Modern Astronomy

Part 1. Interstellar Medium (ISM)

Lecture 1
2026 March 4 (Monday), 9AM
updated on 02/23

선광일 (Kwangil Seon)
UST / KASI

Professors & Classroom

Professors:

1- 4th weeks: Prof. Seon, Kwangil (선광일, kiseon@kasi.re.kr)

5- 8th weeks: Prof. Yun, Youngjoo (윤영주, yjyun@kasi.re.kr)

9-12th weeks: Prof. Lee, Sang-Sung (이상성, sslee@kasi.re.kr)

13-16th weeks: Prof. Hong, Sungwook (홍성욱, swhong@kasi.re.kr)

Day & Time:

Wednesday 9-12AM

Classroom:

이원철홀(LWC) 320 : 선광일 / 홍성욱

장영실홀(JYS)/세종홀(SJH) : 윤영주 / 이상성

Syllabus

Week	Date	
1	03-04	Introduction / Interstellar Medium (ISM)
2	03-11	Atomic Gas / Multiphase Medium
3	03-18	Molecular Clouds and Dust
4	03-25	Formation of Stars and Planets
5	04-01	Stars: The Hertzsprung-Russell Diagram
6	04–08	The Evolution of Stars
7	04-15	Star Deaths
8	04-22	The Milky Way Galaxy
9	04-29	Galaxies beyond the Milky Way
10	05-06	Hubble’s Law and Distance Scale
11	05-13	Active Galaxies 1
12	05-20	Active Galaxies 2
13	05-27	Relativity and Friedmann Equation
14	06-03	Evolution of Universe and Inflation Cosmology
15	06-10	Density Pertubations and Nonlinear Structure Formation
16	06-17	Survey and Computer Simulation; Final Exam

Textbooks / Lecture Notes of Part 1

- Textbooks
  - Introduction to the Interstellar Medium (Jonathan P. Williams)
  - Fundamentals of Astrophysics (Stan Owocki)

- Other References
  - Introductory
    - Introduction to the Interstellar Medium - Jonathan P. Williams
    - The Physics of the Interstellar Medium - J. E. Dyson & D.A. Williams
  - Intermediate
    - Interstellar and Intergalactic Medium - Barbara Ryden

- Lecture Notes
    - https://seoncafe.github.io/Teaching.html

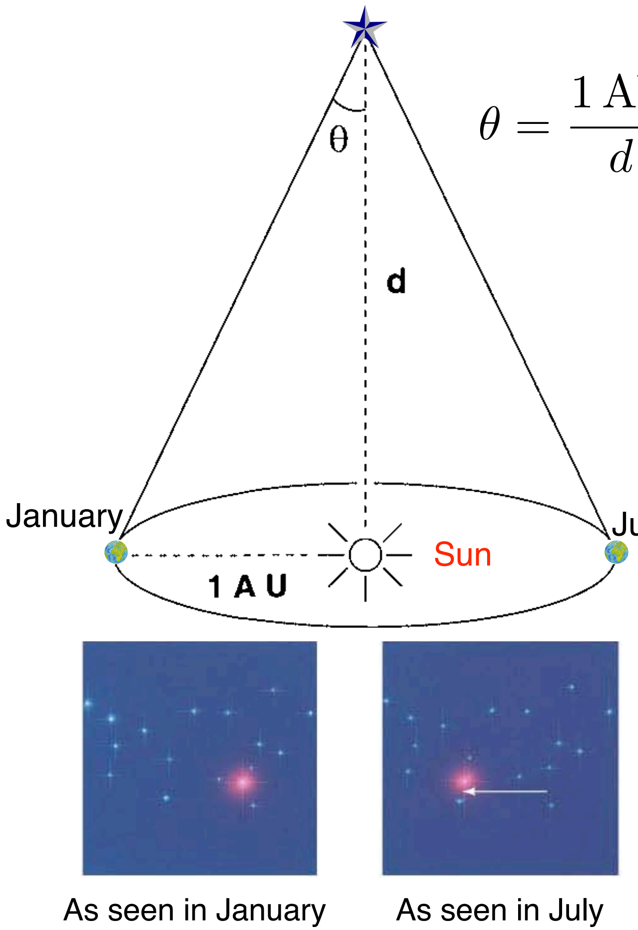
Unit of distance

- **AU (the Astronomical Unit)**: the average distance of the Earth from the Sun

$$AU = 1.50 \times 10^{11}\,\mathrm{m}$$

- ***parallax***: As the Earth goes around the Sun, the nearby stars change their positions very slightly with respect to the faraway stars. This phenomenon is known as parallax. The angle θ is half of the angle by which this star appears to shift with the annual motion of the Earth and is defined to be the parallax.

$$\theta = \frac{1\,\mathrm{AU}}{d}$$



- ***parsec (pc)***: the distance where the star has to be so that its parallax turns out to be $1''$.

$$\begin{aligned} \mathrm{pc} &= 3.09 \times 10^{16}\,\mathrm{m} \\ &= 3.26\ \text{light years} \\ &= 206{,}265\ \mathrm{AU} \end{aligned}$$

< The magnitude scale >

- For historical reasons, fluxes in the optical and infrared are measured in magnitudes.

- On the basis of naked eye observations, the Greek astronomer Hipparchus (190-120 BC) classified **all the stars into six classes** according to their apparent brightness.
  - **The brighter ones belong to the first magnitude class.** The faintest ones belong to the sixth magnitude class.

- Pogson (1856) noted that **the faintest stars visible to the naked eye are about 100 times fainter compared to the brightest stars.**
  - The brightest and faintest stars differ by five magnitude classes.
  - Therefore, stars in two successive classes should differ in apparent brightness by a factor $100^{1/5}$.

- Note that the human eye is more sensitive to a geometric progression ($I_0, 2I_0, 4I_0, 8I_0, \cdots$) of intensity rather than an arithmetic progression ($I_0, 2I_0, 3I_0, 4I_0, \cdots$). In other words, ***the apparent magnitude as perceived by the human eye scales roughly logarithmically with the radiation flux.***

- Suppose two stars have apparent brightnesses F_1 and F_2 and their magnitude classes are m_1 and m_2.

$$\frac{F_2}{F_1} = (100)^{\frac{1}{5}(m_1 - m_2)}.$$

- Then, on taking the logarithm of this, we find

$$m_1 - m_2 = 2.5 \log_{10}\left(\frac{F_2}{F_1}\right).$$

- This is the definition of ***apparent magnitude*** denoted by m, which is a measure of the apparent brightness of an object in the sky.
  - Note that the magnitude scale is defined in such a fashion that ***a fainter object has a higher value of magnitude.***

magnitudes of extinction and optical depth

The observed flux is reduced by the optical depth exponential absorption factor. The level of this ISM absorption can also be characterized in terms of the number of magnitudes of extinction (A).

$$\boxed{F_{\rm obs} = F_0 e^{-\tau}} \qquad A \equiv m_{\rm obs} - m_0 = 2.5 \log_{10}\left(\frac{F_0}{F_{\rm obs}}\right) = 2.5\tau \log_{10} e \quad \Rightarrow \quad \boxed{A \approx 1.086\tau}$$

- We need a measure that quantifies the luminosity or intrinsic brightness of an object.
- The ***absolute magnitude*** of a celestial object is ***the magnitude it would have if it were placed at a distance of 10 pc.***
  - If the object is at a distance d pc, then $(10\,\mathrm{pc}/d)^2$ is the ratio between its apparent brightness and the brightness it would have if it were at a distance of 10 pc.

$$\frac{F(d)}{F(10\,\mathrm{pc})} = \left(\frac{10\,\mathrm{pc}}{d}\right)^2$$

  - Then, the relation between apparent magnitude m and absolute magnitude M is

$$m - M = 2.5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)^2 = 5\log_{10}\left(\frac{d}{10\,\mathrm{pc}}\right)$$

  - The difference $m - M$ is called the ***distance modulus***.

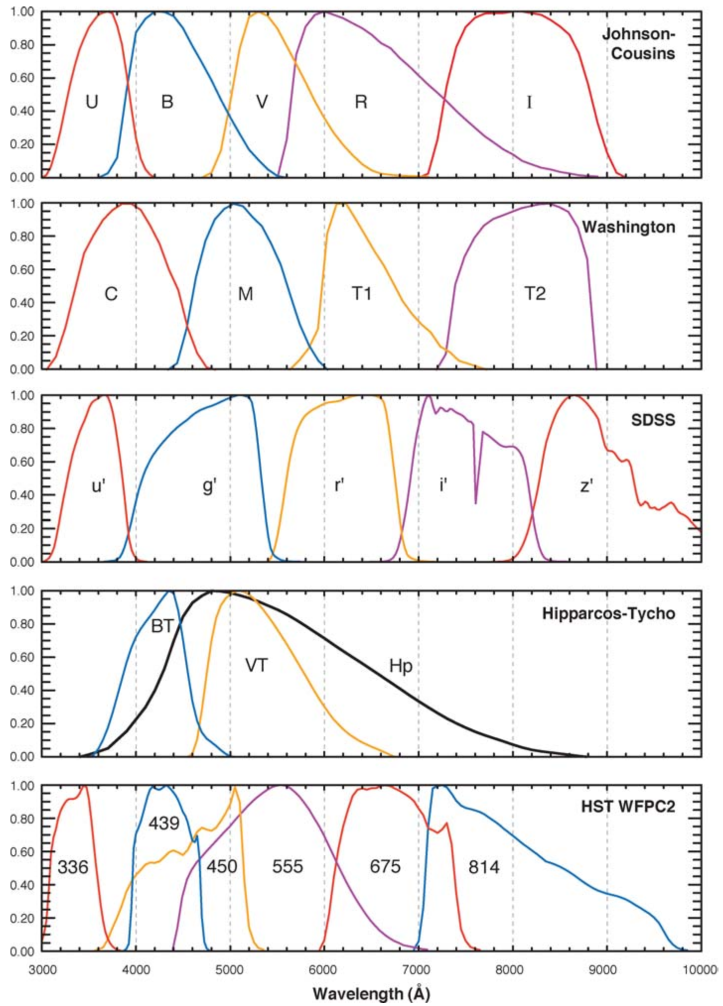
Filters and Wavebands

- Common bandpasses

Johnson system (or Johnson-Morgan system)

Filter	Effective Wavelength
U (ultraviolet)	365 nm
B (blue)	440 nm
V (visible)	551 nm
R (red)	658 nm
I (near-infrared)	806 nm
J	1220 nm
H	1630 nm
K	2190 nm

  - These are the central wavelengths of each band, which extend ~10% in wavelength to either side.
  - Magnitude at each bandpass is denoted by m_U, m_B, m_V, m_R, m_K, etc.



Bessell (2005, ARA&A)

- Zero-points in the Vega magnitude system
  - Note that the magnitude scale has been relatively defined.
  - ***The zero-points are defined such that the magnitude of a standard star (Vega) is 'zero in all wavebands.'***

Vega magnitude system

- In the Vega system, Vega's magnitude is always 0 in every passband:

$$U_{\rm Vega}=0,\;\; B_{\rm Vega}=0,\;\; V_{\rm Vega}=0,\;\; R_{\rm Vega}=0,\;\; I_{\rm Vega}=0$$

Vega does not have a flat spectral energy distribution so it doesn't make much sense to force its magnitudes to be flat.

This becomes even more problematic for UV and IR surveys (surveys outside of the optical), where Vega deviates substantially from a flat SED.

A solution is to calibrate the system using the absolute physical flux.

$\Rightarrow$This system is the AB system.

AB magnitude

- Oke & Gunn (1983) defined the AB magnitude system.

- The **monochromatic AB magnitude** is defined as follows:

$$m_{\rm AB} = -2.5\log_{10} f_\nu({\rm Jy}) + 8.90 \approx -2.5\log_{10}\left(\frac{f_\nu}{3631\,{\rm Jy}}\right)$$

$$m_{\rm AB} = -2.5\log_{10} f_\nu({\rm erg\,s^{-1}\,cm^{-2}Hz^{-1}}) - 48.60$$

Here, ${\rm Jy} = 10^{-23}{\rm erg\,s^{-1}\,cm^{-2}\,Hz^{-1}}$

- The **bandpass AB magnitude** is defined such that the zero point corresponds to a 'constant' spectral flux density of 3631 Jy at all frequencies.

$$m_{\rm AB} = -2.5\log_{10}\left[\frac{\int (f_\nu/h\nu)\,e_\nu d\nu}{\int (3631\,{\rm Jy}/h\nu)\ e_\nu d\nu}\right] = -2.5\log_{10}\left[\frac{\int f_\lambda\,\lambda e_\lambda d\lambda}{\int (c/\lambda) e_\lambda d\lambda}\right] - 48.60$$

Here, e_ν is the filter response function.
Modern systems of passbands, such as the SDSS ugriz filter system are on the AB magnitude system.

$$e_\lambda \equiv e_\nu(\nu = c/\lambda),\ f_\nu d\nu = f_\lambda d\lambda,\ (3631\,{\rm Jy})d\nu = (3631\,{\rm Jy})(c/\lambda^2)d\lambda$$

Introduction to the Interstellar Medium

What is the ISM?

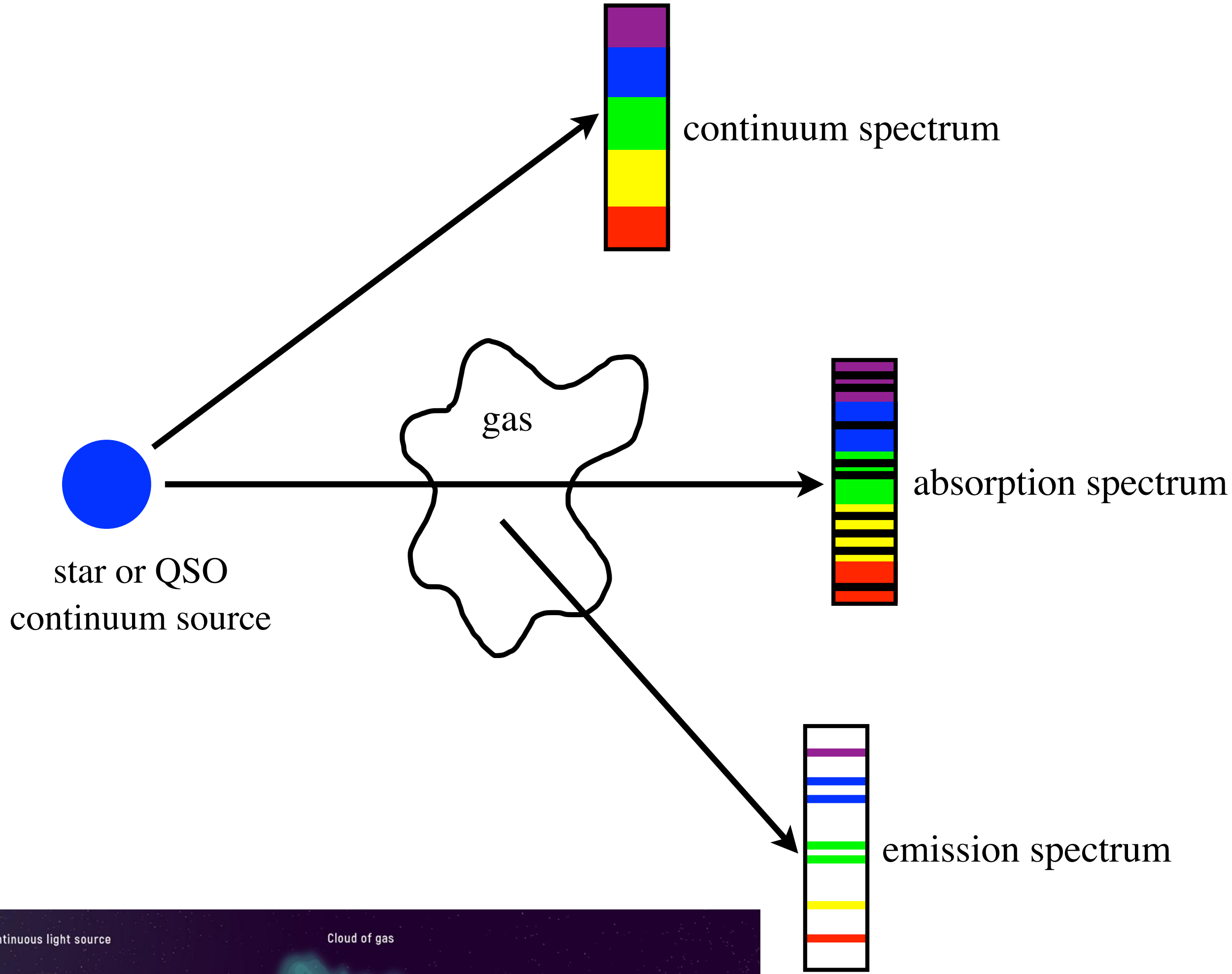
What is the ISM?

- The ISM is anything not in stars. (D. E. Osterbrock)
- Just what it says: The stuff between the stars in and around galaxies, especially our own Milky Way.
- Gas + Dust (solid particles)
  - It is made up almost entirely of gas with a tiny (solid) particles called dust grains.
  - In addition to these, the ISM includes radiation, cosmic rays, and magnetic fields.

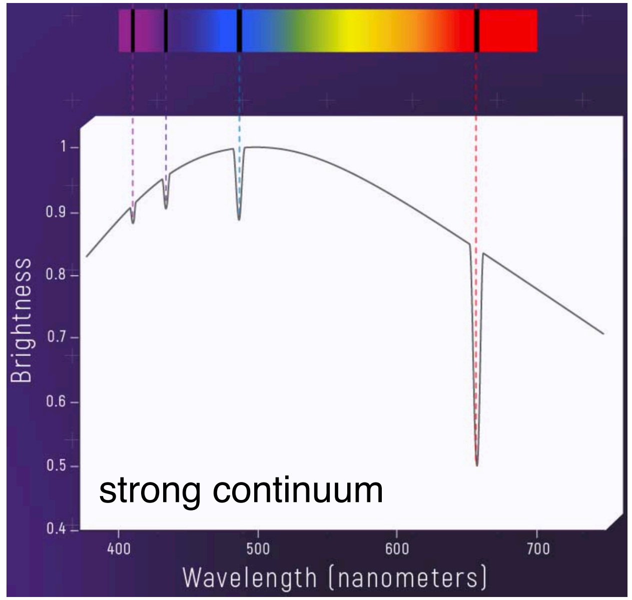
Why do we study the ISM?

- The ISM is everywhere and it affects all sorts of observations, but more often as an essential complement for understanding the Galaxy.
- The ISM is the most important component of galaxies, for it is the ISM that is responsible for forming the stars that are the dominant sources of energy.
- *The ISM is the most beautiful component of galaxies. (B. T. Draine)*
- *The ISM is beautiful, both in the literal sense, as in images of colorful nebulae, and in the physics that helps us understand our origins and the way the Universe works. (J. P. Williams)*

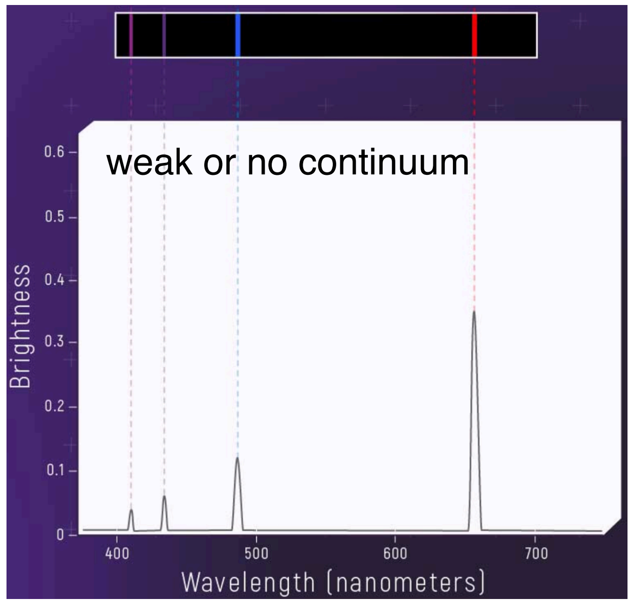
Observations of ISM: Absorption & Emission Lines

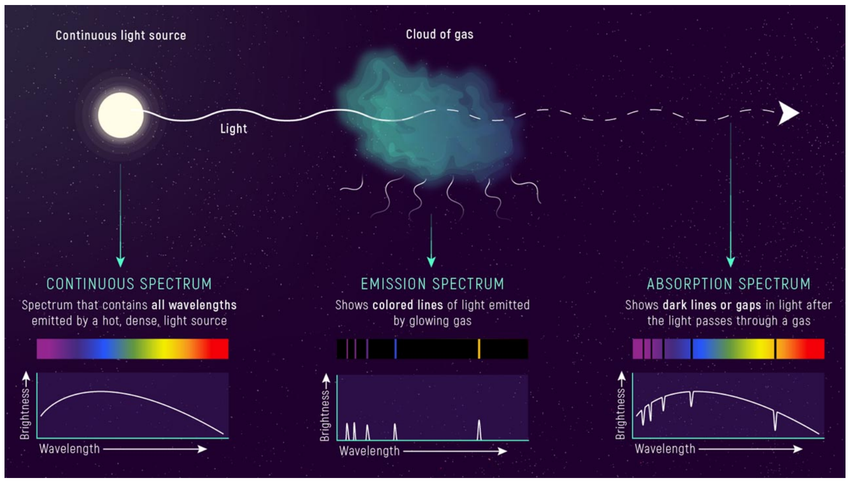


absorption lines

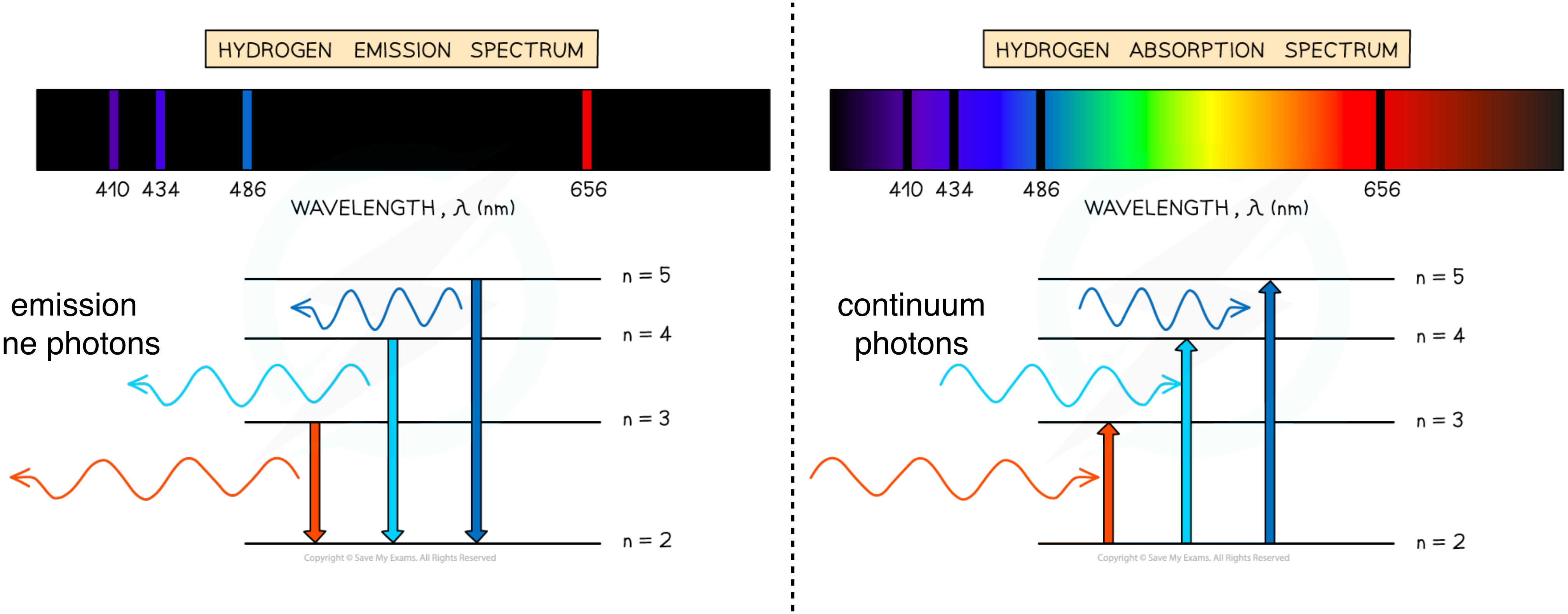


emission lines





(c) Webb Space Telescope

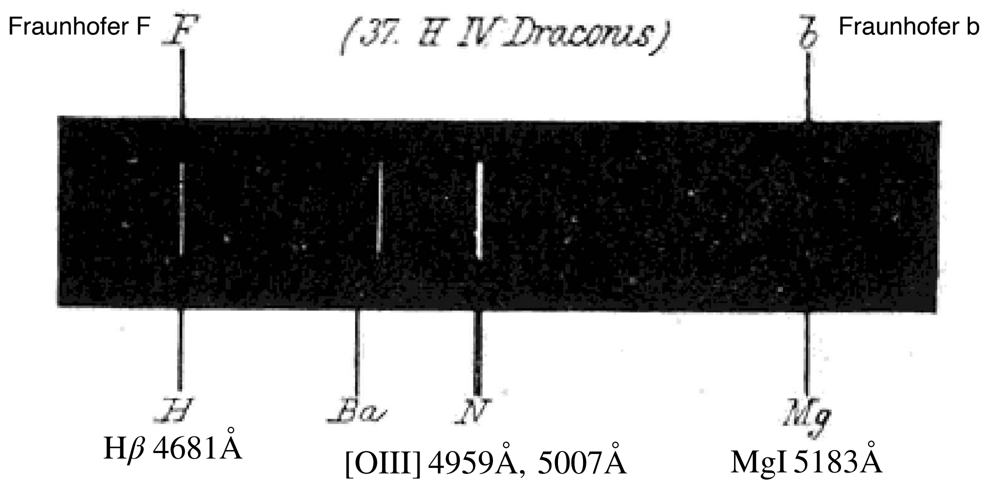


Transition	3 → 2	4 → 2	5 → 2	6 → 2
Name	Hα	Hβ	Hγ	Hδ
Wavelength (nm)	656.3	486.1	434.0	410.2
Energy (eV)	1.89	2.55	2.86	3.03
Color	Red	Cyan	Blue	Violet

History of ISM Studies

the Cat's Eye Nebula (planetary neubla/ HST image)

The first nebula spectrum: the Cat's Eye Nebula (NGC 6543; W. Huggins, 1864)



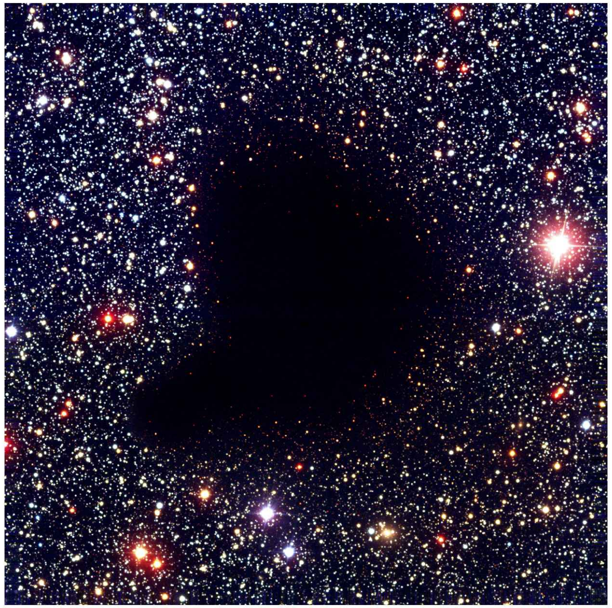
- William Herschel resolved some nebulae into stars. He thought that he had discovered star birth (it actually ejected by a dying star).
- In the 1860s, William Huggins demonstrated that some nebulae have **emission line spectra**, rather than the **absorption line spectra**.
- ***Hypothetical elements***:

***Nebula** means cloud in Latin.*

  - ✦ Huggins attributed 4959Å, observed in the Cat's Eye Nebula, to "nebulum" (or "nebulium"), and 5007Å line to Nitrogen => Ira Bowen discovered that these lines were actually forbidden [O III] lines.
  - ✦ aurorium : 5577Å in the spectrum of the aurora borealis => turned out to be [O I]
  - ✦ coronium: 5303Å in the spectrum of the Sun's corona => Fe XIV

Interstellar Dust

- The existence of dust had been hinted at by the presence of dark nebulae (Barnard 68).
    - ✦ The dark nebulae were originally thought to be due to a lack of stars, but later recognized as being clouds of obscuring material.



Barnard 68 (at $d \sim 150$ pc), in the constellation Ophiuchus.

- Vesto Slipher (1912) discovered that the spectrum of the nebula surrounding the Pleiades shows a continuum with absorption lines superposed.
    - ✦ He conjectured that this is light from stars, reflected from “fragmentary and disintegrated matter”, or dust.

The Pleiades cluster & surrounding reflection nebulae

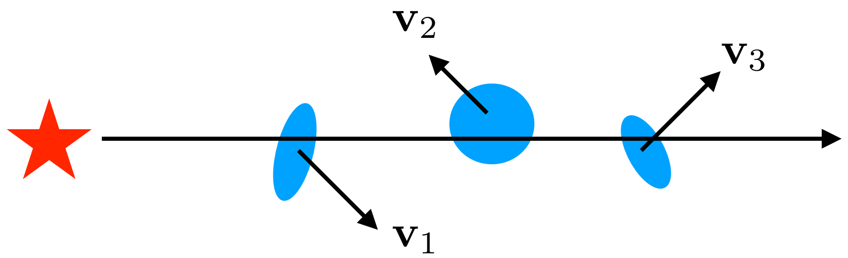
V. Slipher (/slaifer/ 1875-1969) is the first one who measured radial velocities for galaxies and discovered that distant galaxies are redshifted. He was also the first to relate these redshifts to velocity.

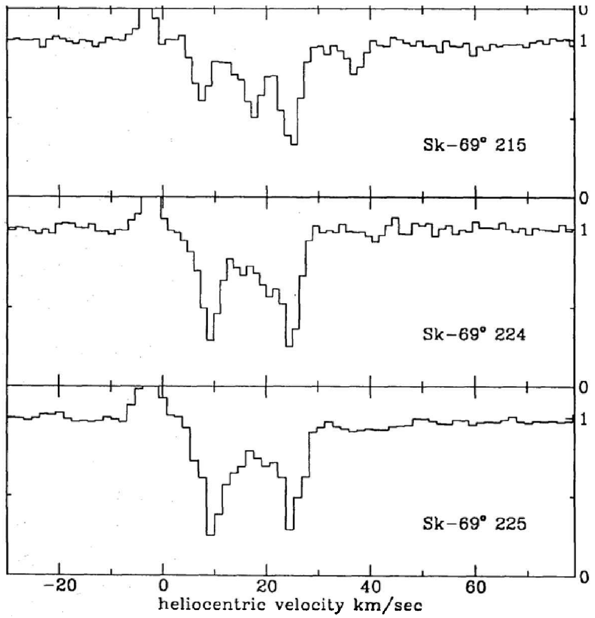
Interstellar gas that is invisible to the eye

- Initially, bright nebulae were thought of as isolated clouds in (nearly) empty space.
- In 1901, Johannes Hartmann found:
    - ✦ The spectrum of binary Delta Orionis (a spectroscopy binary system) shows a narrow calcium absorption line (at $\lambda 3934$) that is in **stationary** in addition to the **time-varying**, broad absorption lines due to the orbital motion of the stars
    - ✦ The stationary Ca absorption line was caused by a gas cloud somewhere along the line of sight to Delta Orionis.
- Later, similar "stationary lines" were found along the sightlines to many other bright stars.
    - ✦ The lines were all narrow, and had strengths correlated with the distance to the background star.
    - ✦ Using higher resolution spectrographs, they had been revealed to have complex structures, consisting of many narrower lines with different radial velocities.
    - ✦ This led to the realization that the ISM has a complex structure, consisting neither of smooth uniform gas nor of isolated blobs drifting about in a near-vacuum.

Observations of Absorption Lines

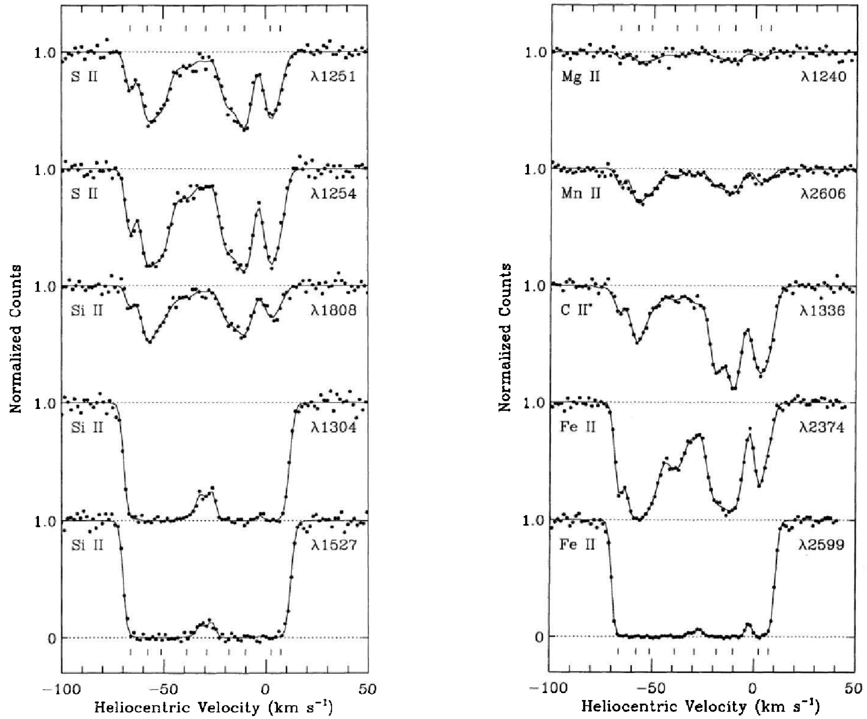
- Neutral medium gives rise to a number of absorption features in the spectra of hot background stars (and quasars).
  - The most prominent absorption lines at visible wavelengths are Ca II K and H lines at $\lambda = 3933, 3968\ \text{Å}$, and Na I D_1 and D_2 doublet lines at $\lambda = 5890, 5896\ \text{Å}$.





Na I D_2 interstellar absorption line seen along 3 lines of sight to stars in LMC (Molaro et al. 1993)

[Note] The cold gas is ~100 pc away from Earth, meaning that 5 arcmin corresponds to ~ 0.15 pc.



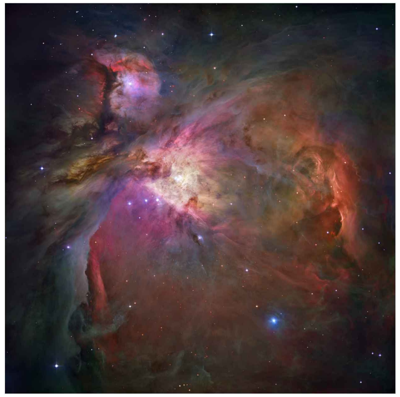
UV interstellar absorption lines toward an O-type star HD93521. (Spitzer & Fitzpatrick 1993)

[Note] (1) multiple velocity components and (2) line saturation on Si II and Fe II.
The multiple velocities are due primarily to the differential rotation of our galaxy. (clouds at different distances)

Diversity of the ISM

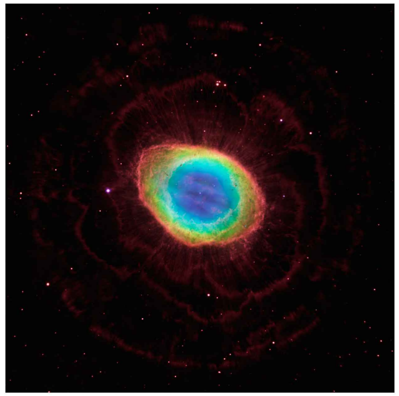
Ionized nebulae

- H II regions
  - are regions of interstellar gas heated and photoionized by embedded O or B-type stars with $T_{\rm eff} > 25{,}000\,{\rm K}$.
  - In 1939, Bengt Stromgren developed the idea that bright nebulae with strong emission lines are regions of photoionized gas, surrounding hot star or other source of ionizing photons.
  - ex) Orion Nebula
- Planetary nebulae
  - are regions of ejected stellar gas heated and photoionized by the hot remnant stellar core, which is becoming a white dwarf.
  - ex) Ring Nebula, Cat's Eye Nebula
  - Ring Nebula:
    - ✦ central region: blue color, from He II 4686.
    - ✦ middle region: blue-green colors from [O III] 4959, 5007
    - ✦ outer reddish colors from Hα 6563, [N II] 6548, 6583



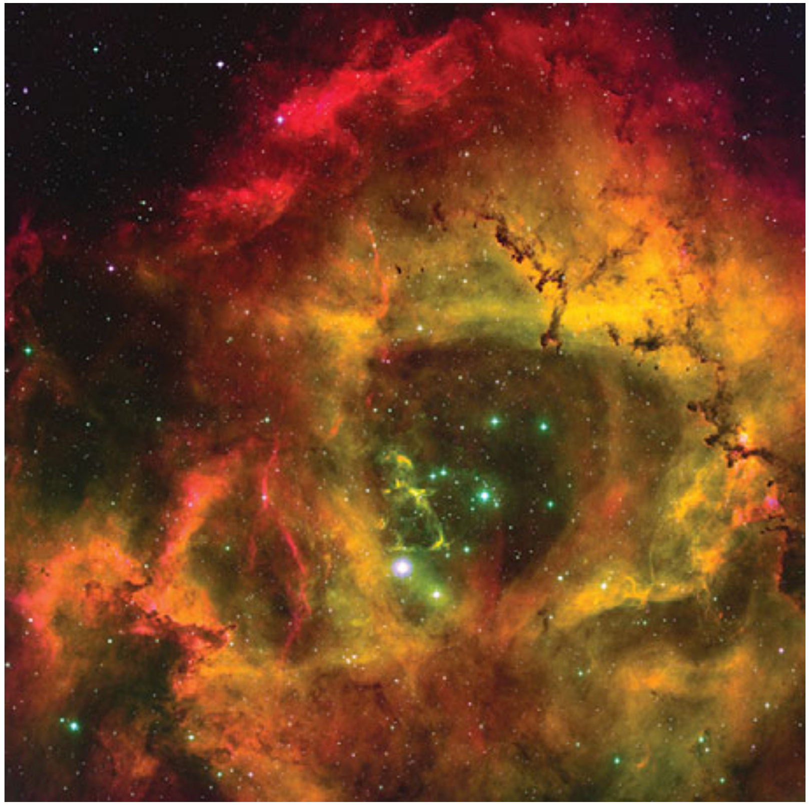
Orion Nebula (d ~ 410 pc)
HST image

Cat's Eye Nebula (HST image)



Ring Nebula (HST image)

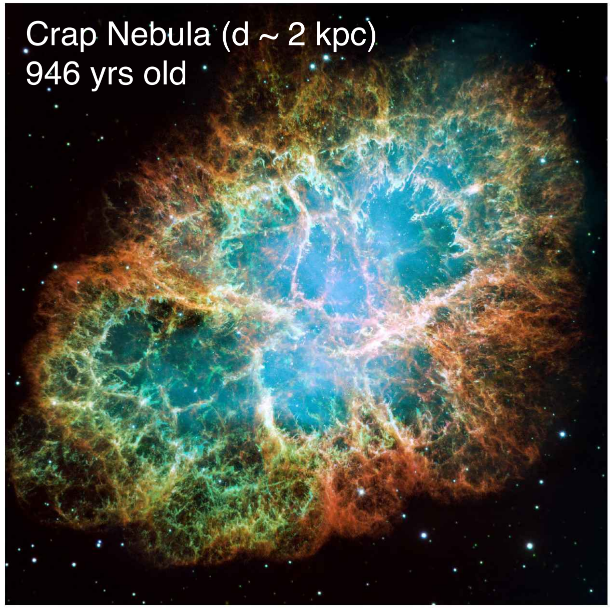
H II regions

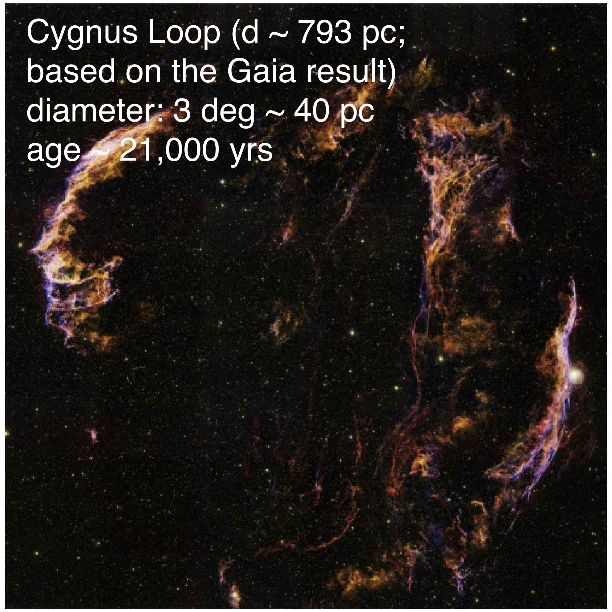


[Left] True-color optical image of the Rosetta Nebula. The reddish glow is from Hα line emission from recombination of the ionized hydrogen. The central cavity has been evacuated by the strong, high-speed stellar winds from the central cluster of hot stars.

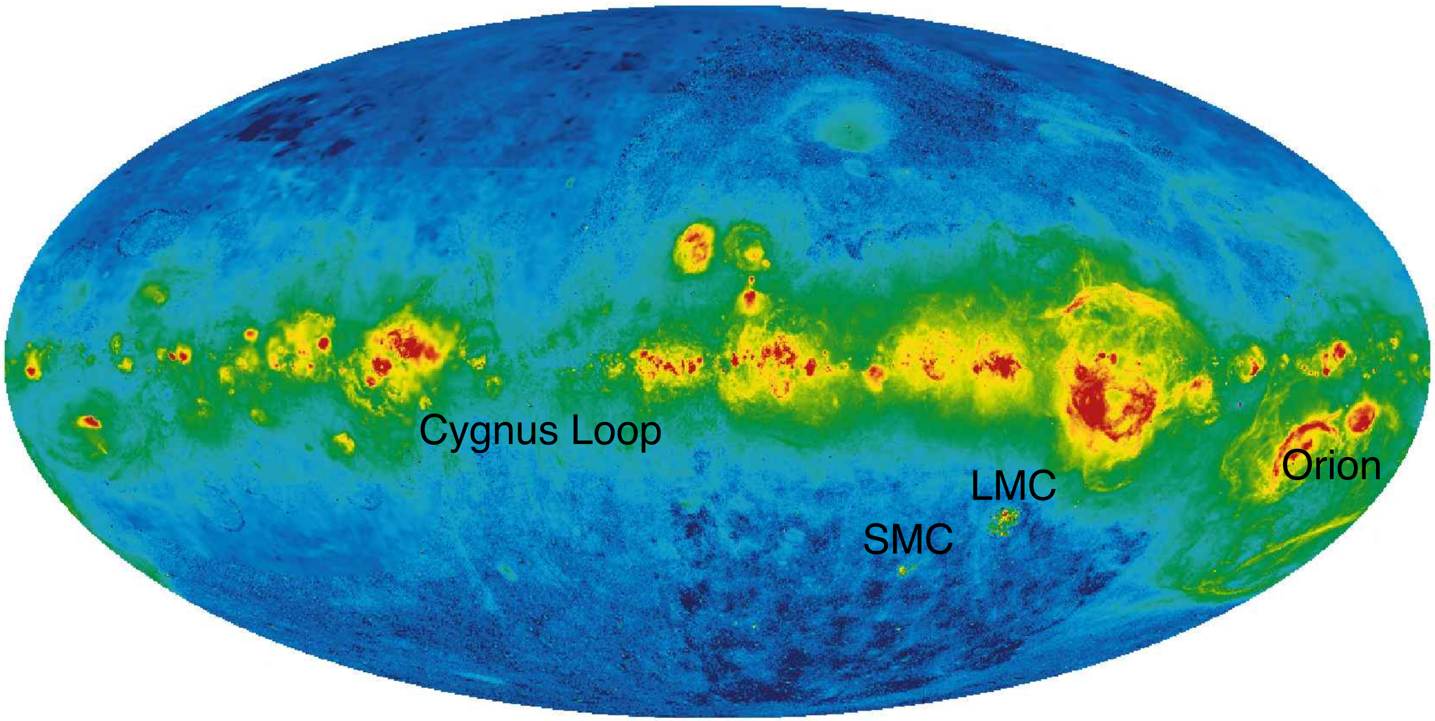
[Right] Composite false-color image showing the emission in Hα (red), and lines of [O III] (green) and [S II] (blue). Credit: NASA/HST [Owocki]

- Supernova remnants
  - are regions of gas heated by the blastwave from a supernova explosion.
  - Crab Nebula
    - ✦ a young ($t \sim 1000$ yr) pulsar-containing supernova remnant
    - ✦ are filled in with luminous gas.
    - ✦ are photoionized by its central pulsar.
    - ✦ are sometimes called `plerions' meaning "full."
  - Cygnus Loop (Veil Nebula)
    - ✦ most of the gas has been plowed up by the blast wave, leaving the center part empty.
    - ✦ The visible loop (or veil) is where the gas has cooled to T ~ 10,000 K.
    - ✦ is a middle-aged supernova remnant ($t \sim 10^4$ yr).





- Warm Ionized Medium (Diffuse Ionized Gas)
  - About 20-80% of the ionized hydrogen in our galaxy lies in the relatively low density WIM.
  - Balmer line emission from recombining hydrogen fills the entire sky.
  - Although many ionized nebula (Orion, Crab, Cat's eye, etc) can be seen as the bright red blotches, they are not the dominant repository of recombining hydrogen in our galaxy.



All-sky map of Hα (6563Å) in a log scale from 0.03 Ry to 160 Ry.
Ry (rayleigh) = $10^6/4\pi$ photons cm^{-2} s^{-1} Hz^{-1} sr^{-1}

- Neutral Hydrogen Gas
  - All-sky map of H I 21-cm line intensity from the LAB survey (Kalberla et al. 2005), with an angular resolution ~ 0.6 deg.
  - Scale gives $\log_{10}$ N(H I) [cm^{-2}]. The LMC and SMC are visible, with a connecting H I "bridge".

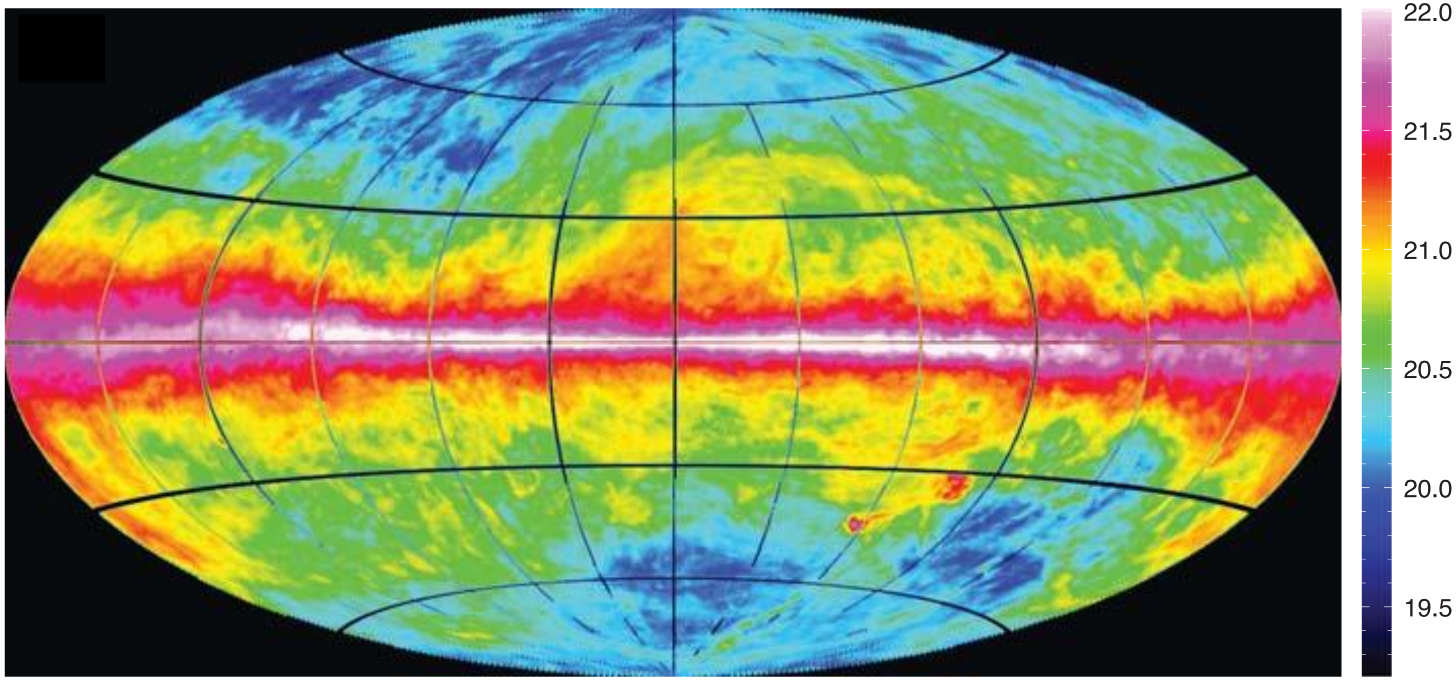


Plate 3 in [Draine]

column density = total amount of matter along a specific line of sight, expressed as the number of particles per unit area

$$\boxed{N = \int n d\ell \quad [\mathrm{cm}^{-2}]}$$

ISM in external galaxies

[Left] HST optical image of M51 (Whirlpool galaxy).

The reddish blotches are from Hα line emission from giant H II regions, which arise when dense regions of hydrogen are photoionized by the UV radiation from numerous, recently formed, hot massive stars. Note their proximity to dark bands formed from absorption of background stellar light by cold interstellar dust, which outline the galactic spiral arms.

[Right] Composite image of M51 from 4 space missions.

X-rays (purple) detected by the Chandra X-ray Observatory reveal point-like sources (black holes and neutron stars in binary systems) as well as diffuse gas. Optical data from HST (green) and infrared emission from the Spitzer Space Telescope (red) both highlight long lanes in the spiral arms that consist of stars and gas laced with dust. UV light (blue) from GALEX comes from hot, young stars, showing how well these track the H II giants and star-forming GMCs along the spiral arms.

Credit: NASA/HST/CXO/SST/GALEX [Owocki]

Baryonic Matter

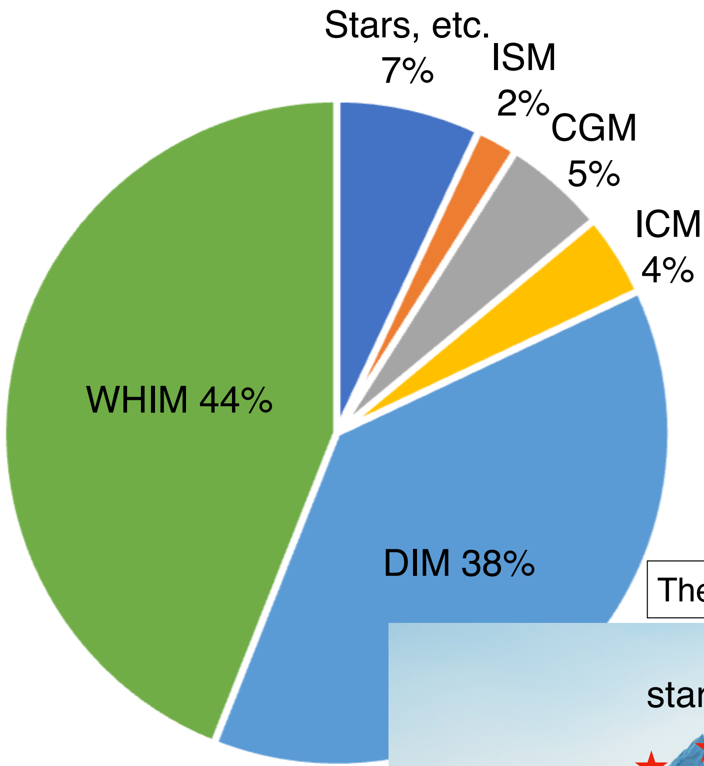
Definitions:

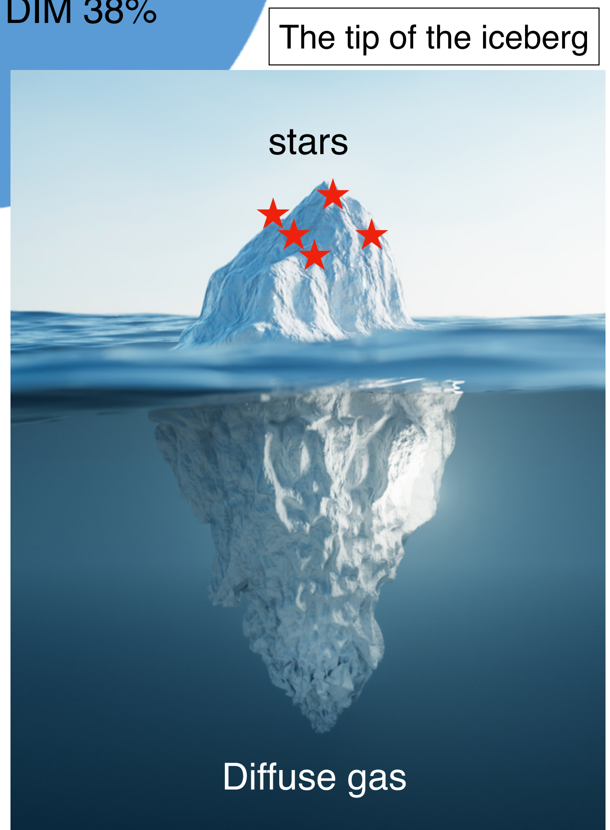
- Baryons = protons, neutrons and matter composed of them (i.e. atomic nuclei)
- Leptons = electrons, neutrinos

- In astronomy, however, the term **‘baryonic matter’** is used more loosely to refer to **matter that is made of protons, neutrons, and electrons**, since protons and neutrons are always accompanied by electrons. Neutrinos, on the other hand, are considered non-baryonic by astronomers. (Note that black holes are also included as baryonic matter.)

The baryonic mass density

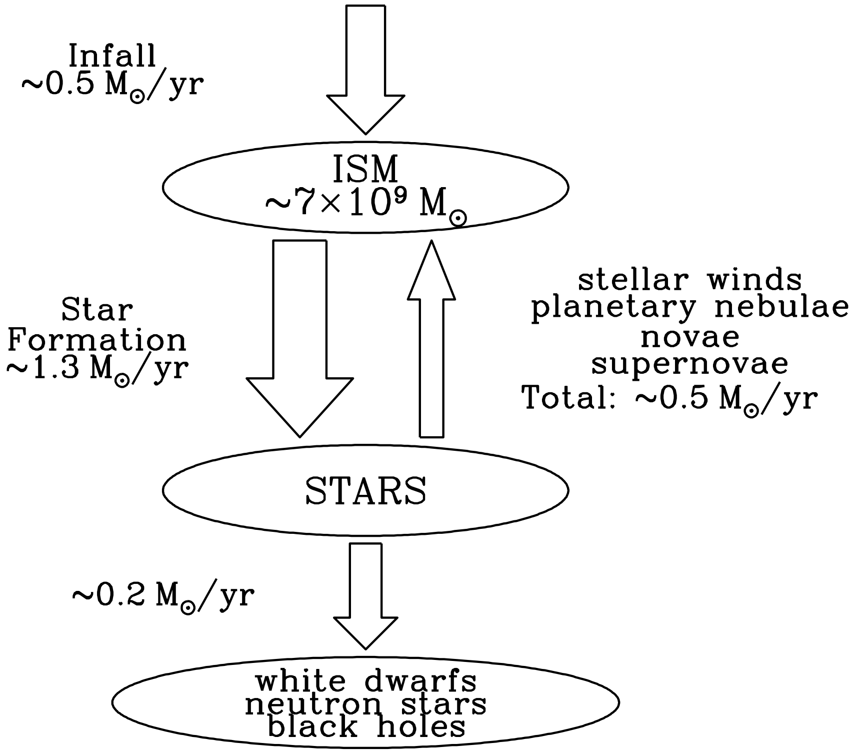
- 7% : stars + compact objects (such as stellar remnants, brown dwarfs, and planets)
- 2% : interstellar medium (ISM), filling the volume between stars.
- 5%: circumgalactic medium (CGM), bound within the dark halo of a galaxy, but outside the main distribution of stars.
- 4% : intracluster medium (ICM) of clusters of galaxies, bound to the cluster as a whole, but not to any individual galaxy.
- 38%: diffuse intergalactic medium (DIM), made of low density, mostly photo-ionized gas ($T < 10^5$ K).
- 44% : warm-hot intergalactic medium (WHIM), made of shock-heated gas ($10^5 \text{ K} < T < 10^7 \text{ K}$).





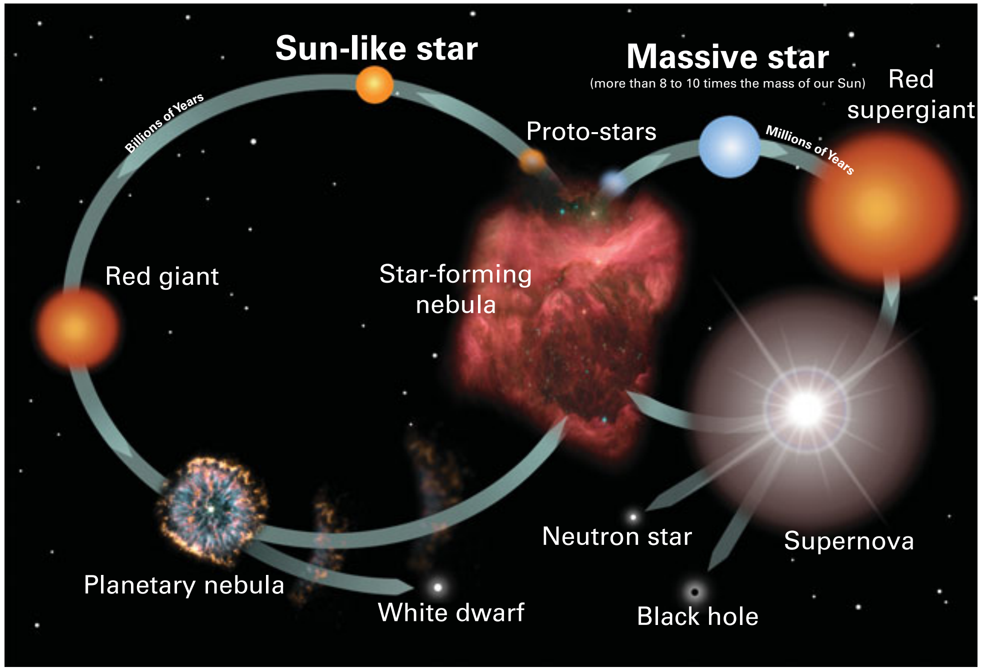
Mass flow of the baryons in galaxies

- At early times, the baryonic mass in galaxies was primarily in the gas of the ISM.
- As galaxies evolve, the ISM is gradually converted to stars, and some part of the interstellar gas may be ejected from the galaxy in the form of galactic winds, or in some cases stripped from the galaxy by the IGM.
- About 10% of the baryons in the Milky Way are to be found in the ISM.



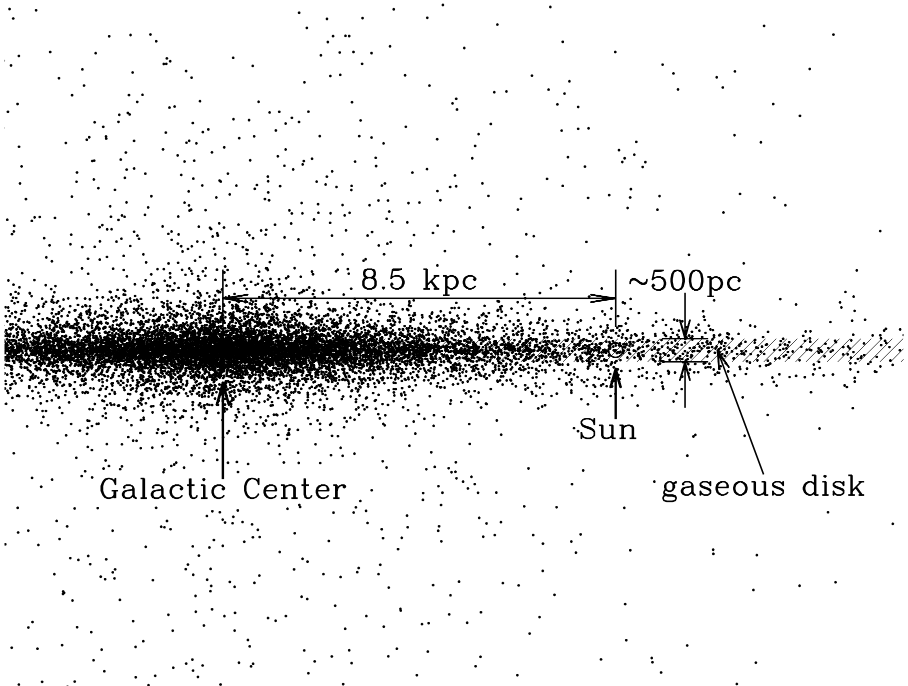
Flow of baryons in the Milky Way.

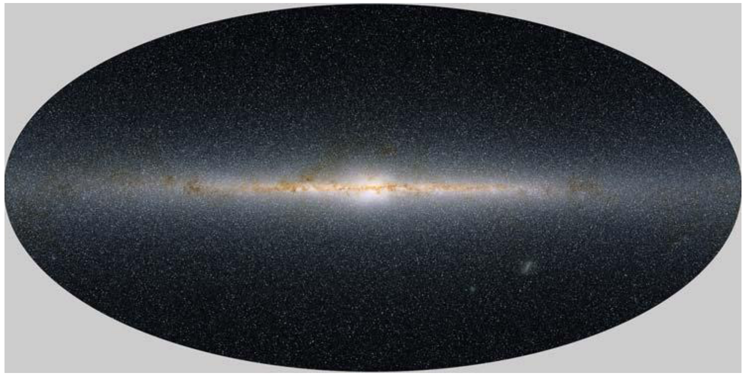
B. T. Draine



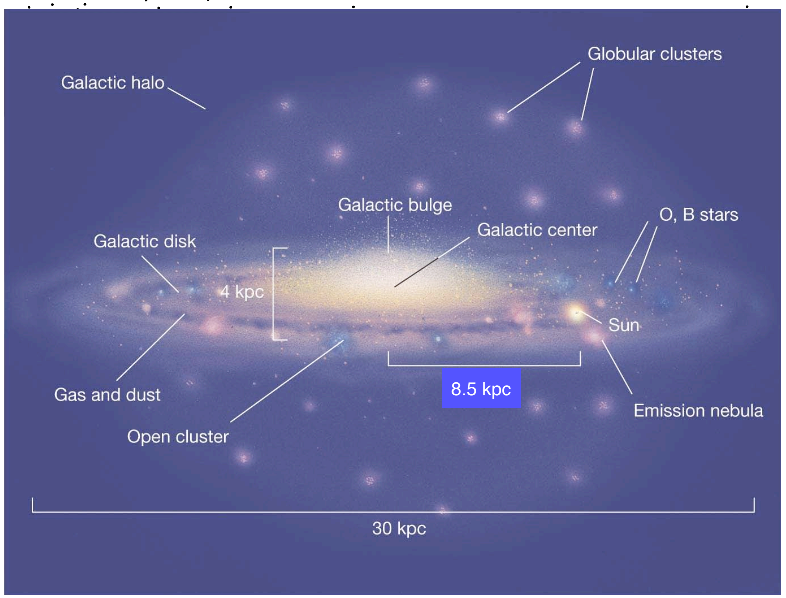
Credit: NASA, Night Sky Network

Structure of the Milky Way

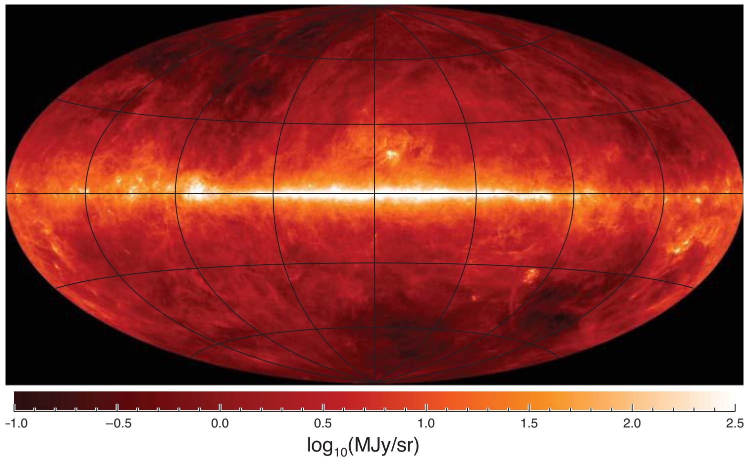




2MASS survey
$\sim 5 \times 10^8$ stars
blue = 1.2 μm
green = 1.65 μm
red = 2.2 μm



This artist's conception shows the various parts of our galaxy, and the position of our Sun.



IRAS+COBE
100 μm
dust emission

(Jansky, Jy = 10^{-23} erg s^{-1} cm^{-2} Hz^{-1})

- Total mass of the Milky Way ~ $10^{11} M_\odot$ ($M_\odot = 1.989 \times 10^{33}$g)
  - stars $\sim 5 \times 10^{10} M_\odot$
  - dark matter $\sim 5 \times 10^{10} M_\odot$
  - interstellar gas $\sim 7 \times 10^{9} M_\odot$ (mostly H + He)
    - ✦ Hydrogen mass: neutral H atoms ~ 60%, H_2 molecules ~ 20%, ionized H^+ atoms ~ 20%

Phase	$M\,(10^9\ M_\odot)$	fraction
Total H II (not including He)	1.12	23%
Total H I (not including He)	2.9	60%
Total H_2 (not including He)	0.84	17%
Total H II, H I and H_2 (not including He)	4.9	
Total gas (including He)	6.7	

Abundance of elements in the local ISM

Asplund (2009)

Element	Abundance (ppm)	Atomic number	1st ionization energy (eV)
hydrogen (H)	911,900	1	13.60
helium (He)	87,100	2	24.59
oxygen (O)	490	8	13.62
carbon (C)	270	6	11.26
neon (Ne)	85	10	21.56
nitrogen (N)	68	7	14.53
magnesium (Mg)	40	12	7.65
silicon (Si)	32	14	8.15
iron (Fe)	32	26	7.90
sulfur (S)	13	16	10.36

(ppm = parts per million)

H : 91.2% by number
He: 8.7%
others: 0.1%

- The interstellar gas is primarily H and He originating from the Big Bang.
- A small amount of heavy elements was produced as the result of the return to the ISM of gas that has been processed in stars and stellar explosions.

solar metallicity:

$$Z_\odot = M(Z > 2)/M_{\rm tot} \approx 0.013 - 0.02$$

X, Y, Z are often used to denote the mass fractions of hydrogen, helium, and metals, respectively.	Anders & Grevesse (1989)	Asplund (2009)
	$X_\odot \approx 0.70$	$X_\odot \approx 0.7380$
	$Y_\odot \approx 0.28$	$Y_\odot \approx 0.2485$
	$Z_\odot \approx 0.02$	$Z_\odot \approx 0.0134$

$$M(Z > 2)/M_{\rm H} \approx 0.02$$
$$M({\rm total})/M_{\rm H} \approx 1.40$$

Metallicity = the abundance of the elements heavier than hydrogen and helium

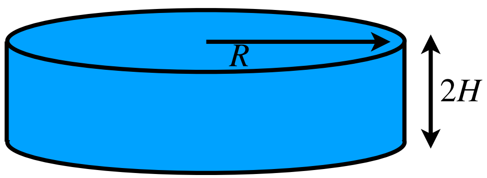
Density of the ISM

By terrestrial standards, the ISM is an almost perfect vacuum.

Let's estimate the density of the ISM.

- The typical distance between stars is ~ 2 pc = 6×10^{16} m.
  - This is ~ 100 million times greater than the solar radius and 4000 times greater than the size of its heliosphere.

- ISM density
  - Total ISM mass is $\sim 7 \times 10^9 M_\odot$.
  - Approximating the Galaxy as a cylinder with a radius $R \sim 10\,\mathrm{kpc}$ and a scale height $H \sim 250\,\mathrm{pc}$, this implies an average density



$$\rho = \frac{M}{\pi R^2 \times 2H} \approx 3 \times 10^{-21}\ \mathrm{kg\ m^{-3}}$$

$$\rho = n_\mathrm{H} m_\mathrm{H} + n_\mathrm{He} m_\mathrm{He} \approx \left(1 + \frac{1}{10} \times 4\right) n_\mathrm{H} m_\mathrm{H} \longleftarrow \begin{array}{l} n_\mathrm{He} \sim 0.1\ n_\mathrm{H} \\ m_\mathrm{He} \sim 4\ m_\mathrm{H} \end{array}$$

$$\boxed{n_\mathrm{H} \approx \frac{\rho}{1.4 m_\mathrm{H}} \simeq 1.3\ \mathrm{cm^{-3}}}$$

- Density of Air
  - From the ideal gas law using the pressure at sea level, $P = 10^5\,\mathrm{N\,m^{-2}}$ (1 bar), and temperature $T \approx 300\,\mathrm{K}$, we get

$$\boxed{n = P/k_\mathrm{B}T \approx 2.4 \times 10^{19}\ \mathrm{cm}^{-3}}$$

This density is **19 orders of magnitude higher than the average density in the ISM**.

  - The extremely low density in the ISM mean that particle collisions are relatively rare, which allows us to observe some physical processes that we don’t see on Earth (e.g., forbidden lines).

ideal gas:

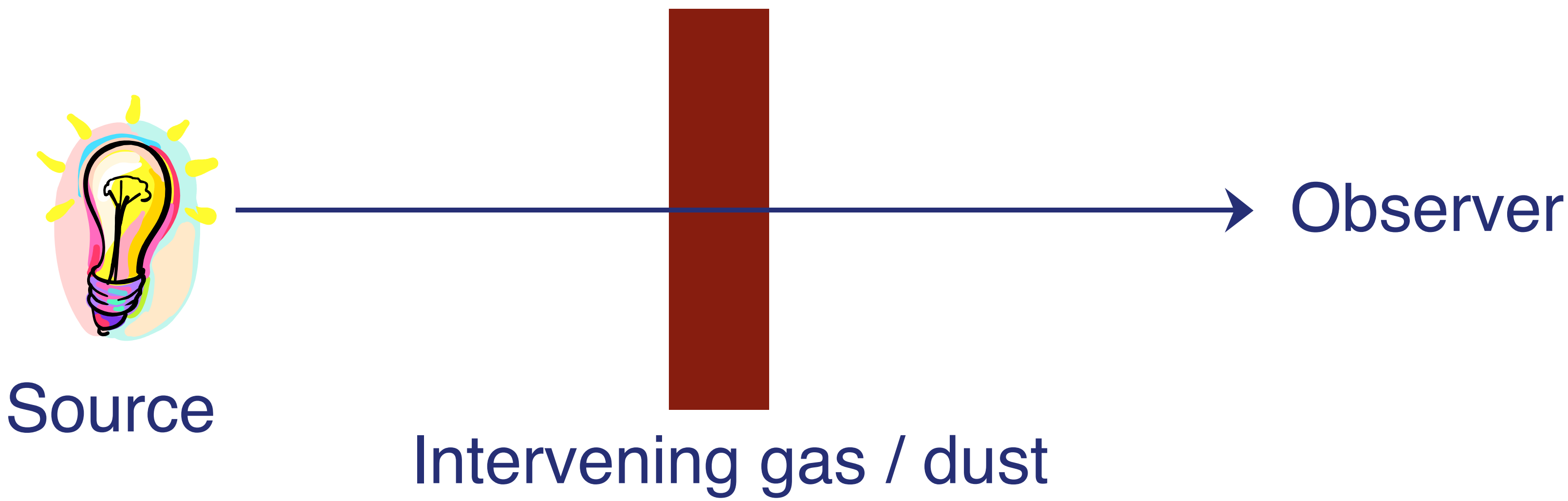
a theoretical gas composed of randomly moving, non-interacting particles with negligible volume that undergo perfectly elastic collisions.

It approximates real gases at high temperature and low pressure.

Radiative Transfer

Radiative Transfer (복사전달)

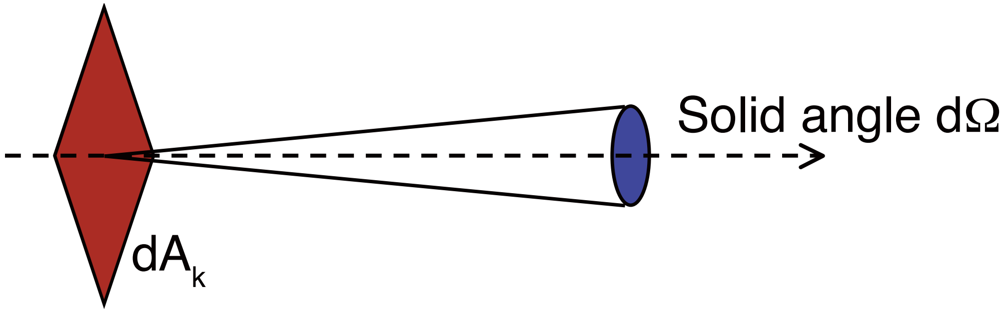
- How is radiation affected as it propagates through intervening gas and dust media to the observer?



- What we can learn?
  - gas/dust temperature, degree of ionization
  - gas kinematics (inflow, outflow)
  - elemental abundances
  - excitation sources

'Specific' Intensity (Surface Brightness)

- ***Intensity is the energy carried along by individual rays.***



$\mathbf{k}$ = direction of propagation

- Let dE_ν be the amount of radiant energy which crosses the area dA_k perpendicular to a direction $\mathbf{k}$ within solid angle $d\Omega$ about it in a time interval dt with photon frequency between ν and $\nu + d\nu$.
- The monochromatic specific intensity I_ν is then defined by the equation.

$$I_\nu(\mathbf{k}, \mathbf{x}, t) = \frac{dE_\nu}{dA_\mathrm{k} d\Omega d\nu dt}$$

- Unit: $\mathrm{erg\ s^{-1}\ cm^{-2}\ sr^{-1}\ Hz^{-1}}$

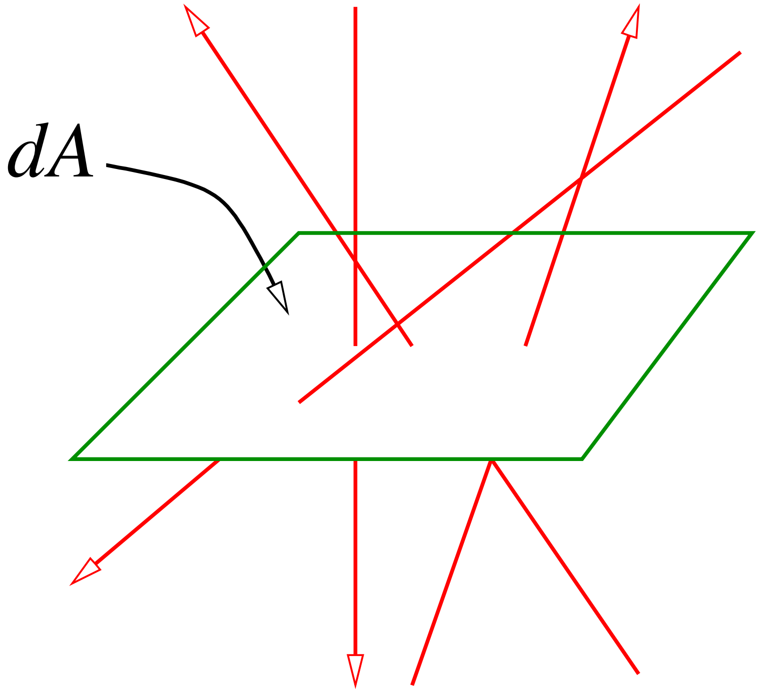
- From the view point of an observer, the specific intensity is called ***surface brightness***.

Flux 'Density'

- Definition
  - ***Flux is a measure of the energy carried by all rays passing through a given area***
  - Consider a small area dA, exposed to radiation for a time dt.
  - Flux F_ν is defined as ***the total (net) energy passing through a unit area in all directions within a unit time interval.***

$$F_\nu = \frac{dE_\nu}{dA d\nu dt}$$

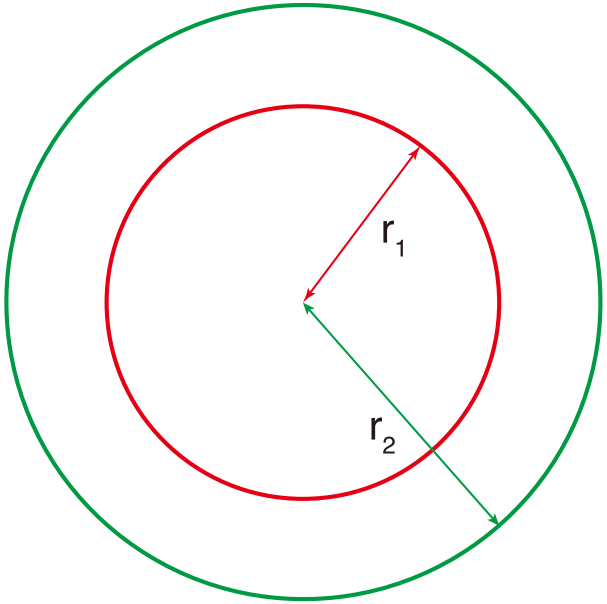
  - Note that F_ν ***depends on the orientation of the area element*** dA.
  - Unit: $\mathrm{erg\ cm^{-2}\ s^{-1}}$



- F_ν is often called the "flux density."
- Radio astronomers use a special unit to define the flux density: $1\ \mathrm{Jansky\ (Jy)} = 10^{-23}\ \mathrm{erg\ s^{-1}\ cm^{-2}\ Hz^{-1}}$

Inverse Square Law

- Flux from an isotropic radiation source, i.e., a source emitting equal amounts of energy in all directions.



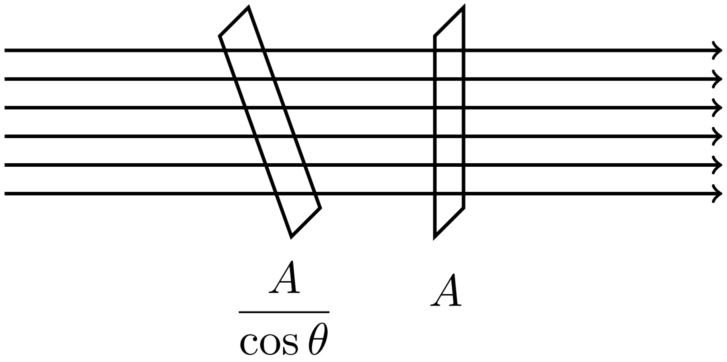
  - Because of energy conservation, flux through two shells around the source must be the same.

$$4\pi r_1^2 F(r_1) = 4\pi r_2^2 F(r_2)$$

  - Therefore, we obtain the inverse square law.

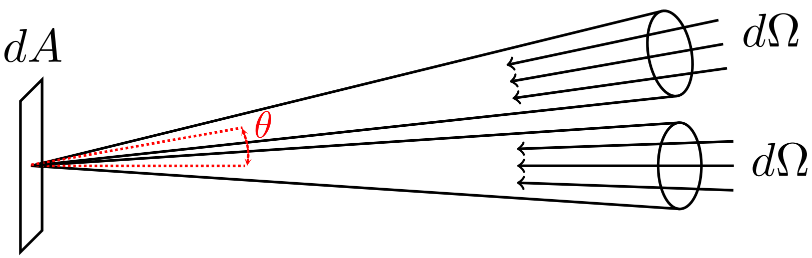
$$F = \frac{\text{const.}}{r^2}$$

Flux vs. Intensity



The power delivered to the two surfaces are equal although their areas differ.

The flux is **the power per unit area** so the tilted surface gets less flux.



Two intensities are equal.
The upper set or rays delivers less flux.

The rate that energy is delivered to a surface from light traveling around a direction θ is $I\cos\theta dA d\Omega$.

Relation between the flux density and the specific intensity

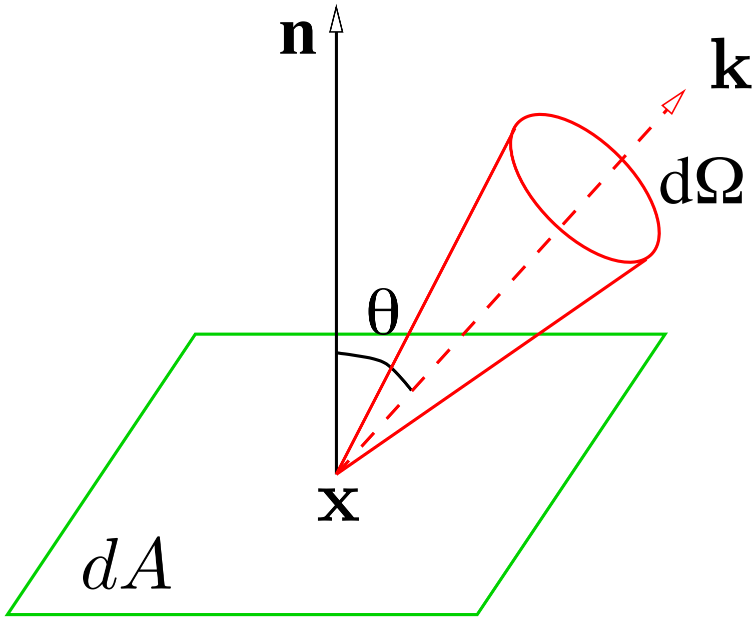
- Let's consider a small area dA, with light rays passing through it at all angles to the normal vector $\mathbf{n}$ of the surface.

- For a ray centered about $\mathbf{k}$, the area normal to $\mathbf{k}$ is

$$dA_{\mathbf{k}} = dA\cos\theta$$

  - By the definition,

$$F_\nu dA d\nu dt = \int I_\nu(\mathbf{k}, \mathbf{x}, t) dA_{\mathbf{k}} d\Omega d\nu dt$$



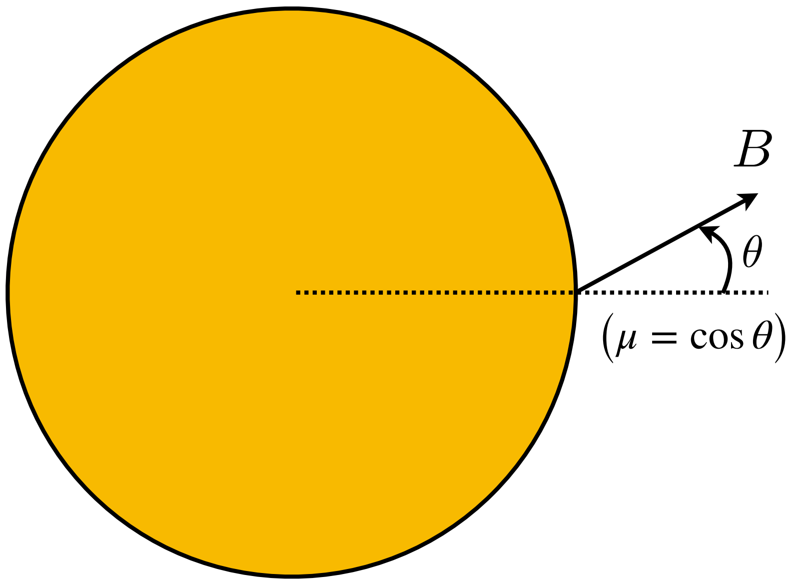
- Hence, net flux in the direction of $\mathbf{n}$ is given by integrating over all solid angles:

$$\boxed{F_\nu = \int I_\nu \cos\theta d\Omega = \int_0^{2\pi}\int_0^{\pi} I_\nu \cos\theta \sin\theta d\theta d\phi}$$

[Note] **flux** **= sum of all ray vectors projected onto a normal vector**
intensity **= absolute value of a single ray vector**

Flux from the surface of a uniformly bright sphere

- Calculate the flux at P on a sphere of uniform brightness B



$$F = \int B\cos\theta d\Omega = \int_0^1 \int_0^{2\pi} B\mu d\mu d\phi$$

$$F = \pi B$$

The total luminosity from the sphere is then

$$\boxed{L = (4\pi R^2)F = (4\pi R^2)\pi B}$$

- In stellar atmosphere, the **astrophysical flux** is defined by F/π .

Note — SED

- Intensity can be defined as per wavelength interval.

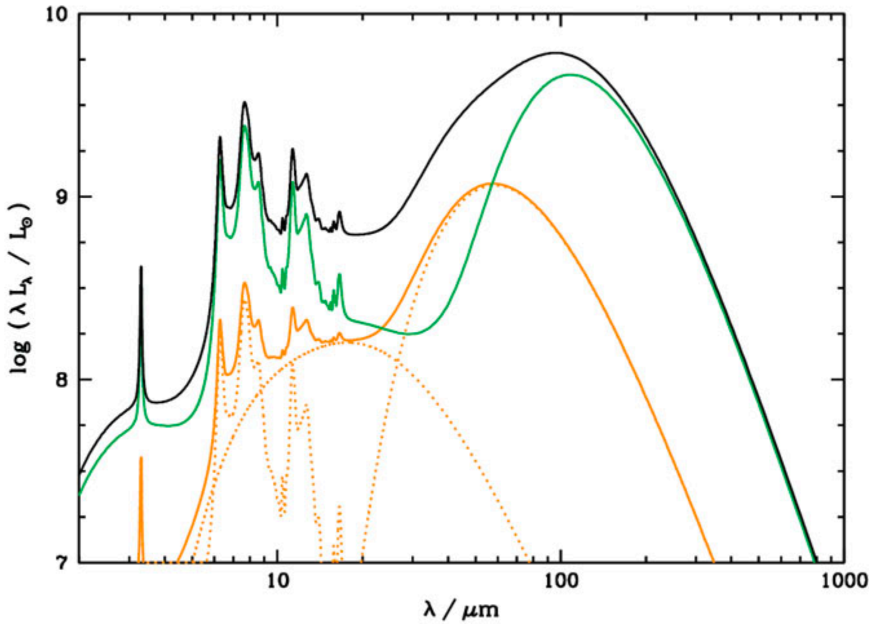
$$\begin{aligned} I_\nu |d\nu| &= I_\lambda |d\lambda| \\ \nu I_\nu &= \lambda I_\lambda \end{aligned} \quad \leftarrow \left|\frac{d\nu}{d\lambda}\right| = \frac{c}{\lambda^2} = \frac{\nu}{\lambda} \quad \longleftarrow \quad \nu = \frac{c}{\lambda}$$

- Integrated intensity is defined as the intensity over all frequencies.

$$I = \int_0^\infty I_\nu d\nu = \int_0^\infty I_\lambda d\lambda$$

- In astrophysics, we plot the ***spectral energy distribution (SED)*** as νI_ν versus ν or λI_λ versus λ.

Galaxy SEDs
da Cunha et al. (2008)



Luminosity

- To determine the energy per unit time, we integrate flux over area.
  - ***Monochromatic luminosity***: Considering a sphere centered on a source with radius *R*, the monochromatic luminosity is

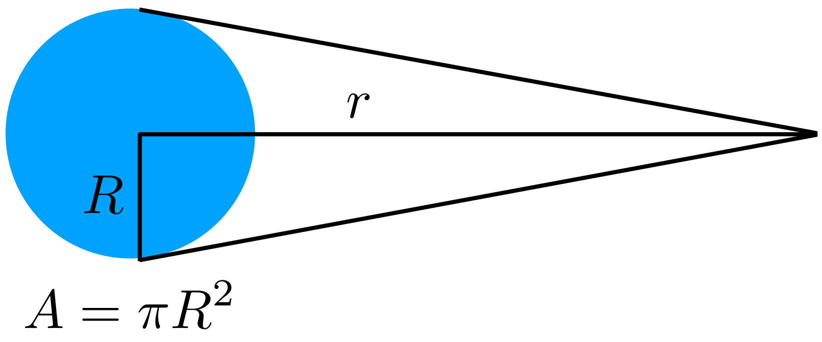
$$L_\nu = R^2 \int d\Omega F_\nu$$
$$= 4\pi R^2 F_\nu \qquad \text{for an isotropic source}$$

  - The ***bolometric luminosity*** is

$$L_{\rm bol} = \int L_\nu d\nu = \int L_\lambda d\lambda = 4\pi R^2 \int F_\nu d\nu$$

- Flux and Luminosity of an extended source

$$F = \pi I \left(\frac{R}{r}\right)^2 = I \frac{A}{r^2}$$
$$= I\Omega_{\rm source}$$
$$L = (4\pi r^2)F = (4\pi r^2) I\Omega_{\rm source}$$

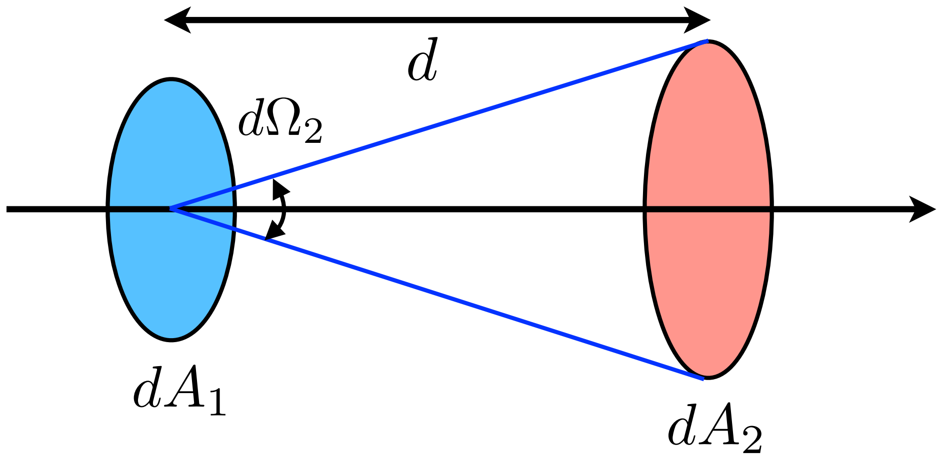


< Radiative Transfer Equation > — in free space

- How does intensity changes along a ray in free space
  - Suppose a bundle of rays and any two points along the rays and construct two "infinitesimal" areas dA_1 and dA_2 normal to the rays at these points.
  - What are the energies carried by the rays passing through both areas?

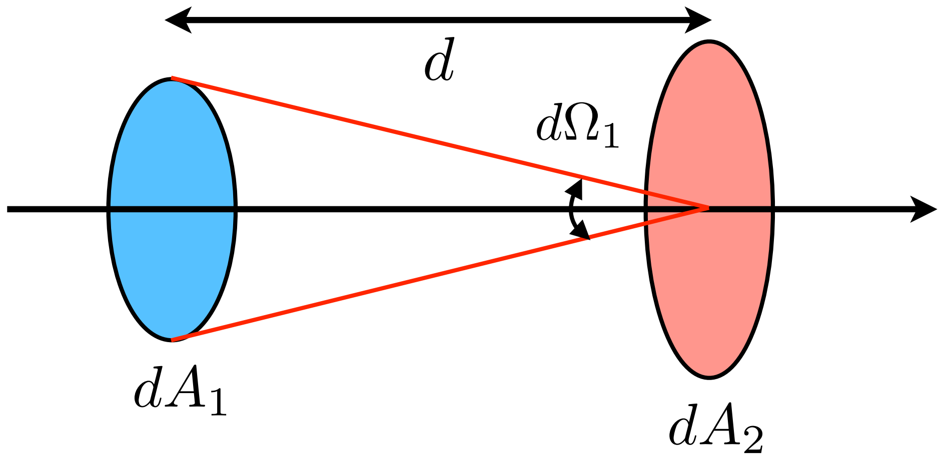
energy passing through 1

$$dE_1 = I_1 dA_1 d\Omega_2 d\nu dt$$

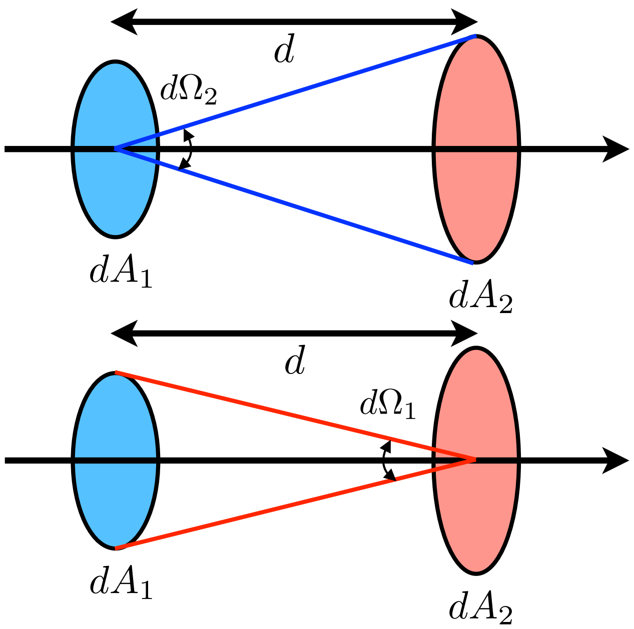


energy passing through 2

$$dE_2 = I_2 dA_2 d\Omega_1 d\nu dt$$



- Here, $d\Omega_2$ is the solid angle subtended by dA_2 at the location 1 and $d\Omega_1$ is the solid angle subtended by dA_1 at the location 2.



$$d\Omega_2 = \frac{dA_2}{d^2}$$

$$d\Omega_1 = \frac{dA_1}{d^2}$$

Conservation of energy:
Because energy is conserved,

$$dE_1 = dE_2 \quad \rightarrow \quad I_1 = I_2$$

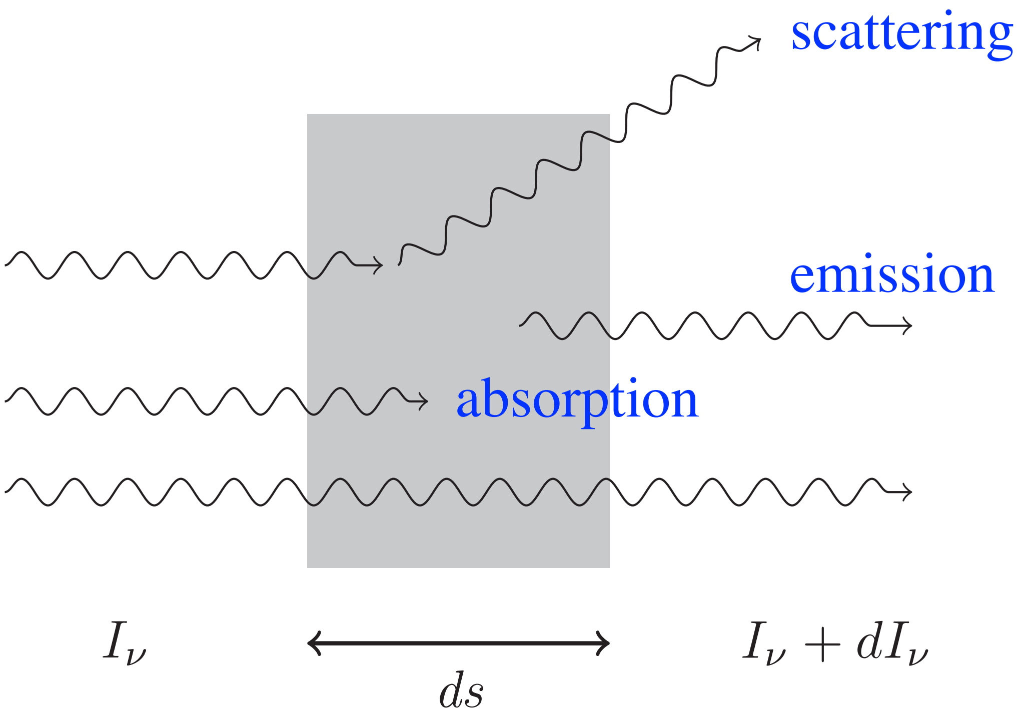
- Conclusion (***the constancy of intensity***): $I_1 = I_2 \longrightarrow \boxed{\dfrac{dI}{ds} = 0}$
    - the specific intensity remains the same as radiation propagates through free space.

- We receive the same specific intensity at the telescope as is emitted at the source.
    - Imagine looking at a uniformly lit wall and walking toward it. As you get closer, a field-of-view with fixed angular size will see a progressively smaller region of the wall, but this is exactly balanced by the inverse square law describing the spreading of the light rays from the wall.

< Radiative Transfer Equation > — Emission & Absorption

- In reality, as a ray passes through matter, energy may be added, subtracted, or scattered from it by emission, absorption, or scattering.

  - The intensity will not in general remain constant.
  - These interactions are described by the ***radiative transfer equation***.



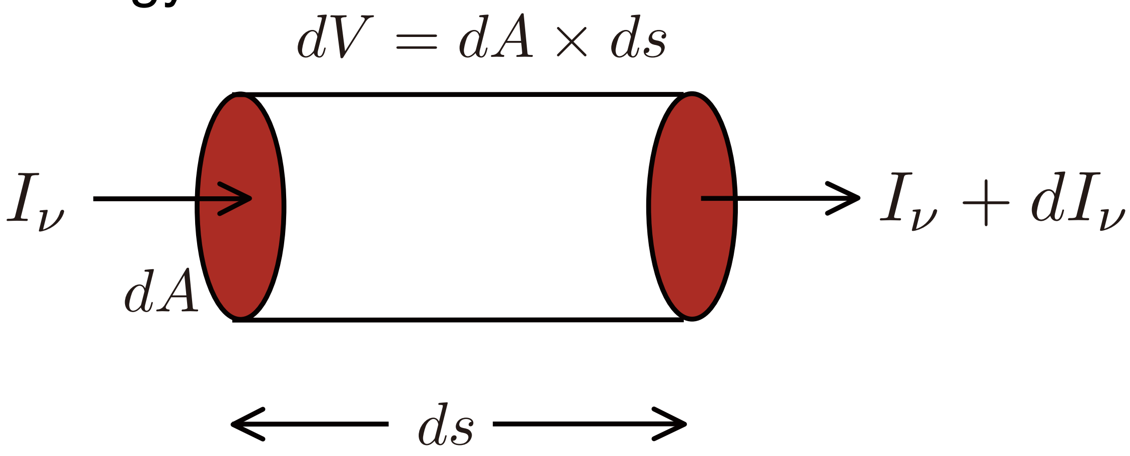
loss: scattering & absorption

gain: emission

[J. P. Williams]
Introduction to the Interstellar Medium

Emission

- If the radiation travels through a medium which is itself emitting radiation, that will add to the energy:



- Spontaneous ***"emission coefficient" or "emissivity"*** j_ν is the amount of energy emitted per unit time, per unit solid angle, per unit frequency, and per unit volume:

$$dE = j_\nu dV d\Omega dt d\nu \quad (j_\nu : \mathrm{erg\ cm^{-3}\ s^{-1}\ sr^{-1}\ Hz^{-1}})$$

- In going a distance ds, a beam of cross section dA travels through a volume $dV = dAds$. Thus the intensity added to the beam is by ds is

$$dI_\nu = j_\nu ds \quad \longleftarrow \quad dE = (dI_\nu) dA d\Omega dt d\nu$$

- Therefore, the equation of radiative transfer for pure emission becomes:

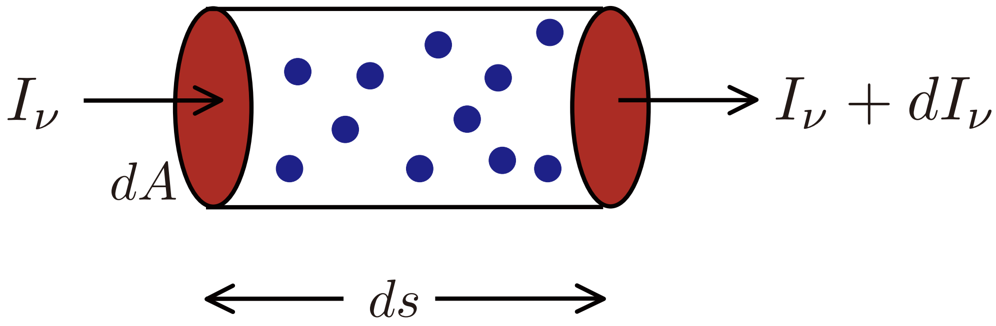
$$\frac{dI_\nu}{ds} = j_\nu$$

  - If we know what j_ν is, we can integrate this equation to find the change in specific intensity as radiation propagates through the medium:

$$I_\nu(s) = I_\nu(0) + \int_0^s j_\nu(s')ds'$$

Absorption

- If the radiation travels through a medium which absorbs radiation, the energy in the beam will be reduced:



- Let n denote the number density of absorbers (particles per unit volume).
- Assume that each absorber has a cross-sectional area of σ_ν (in units of cm^2).

'geometric' cross section: $\sigma = \pi r^2$ for a spherical particle with a radius r

- If a beam travels through ds, total area of absorbers is

$$\text{number of absorbers } \times \text{cross section} = \left(n \times dA \times ds\right) \times \sigma_\nu$$

Fraction of radiation absorbed = Fraction of area blocked

$$\frac{dI_\nu}{I_\nu} = -\frac{ndAds\sigma_\nu}{dA} = -n\sigma_\nu ds$$

$$dI_\nu = -n\sigma_\nu I_\nu ds \equiv -\alpha_\nu I_\nu ds$$

$$\longrightarrow \quad \boxed{\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu}$$

- ***Absorption coefficient*** is defined as $\alpha_\nu \equiv n\sigma_\nu$ (units: cm^{-1}), meaning the ***total cross-sectional area per unit volume***.

$$\boxed{\begin{aligned} \alpha_\nu &= n\sigma_\nu \quad [\mathrm{cm}^{-1}] \\ &= \rho\kappa_\nu \end{aligned}}$$

Here, n = number density (particles cm^{-3}),

σ_ν = cross section (cm^2 per particle),

ρ = mass density (gram cm^{-3}), and

κ_ν = **mass absorption coefficient** or **opacity coefficient** (cm^2 per gram)

Emission + Absorption

- ***Radiative transfer equation*** with both absorption and emission is

$$\frac{dI_\nu}{ds} = -\underbrace{\alpha_\nu I_\nu}_{\text{absorption}} + \underbrace{j_\nu}_{\text{emission}}$$

  - We can rewrite the radiative transfer equation using the optical depth as a measure of \`distance' rather than s:

$$\frac{dI_\nu}{\alpha_\nu ds} = -I_\nu + \frac{j_\nu}{\alpha_\nu}$$

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

Here, $S_\nu \equiv j_\nu / \alpha_\nu$ ***is called the source function***.

This is an alternative and sometimes more convenient way to write the equation.

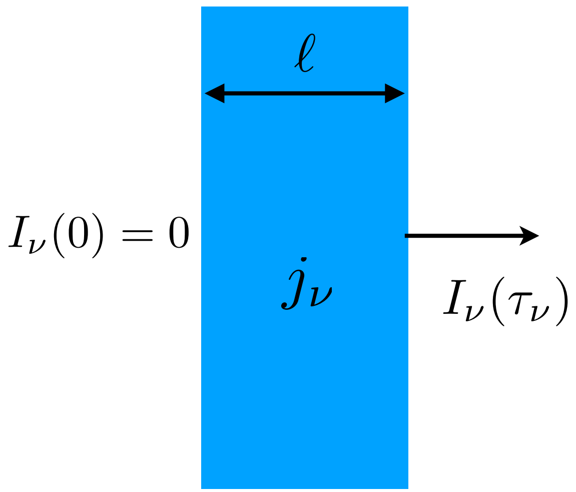
Solution: Emission Only

- For pure emission, $\alpha_\nu = 0$

$$\frac{dI_\nu}{ds} = j_\nu$$

$$I_\nu(s) = I_\nu(0) + \int_0^s j_\nu(s')ds'$$

  - The brightness increase is equal to the emission coefficient integrated along the line of sight.



$$I_\nu = j_\nu \ell$$

$$\text{if } I_\nu(0) = 0 \text{ and } j_\nu = \text{constant}$$

Solution: Absorption Only

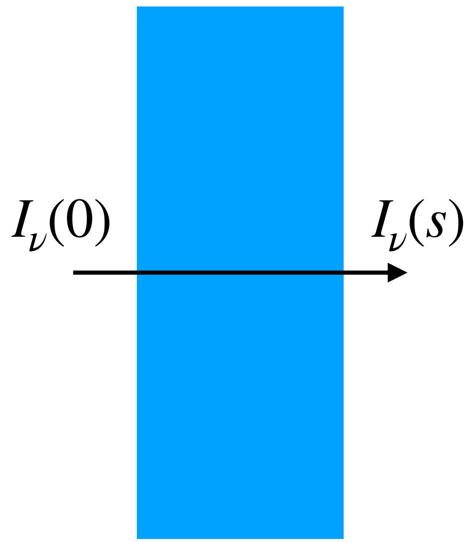
- Pure absorption: $j_\nu = 0$

  Rearranging the previous equation, we obtain the equation of radiative transfer for pure absorption:

$$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu$$

  - The amount of reduced energy depends on how much radiation we already have.
  - Integrate to find how radiation changes along path:

$$\boxed{I_\nu(s) = I_\nu(0)\exp\left[-\int_0^s \alpha_\nu(s')ds'\right]}$$



- The brightness decreases along the ray by the exponential of the absorption coefficient integrated along the line of sight.

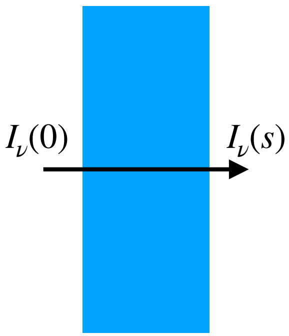
Optical Depth

- ***Optical depth***:

Imagine radiation traveling into a cloud of absorbing gas, the exponential defines a scale over which radiation is attenuated.

We define the optical depth τ_ν as:

$$\tau_\nu(s) = \int_0^s \alpha_\nu(s')ds' \quad \text{or} \quad d\tau_\nu = \alpha_\nu ds$$



Transmitted Light

$$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu}$$

Absorbed Light

$$I_\nu^{\text{abs}}(\tau_\nu) = I_\nu(0)(1 - e^{-\tau_\nu})$$

- A medium is said to be ***optically thick*** at a frequency ν if the optical depth for a typical path through the medium satisfies:

$$\tau_\nu(s) > 1 \qquad I_\nu(\tau_\nu) \to 0 \qquad I_\nu^{\text{abs}}(\tau_\nu) \to I_\nu(0)$$

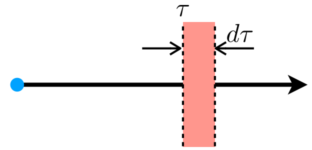
- The medium is ***optically thin*** if, instead:

$$\tau_\nu(s) < 1 \qquad I_\nu(\tau_\nu) \to I_\nu(0) \qquad I_\nu^{\text{abs}}(\tau_\nu) \to 0$$

An optically thin medium is one through which a typical photon (of frequency ν) can travel without being (significantly) absorbed.

Mean Free Path

- From the exponential absorption law, the ***probability of a photon absorbed*** between optical depths τ_ν and $\tau_\nu + d\tau_\nu$ is



$I_\nu(\tau_\nu) = I_\nu(0)e^{-\tau_\nu}$

probability = $\dfrac{|dI_\nu|}{I_\nu(0)} = \dfrac{1}{I_\nu(0)}\left|\dfrac{dI_\nu}{d\tau_\nu}\right| d\tau_\nu = e^{-\tau_\nu}d\tau_\nu \;\rightarrow\; P(\tau_\nu) = e^{-\tau_\nu}$

= **probability density function** for the absorption at an optical depth τ_ν

- The ***mean optical depth*** traveled is thus equal to unity:

$$\langle\tau_\nu\rangle = \int_0^\infty \tau_\nu P(\tau_\nu)d\tau_\nu = \int_0^\infty \tau_\nu e^{-\tau_\nu}d\tau_\nu = 1$$

- ***The mean free path is defined as the average distance a photon can travel through an absorbing material until it is absorbed.*** In a homogeneous medium, the mean free path is determined by

$$\langle\tau_\nu\rangle = \alpha_\nu \ell_{\rm mfp} = 1 \quad \rightarrow \quad \ell_{\rm mfp} = \frac{1}{\alpha_\nu} = \frac{1}{n\sigma_\nu}$$

- A local mean path at a point in an inhomogeneous material can be also defined.

- The probability of a photon being absorbed within an optical depth τ_ν is

$$\int_0^{\tau_\nu} P(\tau'_\nu)d\tau'_\nu = 1 - e^{-\tau_\nu}$$