	2.5m