# Interstellar medium - Summary

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This summary is based on the book Chapter 6 from Arnab Rai Choudhuri: Astrophysics for physicists.

# 1 The Milky Way

We live in the Milky Way, a typical spiral galaxy. It is possible to determine the shape of our galaxy with the following methods:

- mapping the distribution of stars - needs accurate distance estimates
- mapping the sistribution of gas (e.g. H I)

**Malmquist bias** - when mapping the distribution of astrophysical objects, we see brighter objects at larger distances compared to fainter objects. This introduces a bias, that we need to take into account when measuring distributions.

The main components of the Galaxy are the following:

- disk (stars, interstellar dust and gas) with two sub-components: thin disk (young stars), thick disk (older stars)
- a spherical bulge, which contains the Galactic Centre with the supermassive black hole (Sgr $A^\star$)
- A bar in the centre
- Open star clusters near the disk
- Globular clusters distributed all over the halo
- Stellar streams in the halo, from shreded dwarf galaxies
- A large gamma ray bubble above and below the centre
- Small companion (satellite) galaxies, the Large and the Small Magellanic Clouds

The Sun is about halfway between the edge and the centre, approximately 8kpc from the Galactic Centre.

In terms of mass the Galaxy has the following components:

- dark matter
- stars
- gas
- dust

**Interstellar extinction or reddening:** dust in the interstellar medium absorbs some of the light from stars. There is more absorption at shorter (bluer) wavelength, which means that the light of stars appears redder. The magnitude formula gets the following modification:

$$m = M + 5log_{10}d - 5 + A_\lambda$$

$A_\lambda$ is the interstellar extinction, which can also be expressed as E(B-V) reddening. Most of the dust is confined in a thin layer (±150 pc) in the disk of the galaxy. This zone if also called the **zone of avoidance** in extragalactic astrophysics.

# 2 Galactic dynamics

There are two main types of motion in the Galaxy:

- rotation in the disk - centrifugal force
- random motions in the spherical components, the halo and the bulge

We can determine the motion of the Sun in the disk of the galaxy, by comparing it to the far away globular clusters in the halo. → the Sun rotates around the Galactic Centre in an approximately circular orbit ($\Theta_0 = 220$ km s$^{-1}$). We can estimate the dynamic mass of the Galaxy inside of certain radii if we measure the motion of stars. An estimate for the mass of our galaxy based on this is $\sim 10^{11} M_\odot$. Measuring the motion of stars at different radii makes it possible to construct a **rotation curve.** The shape of the rotation curve is surprisingly flat in the outer parts of the Galaxy, which indicates the presents of **dark matter**.

The motion of nearby stars can be determined compared to the motion of the Sun. We can express the radial and the tangential velocity components in terms of the Oort constants (A,B). We can measure the Oort constants from the motion of nearby stars (e.g. measurements from the Gaia satellite). A - represents shearing motion in the disk near the orbit of the Sun. B - represents the angular momentum gradient near the Sun.

# 3 Stellar populations

- Population I $\rightarrow$ metal-rich young stars in the disk, usually with surrounding interstellar medium
- Population II $\rightarrow$ metal-poor old stars in the spherical components (halo, bulge), usually with no surrounding interstellar medium
- Population III $\rightarrow$ a theoretical population of stars, which are the oldest and most metal-poor. These are supposedly the first stars in the Universe

# 4 The Interstellar medium

The interstellar medium has two main components: dust and gas. We can measure the gas in the interstellar medium trough spectral lines. The earliest measurements were narrow absorption lines in the spectra of stars, originating from cold gas clouds in the foreground of stars. The more modern measurements can map the distribution of various atoms and molecules in radio emission lines (e.g. HI and CO).

## 4.1 Neutral Hydrogen - HI

The **21 cm (1.4 GHz) hydrogen line** is a spin flip transition of the neutral hydrogen atom. We can observe the HI line all over the Galaxy in HI emission. Most of the HI is in the disk of the Galaxy. Since this is a spectral line, we can observe the motion of the gas based on the Doppler-shift of the line. $\rightarrow$ We can map the distribution of the gas in the disk. $\rightarrow$ We can observe the **spiral arm structure** of our Galaxy $\rightarrow$ We can use it to construct a **rotation curve** $\rightarrow$ and measure the dynamical mass of the galaxy, similar to the measurements with the stars. The HI disk is more extended than the stellar disk.

There is a gas cycle in the Galaxy: gas gets heated and cooled by various processes.

## 4.2 Emission and absorption in the ISM

There is generally no thermodynamics equilibrium (TE) in the ISM. However, we can describe the emission and absorption processes using basic quantum mechanical principles: the Einstein coefficients of radiative transitions between energy states:

- spontaneous transition $A_{ul}$
- induced transition $B_{ul}, B_{lu}$

We can express the emission ($j_\nu$) and absorption ($\alpha_\nu$) coefficients as a function of the Einstein coefficients. In TE we get the same relations discussed in the radiative transfer chapter.

## 4.3 Phases of the ISM

- cold H I: average 80K, clumpy clouds, denser, observed in narrow absorption lines
- warm H I: average 8000K, less dense, more extended HI, observed in emission lines

The absorption lines give the integral: $\int \frac{n_H}{T} ds$ where $ds$ is the path length, $n_H$ is the number density of Hydrogen atoms and $T$ is the temperature.

The emission lines give the following integral: $\int n_H ds$. Combining the emission and absorption lines we can estimate the amount of hydrogen present in the ISM and the temperature of the gas. In the optically thin case, the integrated H I emission line directly gives the column density of the gas.

# 5 Molecular gas

- cold dense regions of the ISM

- 10-30 K
- $\sim 1\%$ in volume and $\sim 40\%$ of the mass of the ISM → mostly in a clumpy structure in molecular clouds
- we can observe it with molecular lines in the radio domain e.g. CO lines
- the **most abundant species is** $H_2$, however it is difficult to observe (only has absorption lines in the UV) → **we observe CO instead** (has rotational line transitions in radio).
- CO maps of the Galaxy → most of the CO is in a thin disk in molecular clouds
- stars form from molecular gas in molecular clouds

# 6 Masers

- very bright OH (hydroxide) emission
- maser - **microwave amplification by stimulated emission of radiation**
- masers are essentially lasers (amplified electromagnetic emission) in the millimetre wavelength regime
- sources: e.g. molecular clouds, AGN, planetary atmospheres, stellar atmospheres

# 7 Hot interstellar gas

## 7.1 HII regions

- **bubble shaped regions** of ionised hydrogen (HII)
- found **around O and B stars** → associated with star formation regions
- O,B stars produce lots of UV photons → which have high ionisation potential → ionise the gas around the new stars → recombination lines
- detectable in many wavelengths: e.g. optical and radio
- can also have other partially ionised elements: e.g. C, O, N

## 7.2 Hot halo gas

Typical temperature of millions of K, very low density, found outside the disk of the galaxy in the spherical halo. Can be detected as spectral lines or in X-ray continuum emission.

# 8 Galactic magnetic fields

- we can map the Galactic magnetic field with **polarisation measurements** (star light polarisation or dust polarisation) or radio continuum emission (from syncrotron radiation) → these provide the direction of the magnetic field
- the most modern map is from the Planck satellite
- we can measure the strength of the field based on pulsar data (dispersion + Faraday rotation)
- **Faraday rotation:** magnetic field present in the plasma can make the plane of polarization rotate
- **syncrotron radiation** (radio continuum) from cosmic rays spiralling in the magnetic field
- origin of the magnetic field: turbulent motion in the plasma