[Theoretical]

Astrophysics (765649S)

III

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Part III

Theoretical Astrophysics

Stellar Atmospheres

Interacting Binary Stars

Stellar Structure and Evolution

Interstellar Medium

A very short introduction

+ Radiative processes

The topics which will be discussed in the given course

A short introduction to the Interstellar Medium

DEFINITION OF THE INTERSTELLAR MEDIUM
HISTORY
THE ZOO OF OBJECTS IN THE ISM
BASIC PROPERTIES AND PHASES OF THE ISM

Definition of the interstellar medium

- The interstellar medium, or ISM, is the nearly-empty space inside our Galaxy in which all the objects we've studied thus far are embedded (note that there is also an intergalactic medium in the spaces between galaxies).

- The Milky Way (as well as other galaxies) is full of gas, dust, cosmic rays, and radiation. This forms a very complex medium, that often affects many processes involving stars and compact objects, as well as our observations of these objects.
  - The radiation of the ISM is faint, and the bulk of photons are emitted in the radio and infrared wavelength regime.
  - The ISM hosts only a few percent of the total mass of the galaxy.
  - The composition of the ISM is continuously modified by the stellar evolution.
  - The distribution and chemical composition of the ISM is also continuously modified by accretion of matter by the galaxy.
  - Density and temperature variations within the ISM trigger the star formation rate of a galaxy.

History (1)

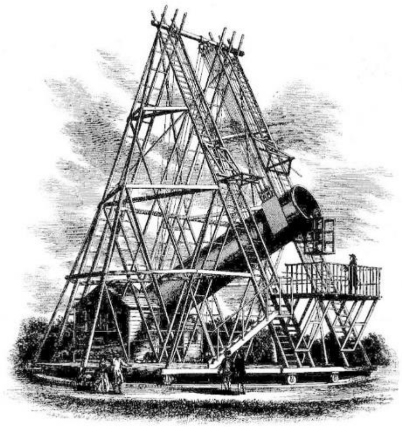
In 17th-19th centuries, it was assumed that the vast space between the stars is completely empty (vacuum).

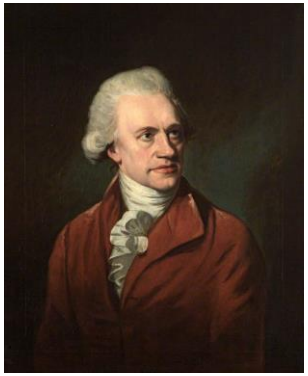
1610 - Discovery of the Orion Nebula (Nicolas Fabri de Peiresc) - “surprised to find a small illuminated cloud”.

1656 - First detailed description of the Orion Nebula (Christian Huygens).

History (2)

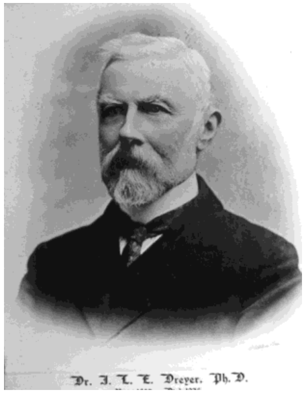
- 1781 - Charles Messier compiled a catalogue of 103 objects:
  - The majority clusters of stars
  - galaxies (35)
  - nebulae (11)





- 1786-1802 – John Herschel discovered 2500 objects, later added 2200 objects:
  - Many of these were dark clouds: “here is truly a hole in Heaven”

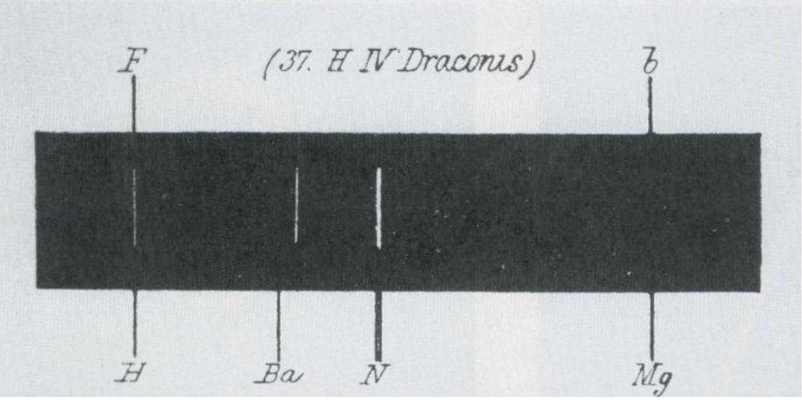
- 1888 - New General Catalog (NGC) by J.L. Dreyer was published (13,000 objects)



19th-century: Advent of spectroscopy

Helped distinguish between stellar and gas content:

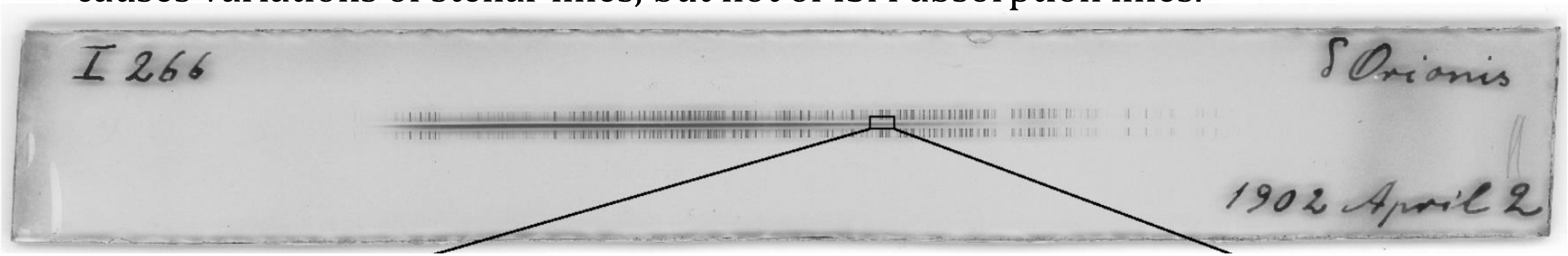
- 1864: Sir William Huggins observed the Cat's Eye Nebula and found no continuous spectrum like that seen in the Sun, but just a few strong emission lines.
- Two lines were first thought to be from nitrogen (hence the tag "N“).
- However, it appeared later that these lines did **not** correspond to any known elements on Earth. These lines were attributed to an anonymous element called Nebulium.



- 1927: Ira Sprague Bowen showed that these lines belonged to forbidden transitions of oxygen [O III] at 5007 and 4959 Å.

Interstellar absorption lines

- In the beginning of 20th century, in 1904, Johannes Hartmann using spectral analysis found 2 **static** lines of Ca II H&K in the spectra of the binary star δ Orionis. Hartmann attributed these lines to interstellar medium (ISM). Doppler effect causes variations of stellar lines, but not of ISM absorption lines.

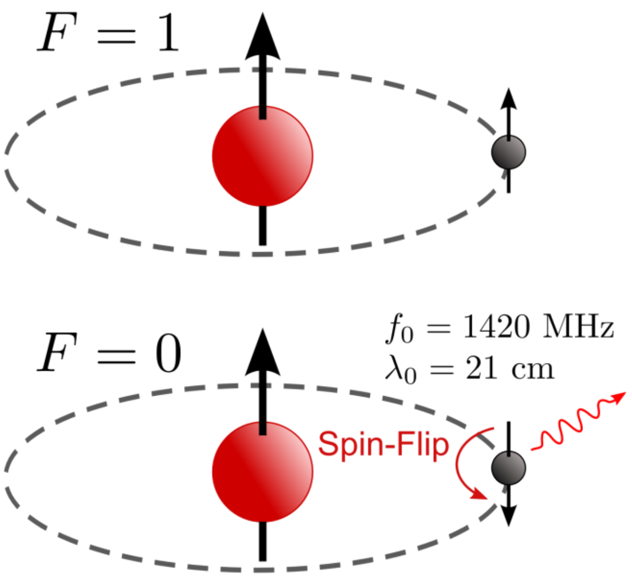


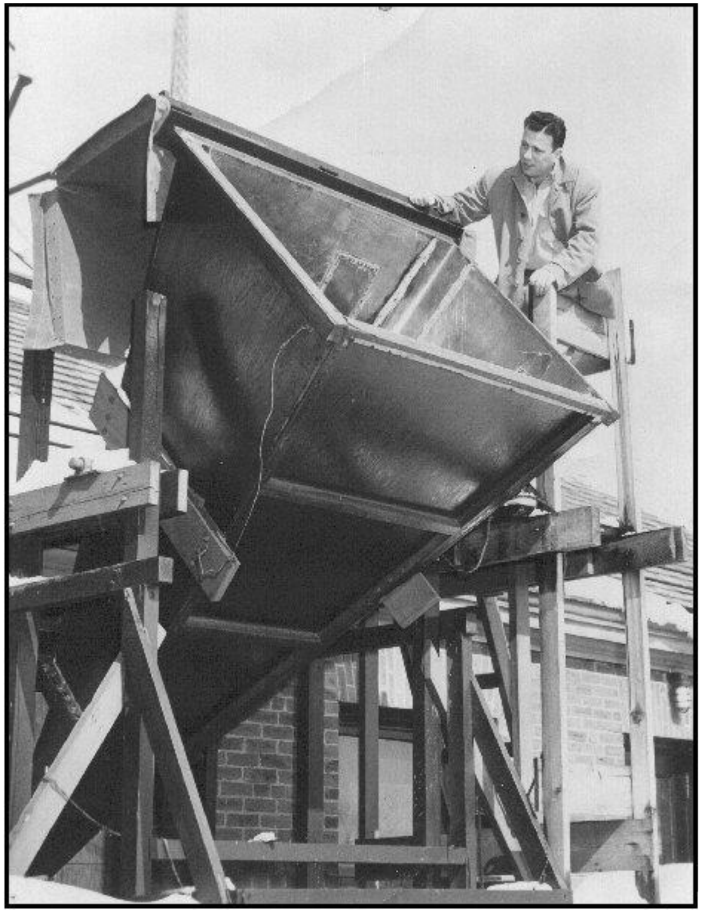
  - Why Ca (also Na) was observed, but not H or He lines? Most atoms in the ISM are on their ground state. They can absorb stellar radiation in resonance lines (strongest). Ca and Na have these lines in the optical band, while H and He have them in the ultraviolet (UV) band (Lyα 1216 Å and 586Å, respectively). Earth atmosphere absorbs radiation with λ<2900Å. In stellar spectra, of course, one observes H and He lines of excited states.

- 1933: Plasket & Pearce found a correlation between the Ca II absorption line strength and the stellar distance.
- 1937: the first interstellar molecules CH, CH^+ and CN were discovered

Radioastronomy and HI 21-cm line

- 1944 - Hendrik van de Hulst predicts the existence of the Neutral Hydrogen 21-cm hyperfine spin-flip transition.
- 1951: The 21 cm line was first detected by Harold "Doc" Ewen and Ed Purcell. Muller & Oort confirmed the detection.

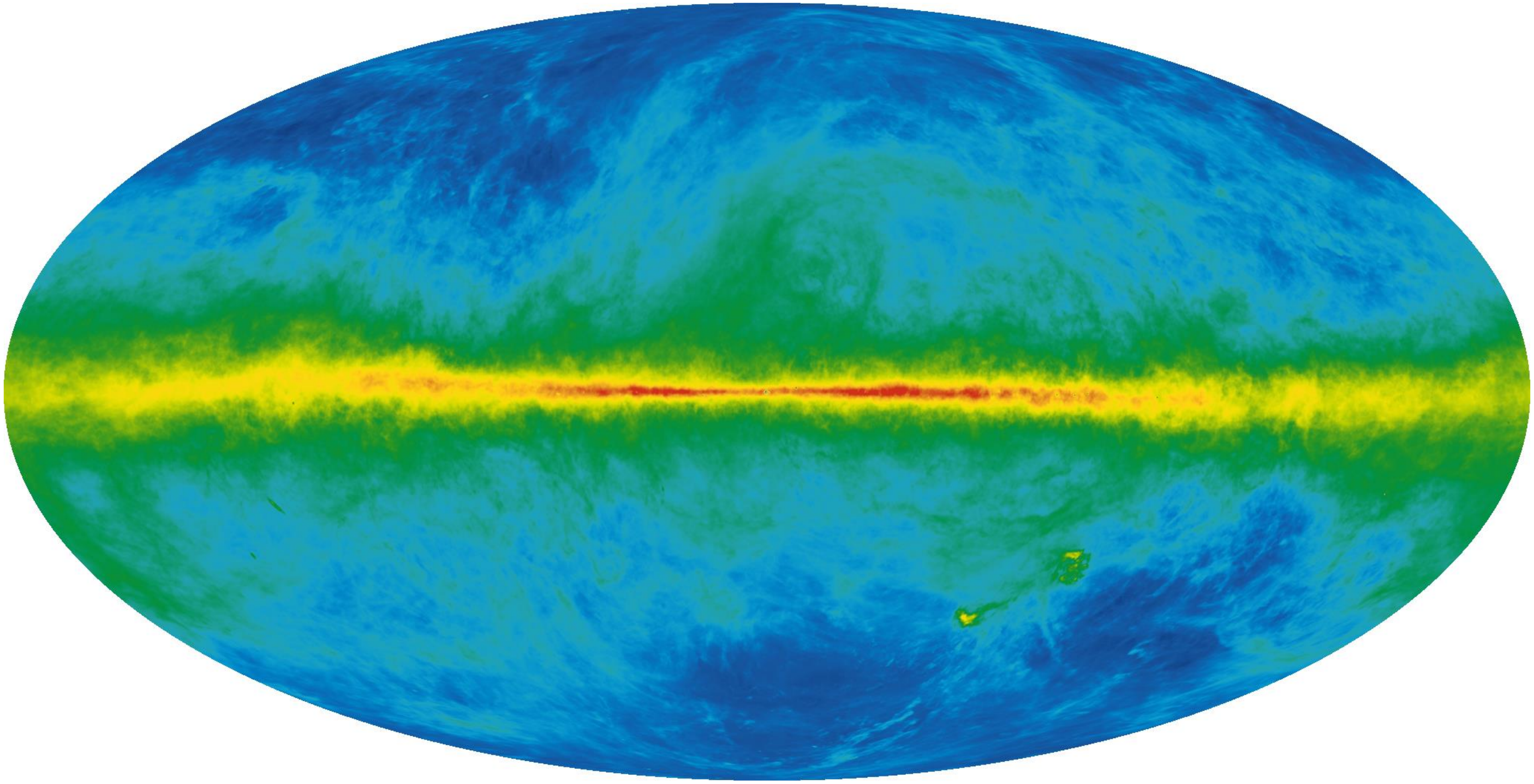




More detail later

The neutral Hydrogen 21-cm line

Cold H I emitting at 21-cm makes up most of the mass of the ISM gas in the Milky Way. Its observation represented a revolution.



Interstellar dust

In 1930s it was shown that space is not transparent in continuum also. Absorption is strongest in the galactic plane. Reddening of the stellar light is observed. **Dust!**

Dust: graphite (C), Si, ice (H_20). Size <1 μm.

Light becomes polarized as it goes through dust, since the elongated dust grains are aligned by interstellar magnetic field.

Spiral galaxy Messier 96

Sombrero Galaxy

The zoo of objects in the ISM

- Dark clouds (molecular clouds) - not associated with bright stars, seen as black patches

Horsehead Nebula

a dark nebula (also known as Barnard 33 in emission nebula IC 434)

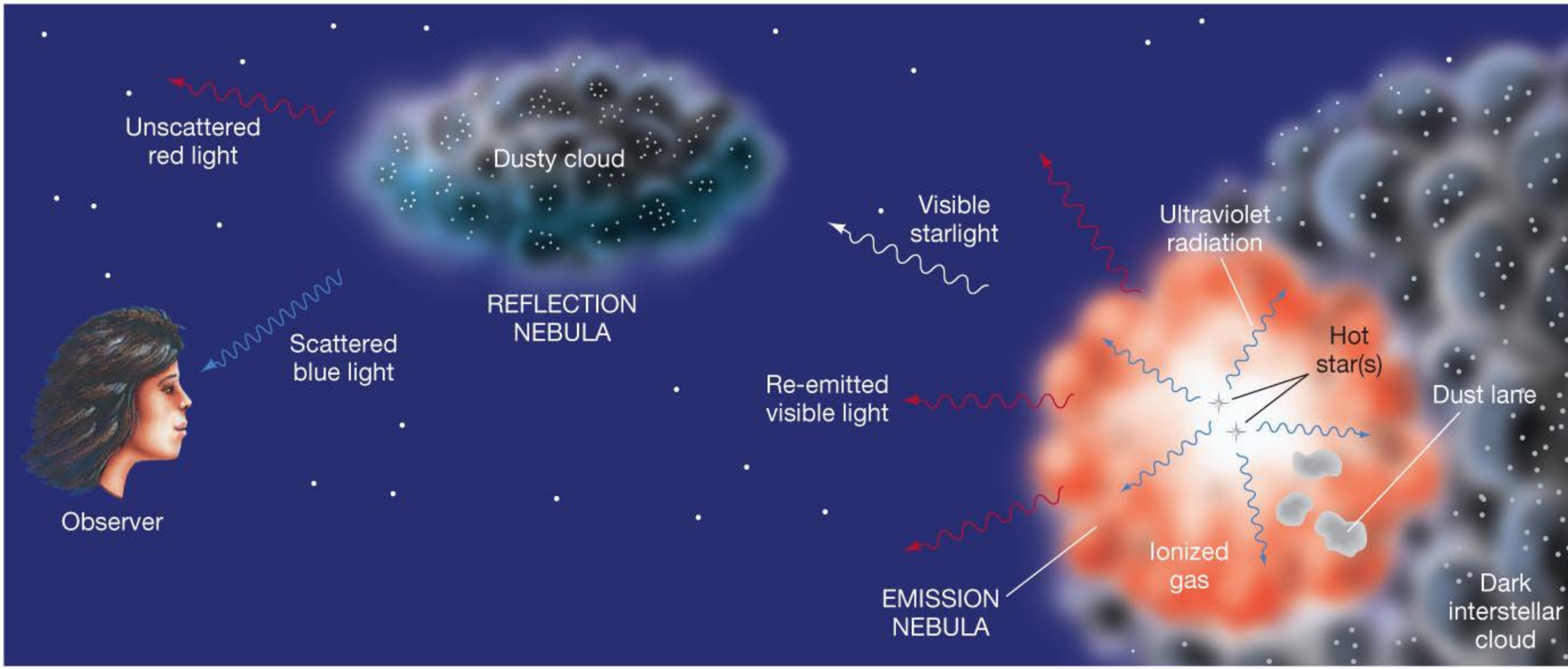
The zoo of objects in the ISM

- Dark clouds (molecular clouds) - not associated with bright stars, seen as black patches
- Reflection nebula - presence of hot stars (25000 K) the dust cloud may scatter the stellar radiation

The Pleiades, an open cluster

Reflection nebulae around the brightest stars were once thought to be left over material from their formation. Now they are considered likely to be an unrelated dust cloud in the interstellar medium through which the stars are currently passing.

Why the reflection nebulae look like we see



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- HII region (or emission nebula) - nebula associated with very hot stars (T_{eff} >25000 K), gas surrounding is photoionized

The HII region Sh 2-252

The field is approximately 35′ × 30′.

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Cat's Eye Nebula

a planetary nebula.

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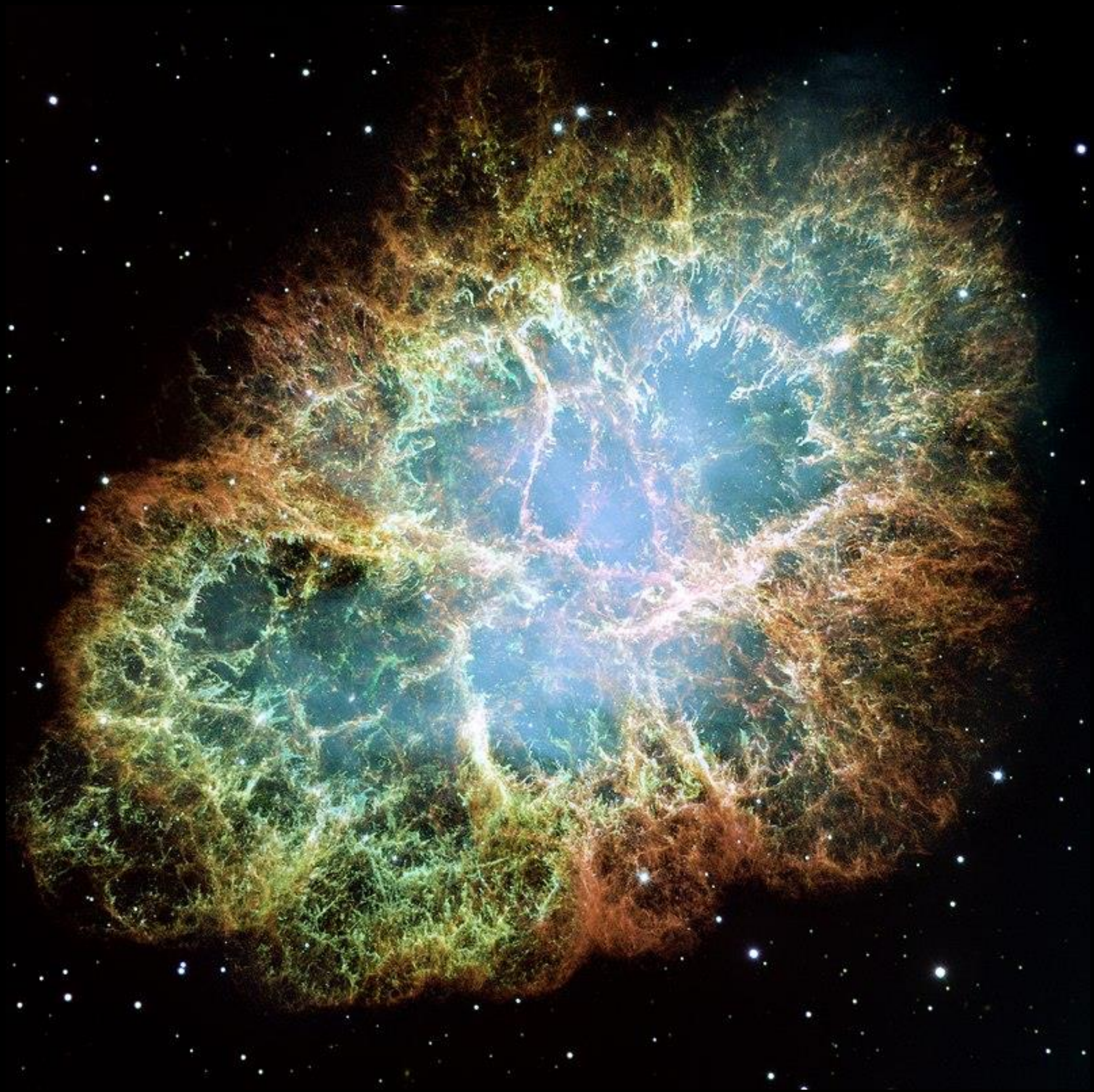
- Planetary nebula - former atmosphere of a solar mass star, now a hot white dwarf
- Supernova remnant - massive star's death, bright gaseous nebula

Crab Nebula

a supernova remnant
and pulsar wind nebula.



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Basic properties of the ISM

- Confined to the Galactic Plane (much flatter than a compact disc!)
- 1% of total visible mass of the Galaxy
- The interstellar medium consists mainly of hydrogen and helium
  - Chemical composition of the ISM comparable to the element's abundance of the Solar System
- Dust: ~1-10% of gas mass (grains: about 1% of the ISM mass)
  - grain size: 0.1 - 0.001 mm
  - ~ 1 grain/10^6 m^3
  - ~ 0.001 $M_\odot$ /pc^3
- Gas: ~1 atom/cm^3
  - ~0.01 $M_\odot$ /pc^3
  - Gas atoms/dust grains by number = 10^{12}.
- Temperature range 4 K < T < 10^6 K
  - The temperature is used as a measure for the physical conditions of the interstellar gas. The "phases" of the interstellar medium are characterized by the average gas temperature.
  - The state of Hydrogen determines the state of the ISM:
    - Molecular region → H_2
    - Neutral region → H I
    - Ionized region → H II or H^+
- Densities 10^{-4} cm^{-3} < n < 10^7 cm^{-3}
- Far from thermal equilibrium! Remember? Not easy to calculate!

ISM phases

Component	Fractional Volume	Temperature (K)	Density (atoms/cm³)	State, Where
Molecular clouds	< 1%	20 - 50	10^3 - 10^6	hydrogen molecules (thin disk)
Cold Neutral Medium (CNM)	1-5%	50 - 100	1 - 10^3	neutral hydrogen atoms (thin disk)
Warm Neutral Medium (WNM)	10-20%	1000 - 5000	10^{-1} - 10	neutral hydrogen atoms (thin disk)
Warm Ionized Medium (WIM)	20-50%	10^3 - 10^4	0.01	ionized hydrogen (thick disk)
H II regions	~10%	10^4	10^2 - 10^4	ionized hydrogen
Coronal gas, Hot Ionized Medium (HIM)	30-70%	10^6 - 10^7	10^{-4} - 10^{-2}	highly ionized (halo)

Is ISM a **vacuum**?

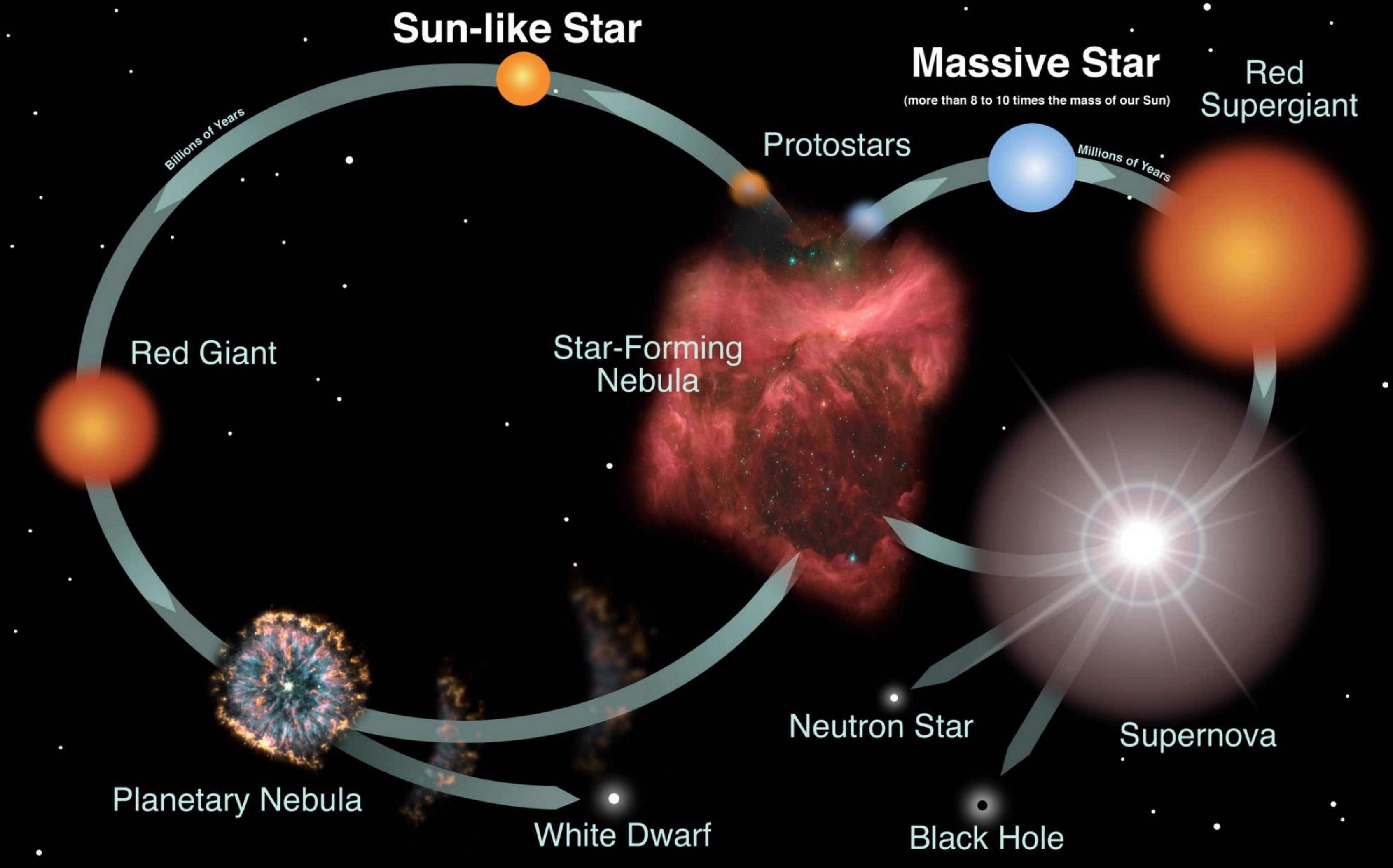
- Vacuum = mean free path l larger than the system size L: $l > L$

- Laboratory lamp: n=10^{12} cm^{-3}, $l = 1/(n\ \sigma)$, σ= 10^{-15} cm^2 , l = 10 m.
  For the lamp size $L \approx$ 1 m, it is vacuum!

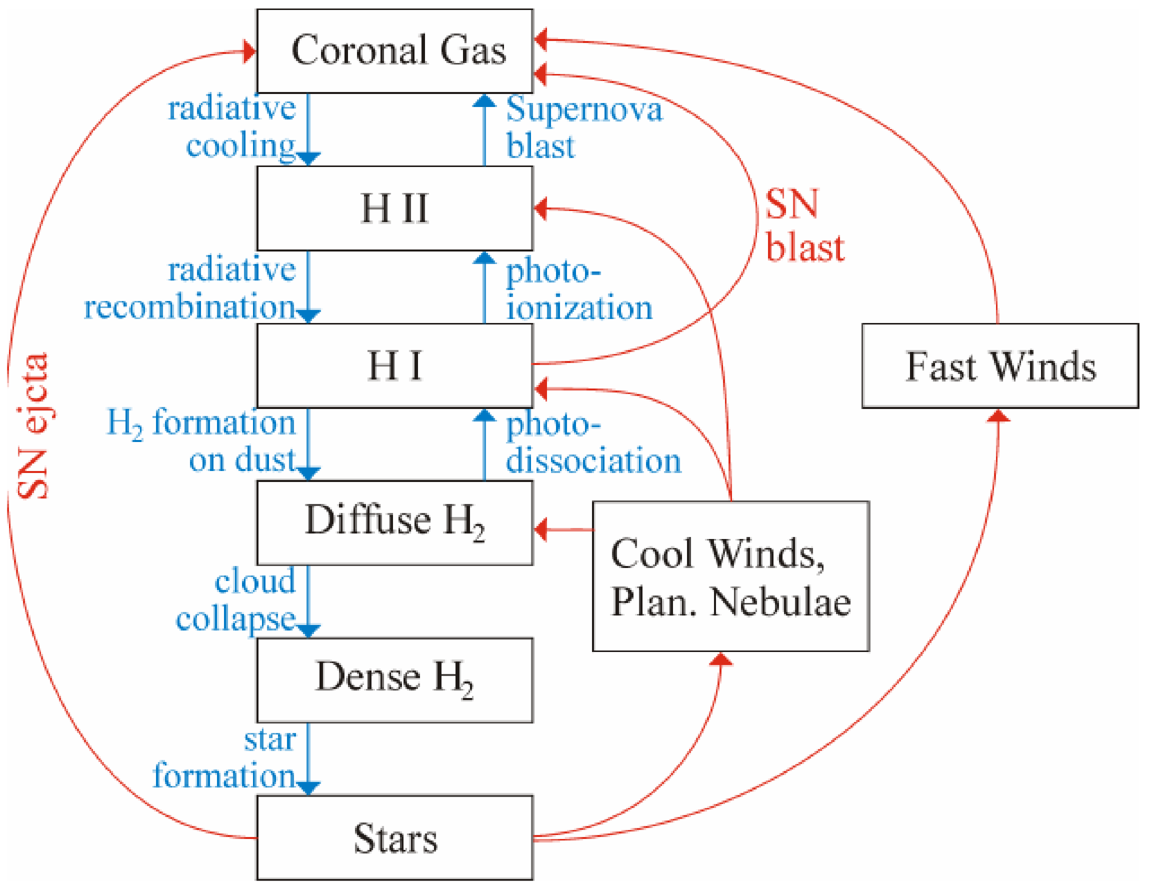
- ISM: n=1 cm^{-3}, l =10^{15} cm=3×10^{-4} pc, L=200 pc.
  $l \ll L$ => **NOT** a vacuum!

  One can apply gas-dynamics laws:
  - The distribution of velocities remains generally Maxwellian and described by a kinetic temperature on scales greater than a mean free path.
  - There are e.g. shock waves.

Phase transitions



Phase transitions



Star formation?

- Earlier (lecture 13) we introduced the concept of the Jeans Mass, the mass required for gravitational collapse to occur:

$$M_J = \left(\frac{\Re}{\mu G}\right)^{3/2} \left(\frac{3}{4\pi}\right)^{1/2} T^{3/2} \rho^{-1/2}$$

- With more convenient for us units it can be written as

$$M_J = 2.3 M_\odot \left(\frac{T}{10\ \mathrm{K}}\right)^{3/2} \left(\frac{n}{10^5\ \mathrm{cm}^{-3}}\right)^{-1/2}$$

- Given the density and temperature of various stages of the ISM, we can calculate the Jeans mass in each phase. We can see why stars form in the molecular (H_2) regions, in which M_J is of the order of a few tens $M_\odot$. **Calculate** M_J for other phases of the IMS and you will see that in H_2 regions it is much less than even in neutral hydrogen gas (> a few hundred $M_\odot$).
- Once the Jeans mass has been reached and gravitational collapse sets in, both n and T will increase in the cloud. These have competing effects: increasing n will tend to decrease the Jeans mass, while increasing T will increase the Jeans mass.
- If "density wins" and the net effect is a decrease in M_J, the large collapsing cloud will then be able to collapse on much smaller scales: the cloud fragments, and the result is multiple collapsing objects. If the collapsing object can no longer easily cool, then it has likely become a protostar. We discussed it in lecture 13.

Summary

So, in the ISM we see:

- Dark clouds of dust
- Emission nebulae, star-forming regions
- Globules
- Protoplanetary disks
- Planetary nebulae
- Supernova remnants
- Radiation
- Cosmic rays
- Magnetic fields

In order to understand the physics of interstellar medium we need:

- Radiative transfer
- Atomic and molecular physics (microphysics):
  - cooling and heating
- Gasdynamics (macro-physics):
  - motions of ISM gases
  - shock fronts
  - ionization fronts
  - stellar winds
  - explosions