Extragalactic Astrophysics - Summary

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This summary is based on the book Chapter 9 from Arnab Rai Choudhuri: Astrophysics for physicists.

1 Galaxy classification

Based on the **morphology** (shape) there are three main categories of galaxies:
- spiral (late-type): younger galaxies, with interstellar medium, star formation, young stars, bluer colours
- elliptical (early-type): older galaxies, typically no interstellar medium, no star formation, older stars, redder colours
- irregular

Both of the elliptical and spiral galaxies have further **sub-types**, which are part of the **Hubble classification** or Hubble tuning fork of galaxies. Ellipticals range from spherical to more elongated shapes and spirals get sub divided based on the following criteria: bar or no bar, brightness of the centre, tightness of the spiral arms.

Luminosity function: describes how many galaxies there are as a function of luminosity. → There are more low luminosity (small) galaxies compared to the high luminosity (massive) galaxies. The function that describes the distribution is called a **Schechter function**.

2 Environment

Galaxies are found in different environments, based on how many other galaxies are around them. Types of environments:
- supercluster: a collection of galaxy clusters and groups
- galaxy clusters: hundreds or thousands of galaxies that are gravitationally bound, typical masses are $10^{14} - 10^{15} M_{\odot}$
- galaxy groups: a few to about 50 galaxies that are gravitationally bound
- field: few galaxies, not bound gravitationally
- void: basically no galaxies

The Milky Way is part of a small galaxy group called the **local Group**. Members of the Local Group include the Andromeda galaxy, the Triangulum galaxy, the Large Magellanic cloud, the Small Magellanic cloud and about a hundred very small galaxies.

Depending on the environment galaxies can undergo various physical processes that change their evolution. For example in galaxy groups and clusters **tidal (gravitational) interactions** are very common. These can remove gas and stars from galaxies. In large galaxy groups there are also hydrodynamic interactions between the hot intracluster gas and the interstellar medium in galaxies. This process called **ram pressure stripping** can remove gas from galaxies.

3 Physical Characteristics of Galaxies

3.1 Elliptical galaxies

- old population II stars
- no interstellar medium → no star formation
- no observable magnetic field
- stars have random motion (they do not rotate together) → velocity dispersion characterises the motion of the stars in the system
- **Faber-Jackson relation:** relation between the velocity dispersion and the luminosity $\sigma \approx 220(\frac{L}{L_{\star}})^{0.25} kms^{-1}$

3.2 Spiral galaxies

- predominantly young stars
- interstellar medium in the disk → star formation in the disk → bluer colour

- observable magnetic field
- most of the stars are in the disk, which rotate around the centre $\rightarrow$ rotational velocity
- the rotation can be mapped using the Doppler shift of spectral lines $\rightarrow$ rotation curve $\rightarrow$ flat rotation curve $\rightarrow$ presence of dark matter
- **Tully-Fisher relation:** relation between the rotational velocity and the luminosity $v_c \approx 220(\frac{L}{L_\star})^{0.22} kms^{-1}$

4 Neutral hydrogen (H I) in galaxies

We can use observations of H I in galaxies to map the structure of the interstellar medium and to map how gas is moving inside the disk of a galaxy. In addition, we can calculate various properties of the galaxies from the H I spectrum:
- systemic velocity of the galaxy $\rightarrow$ estimate the distance to the galaxy using the Hubble flow method ($D = \frac{d}{h_0}$)
- total HI flux $\rightarrow$ is directly proportional to the HI mass
- Doppler broadening of the H I line $\rightarrow$ due to rotation $\rightarrow$ can be used to calculate the dynamic mass of the galaxy

4.1 Hubble Flow

Due to the expansion of the Universe galaxies are moving away from us $\rightarrow$ **Hubble law**: $v = h_0 D$, where v is the systemic velocity of the galaxy, h_0 is the Hubble constant, and D is the distance to the galaxy. $\rightarrow$ We can measure distances based on the systemic velocity of galaxies if they are sufficiently far away, so that their systemic velocity is mainly due to the Hubble flow.

Galaxies in groups and clusters have peculiar velocities from their motion in the group or the cluster, which is combined with the velocity that comes from the Hubble flow.

E.g. the Andormeda galaxy is moving towards the Milky Way and this method can not be used to determine its distance from the Milky Way.

5 Galaxy evolution

Galaxies change during their life as they form stars from their interstellar medium and trough interactions with other galaxies or the gas in galaxy clusters.

Gas removal can transform a spiral galaxy into an elliptical galaxy over time. Processes that can remove gas from a galaxy:
- tidal interactions (gravitational interaction)
- ram pressure stripping (hydrodynamic interaction)
- starvation (running out of interstellar medium due to star formation)

Galaxies can grow trough **mergers**. The growth trough mergers is also referred to as hierarchical model of galaxy formation and evolution. There are two categories of mergers:
- major merger (galaxies with similar mass)
- minor merger (one of the galaxy has much smaller mass compared to the other)

6 Active Galaxies

AGN is an abbreviation for **active galactic nucleus**, which is the supermassive black hole in the centre of the galaxy that is actively feeding (accreting significant amount of material). All galaxies have a supermassive black hole in their centres, however if the black hole is not accreting material the nucleus is not "active". E.g. the Milky Way has a supermassive black hole called Sagitarius A*. Sagitarius A* is not active at the moment, but could have been active in the past. The nearest AGN to us is the nucleus of M82.

There are many phenomena related to AGN activity, based on this there are a few different **historical categories of AGN**:
- **Seyfert I** (broad emission lines) and **Seyfert II** (narrow emission lines) in the cores of spiral galaxies

- **radio galaxies**: giant elliptical galaxies with bright radio emission → core + jet + lobe structure, syncrotron radiation, the jet comes from the supermassive black hole in the centre of the galaxy, the jets hits the intergalactic gas and forms bright radio lobes
- **Quasar** (quasi stellar radio object): compact, bright object visible in radio emission, they are typically very distant (high redshift) → emission from a very small region → from the core of the galaxy
- **QSO** (quasi stellar object): a quasar with only optical emission, also called a rado quite quasar

AGN properties:
- The **Schwarzschield radius** defines the size of the black hole, which is on the order of the distance between the Sun and the Earth for supermassive black holes.
- Typical supermassive black holes have masses on the order of $10^8 M_\odot$.
- **syncrotron radiation** from the jet → strong magnetic fields
- jet is perpendicular to the accretion disk
- the **unified model of AGN**:
  - The black hole is surrounded by an **accretion disk**
  - around the accretion disk there is a **dust and gas torus**
  - the black hole can have a**jet or no jet**
  - There are gas clouds around the system, if the clouds are **fast moving clouds -** they generate broad emission lines
  - if the clouds are **slow moving clouds -** they generate narrow emission lines
  - depending on the viewing angle we see different types of emission → different historical classification

Superluminar motion: due to projection effects the jet of an AGN seems to be moving faster than the speed of light.

Relativistic beaming: a jet of an AGN looks brighter if it is pointing towards us and it is moving with relativistic speed compared to a jet that is not pointing towards us. E.g. one sided jets.
Syncrotron radiation: Synchrotron radiation is the electromagnetic radiation emitted when relativistic charged particles are subject to an acceleration perpendicular to their velocity. It is produced naturally by fast electrons moving through magnetic fields. The radiation produced in this way has a characteristic polarization and the frequencies generated can range over a large portion of the electromagnetic spectrum.

7 Galaxy clusters

- Gravitationally bound structures → galaxies move around the centre → velocity dispersion → can calculate the amount of **dark matter** in the cluster
- about 30% of the dark matter is in galaxies and the rest in between the galaxies
- **intracluster gas**: hot and very diffuse gas in between the galaxies in the cluster → visible in X-rays → **bremstrahlung** → ram pressure stripping of cluster galaxies
- measurement of Fe in the intracluster gas → the gas must have been enriched with gas from member galaxies → gas can be removed from galaxies

8 Large-scale structure

- large surveys of galaxy distributions (distances from Hubble flow)
- galaxies are distributed in groups and clusters that form even larger superclusters and filaments → web like structure with bubble like voids in-between (with no galaxies)
- gravity pulls galaxies into structures that then get pulled towards larger structures trough filaments
- at very large scales the matter distribution of the Universe is uniform → Cosmological principle: the Universe is isotropic and homogeneous

9 Gamma-Ray Bursts (GRB)

- very energetic explosions observed in gamma-rays
- last a few seconds to a few hours
- isotropic distribution → extragalactic
- afterglow in many wavelengths (optical, X-ray etc.)

- **Types:**
  - short ($< 2s$) merger of binary neutron star, or neutron star - black hole merger (e.g. gravitational wave detection + kilonova)
  - long ($> 2s$) core collapse supernova
  - ultra long ($> 10000s$) an extreme version of the previous two scenarios

10 Fast Radio Bursts (FRB)

- very short (millisecond) burst of radio emission
- mostly extragalactic
- most likely related to pulsars, but the origin is yet unknown