Introduction to Astronomy and Astrophysics I

Lecture 10

Yogesh Wadadekar

Aug-Sep 2024

What is the Interstellar Medium?

The interstellar medium (ISM) refers to the matter and radiation that exists in the space between the star systems in a galaxy. It includes:

- Diffuse gas (mostly hydrogen and helium)
- Dust grains
- Cosmic rays
- Magnetic fields
- Thermal and kinetic energy

The ISM plays a crucial role in the formation and evolution of stars and galaxies.

Composition of the ISM

The ISM is composed primarily of:

- 70-80% hydrogen (H)
- 20-25% helium (He)
- <1% metals (C, N, O, etc.)

The relative abundance of these elements is similar to the primordial composition of the universe.

Forms of the ISM

The ISM can exist in various forms:

- **Molecular Clouds**: Dense, cold regions where stars are born
- **HII Regions**: Hot, ionized regions around newly formed, massive stars
- **Diffuse Clouds**: Warm, low-density regions of atomic gas
- **Coronal Gas**: Hot, diffuse gas at millions of Kelvin
- **Dust Grains**: Small solid particles of ice and carbon-rich material

Importance of the ISM

The interstellar medium is crucial for the following reasons:

- Provides the raw material for star formation
- Regulates the evolution of galaxies
- Contributes to the magnetic field structure of a galaxy
- propagates cosmic rays
- Absorbs and scatters starlight, affecting our observations

Understanding the ISM is thus essential for studying the formation and evolution of stars, galaxies, and the universe as a whole.

Observing the ISM

The interstellar medium can be observed using various techniques:

- **Emission Lines**: Atoms and molecules in the ISM emit light at specific wavelengths
- **Absorption Lines**: Photons from background sources are absorbed by atoms and molecules in the ISM
- **Infrared and Submillimeter Emission**: Dust grains in the ISM absorb starlight and re-emit it at longer wavelengths
- **Radio Emission**: Synchrotron radiation from cosmic rays, and spectral lines from molecules
- **Polarization**: The alignment of dust grains in magnetic fields can polarize the light passing through the ISM

Challenges in Studying the ISM

Studying the interstellar medium poses several challenges:

- The ISM is extremely tenuous, with a very low density
- The ISM is highly inhomogeneous, with a wide range of temperatures, densities, and chemical compositions
- Many of the relevant physical processes (e.g., turbulence, magnetic fields, cosmic rays) are not fully understood
- Observations of the ISM can be complicated by foreground and background contamination
- Modeling the ISM requires complex computer simulations that incorporate many different physical processes

Overcoming these challenges is crucial for advancing our understanding of the ISM and its role in the universe.

The Cloudy code

The Cloudy spectral synthesis code is used to model interstellar clouds, including the ISM, and predict their emitted spectra:
Modeling: The code simulates physical conditions in astronomical plasmas and can model a wide range of interstellar clouds, including H II regions, planetary nebulae, Active Galactic Nuclei, and the hot intracluster medium.
Data: The code uses a database of fundamental data and is continually developed to improve the treatment of microphysical processes.
Cloudylines: interface is a file that contains data on the nebular line emission produced by the interaction of the stellar radiation field with the ISM.
The code is widely used in the analysis and interpretation of emission-line spectra. Thousands of scientific papers have cited the Cloudy code. Cloudy has been in development since 1978, led by **Gary Ferland**.

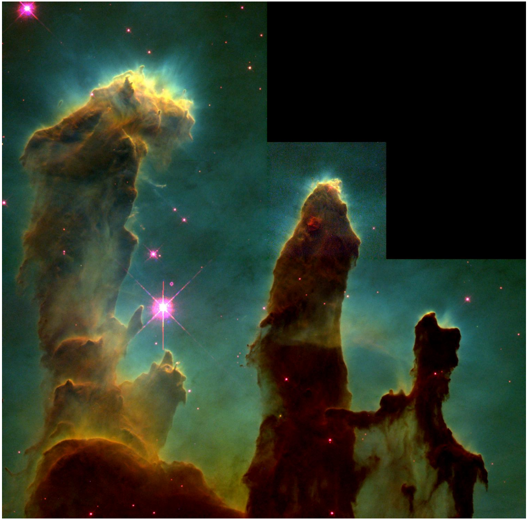
Metallicity and how it evolves with time

Population 3 stars $\Rightarrow$ Population 2 stars

The Carina nebula with JWST

Credit: NASA/STScI

ISM - the most beautiful part of the Universe!



Credit: NASA/STScI

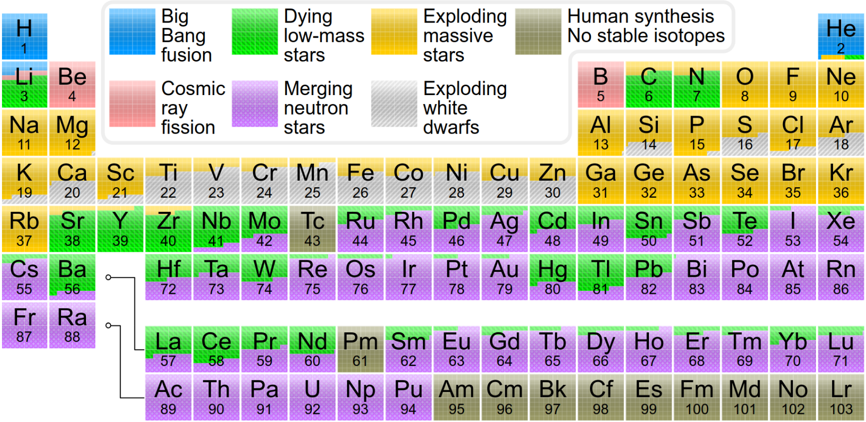
Ongoing ISM Research

- Improving our understanding of the physical processes that shape the ISM, such as turbulence, magnetic fields, and the interaction between different ISM phases
- Exploring the role of the ISM in the formation and evolution of stars, planets, and galaxies
- Investigating the impact of the ISM on the propagation of cosmic rays and the generation of high-energy radiation
- Developing more sophisticated computer models and simulations to accurately represent the complex nature of the ISM
- Utilizing new observational techniques and technologies to study the ISM in greater detail

Research areas of IUCAA and NCRA faculty

- Sun - Divya O, Durgesh T, Nishant S
- Planets - Surhud M
- Stars - Anupam B
- Compact Objects (Neutron stars/Pulsars) - Yashwant G, Bhaswati B, Jayanta R, Dipanjan Mi, Yogesh M, Viswesh M, Krishnakumar M. A.
- ISM/IGM - Nissim K, Srianand R, Neeraj G, Rajeshwari D, Sowgat M, Subhashis R
- Galaxies - Jayaram C, Yogesh W, Kanak S, Nissim K
- Galaxy Clusters - Ruta K
- AGN - Preeti K, Dharam L, CH Ishwara-Chandra, Subhashis R, Yogesh W, Gulab D, Ranjeev M, Vaidehi Sharan P, Dipanjan Mu
- Gravitational Waves - Sanjit M, Debarati C, Shasvath K
- Observational Cosmology - Surhud M, Aseem P, Tirthankar R
- Instrumentation Development - A N Ramaprakash
- Quantum Technologies - Subhadeep De

Where are elements synthesised (as per latest data)?



The centre of our galaxy

Stars in orbit around MW Black Hole

Galaxies are a very active field of research today!

Just over 32% of the refereed papers published in 2023 had the word *galaxies* in keyword/abstract, 9287 refereed papers in 2023 alone. Most things about galaxies we will study in this course were discovered in the last 25 years.

Three ubiqitous basic structures in the Universe

- Atoms
- Stars
- Galaxies

Kant's "Island Universes"

In 1755 he wrote a book called *General Natural History & Theory of the Heavens* in which he said:

1. MW like a huge solar system, rotating; origin from rotating cloud.
2. stars far from disk plane on different orbits
3. disks (like MW) project to ellipses
4. oval nebulae (seen by de Maupertius) = "Island Universe"

Major milestones since Kant

- 1755: Kant's Island Universes
- 1912: Slipher discovered that nebulae are rotating
- 1920: Shapley-Curtis debate “Are Spiral Nebulae Island Universes” - 30 minute presentations by each - Shapley “won” the debate, although Curtis was right.
- 1925: Hubble discovered Cepheids in the Andromeda galaxy

Extragalactic astrophysics $<$ 100 years old!

What are galaxies?

- gravitationally bound agglomerations of stars, dust, gas, dark matter.
- Mass ratio Dust:Gas:Stars:Dark Matter - 1:10:100:1000
- they are the basic building blocks of the Universe on large scales
- they show a **broad range in their physical properties**
- Understanding of galaxy formation and evolution is one of the main outstanding problems in modern cosmology
- there are $\sim 10^{11}$ galaxies in the observable universe
- typical total mass of $10^{8} - 10^{13}\ M_{\odot}$

Counting and cataloging galaxies

- In late 1700s,Messier made a catalog of 109 nebulae so that comet hunters wouldn't mistake them for comets! About 40 of these were galaxies.
- NGC New General Catalogue (Dreyer 1888) had 7840 objects, of which about 50% were galaxies.
- In the 20th century, many catalogs were produced UGC, RC3 etc.
- Nowadays we have automated surveys, e.g. Sloan Digital Sky Survey, with tens to hundreds of millions of galaxies. The next generation surveys will have billions of galaxies.

First step census, second step classification

third step understanding are common steps in any empirical science.
Hubble proposed a scheme for classifying galaxies (the ”tuning fork” diagram) in his 1936 book, *The Realm of the Nebulae*. This scheme survives in its essence to the present day.
ellipticals, lenticulars, spirals and irregulars are the main types.
A better approach may be to look at the properties of subsystems within galaxies (e.g., disks, spheroids, halos, etc.), and deduce their origins and evolution

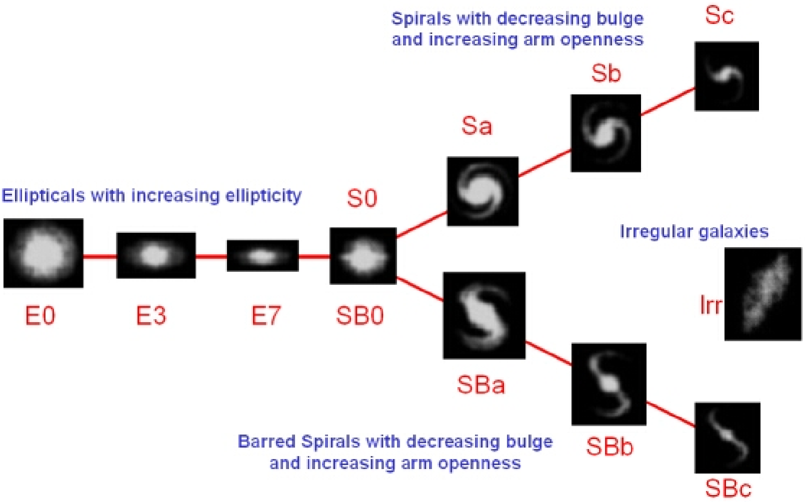
Why is galaxy classification useful?

- Classes bring order to diversity of galaxy forms
- Span/include majority of galaxies
- Unambiguous & easily identified criteria
- Relate to important physical properties $\rightarrow$ provide insight into internal processes, formation, & evolution

Why classify galaxies in the optical band?

Historically, optical photometry was the method used to observe galaxies. Hence Hubble's classification is most widely used. Today, many other criteria such as color indices, spectroscopic parameters (based on emission or absorption lines), the broad-band spectral energy distribution (galaxies with/without radio- and/or X-ray emission) are also used to group similar galaxies together.

Hubble tuning fork diagram



Elliptical Galaxies

- About 20% of field galaxies are Ellipticals, but most E's are in clusters
- There are a number of different subtypes:E's (normal ellipticals), cD's (massive bright ellipticals at the centers of galaxy clusters), dE's (dwarf ellipticals) dSph's (dwarf spheroidals)
- Smooth and almost featureless. no spiral arms or dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Elliptical galaxies are denoted En where:$b/a = 1 - n/10$ i.e. an E4 galaxy has an axis ratio of $b/a = 0.6$, and E0's have circular isophotes.

Elliptical

Lenticular

- are characterised by the presence of a central bulge and disk and the absence of spiral arms i.e. little or no ongoing star formation
- intermediate in many of their properties between ellipticals and spirals.

Lenticular

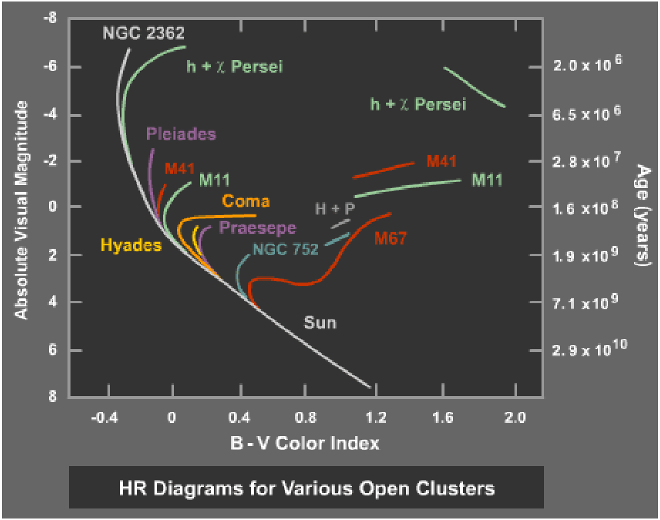
Spiral

Named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), or due to dust lanes.

Which are more massive, O or B type stars?

Grand Design Spiral

Age of open clusters via main sequence turnoff



How to use the HR diagram to find age of open cluster?

M/L ratio for stars

For main sequence stars, we have $L \propto M^{3.5}$, giving :
$(M/L) \propto M^{-2.5} \propto L^{-0.71}$
showing, as one expects, later spectral types have higher M/L.
e.g. K stars : $M \sim 0.5 M_\odot \rightarrow M/L \sim 10$; A stars :
$M \sim 2.0 M_\odot \rightarrow M/L \sim 0.1$

Mass to light ratio M/L of a galaxy

M/L defined in units of $M_\odot/L_\odot$
For galaxies, M/L reflects the average M/L over the population
Pop I (young) : massive stars dominate light; low mass stars dominate mass Pop II (old) : giants dominate light; M.S. stars dominate mass
Typical galaxy (& solar neighborhood) has $M/L_V \sim 6$, $M/L_B \sim 10$ In general : M/L increases with age and metallicity Maximum range : $2 < M/L_B < 20$.