# Interstellar Gas & Dust

Polarization of starlight
Interstellar Atoms and Molecules
Star Formation
Molecular Clouds

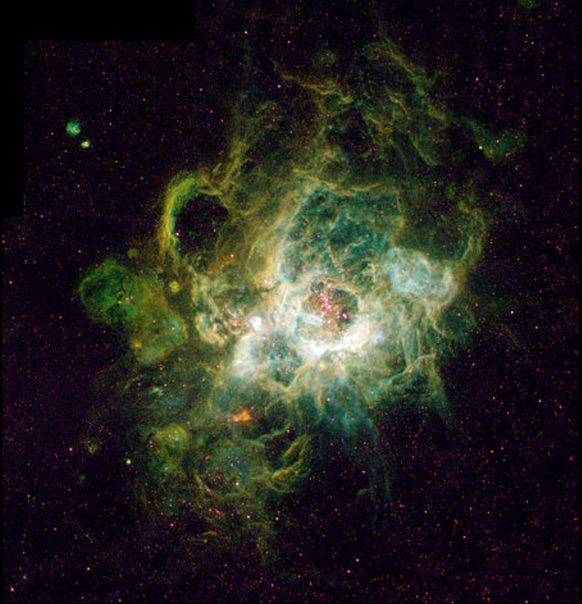
March 5, 2024

University of Rochester

# Interstellar Gas & Dust

- Polarization of starlight
- Refresher on spectral lines
- Interstellar atoms and molecules
- Molecular clouds and gravitational stability
- Cloud collapse and star formation

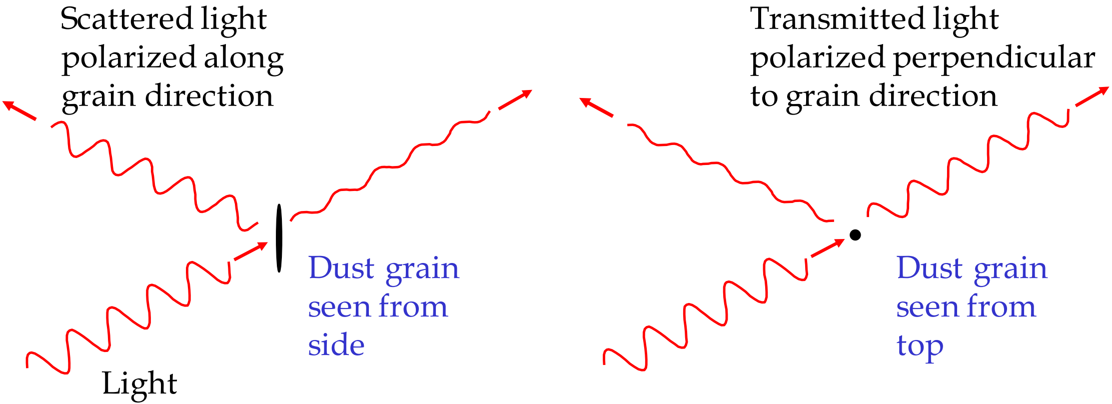
**Reading**: Kutner Ch. 3.1–3.4 & 14.4–14.5, Ryden Ch. 5.1–5.3, 16.2-16.3, and Shu Ch. 11



*H II region NGC 604 in Triangulum (NASA/HST)*

# Polarization of light by nonspherical dust grains

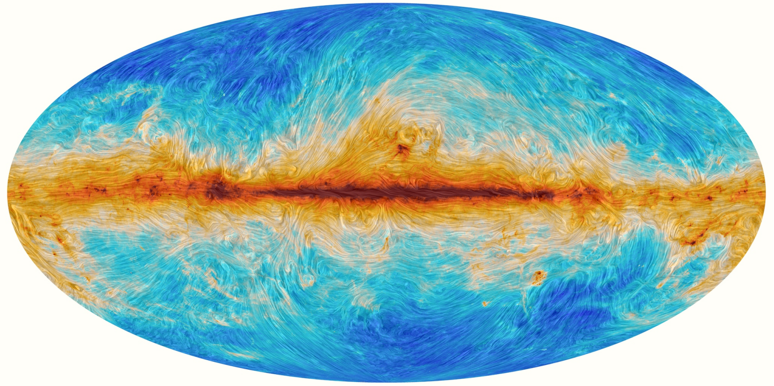
Interstellar dust grains are actually not spherical; they tend to be needle-shaped or flake-like. Thus they can absorb or scatter light with some polarizations — the components of the electric field **E** along the long axis of the grain — better than others.



# Polarization of light by dust grains

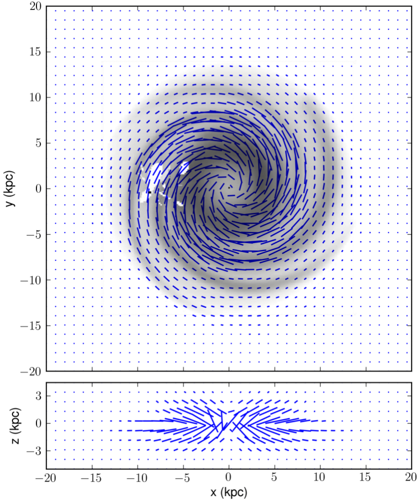
Interstellar dust grains are often aligned with their long axes along some given direction. That direction can be determined by external magnetic fields and/or gas motions.

- Most common alignment: **B** perpendicular to the long axis of spinning dust grains (Davis & Greenstein 1951).

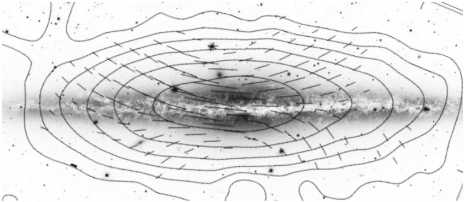


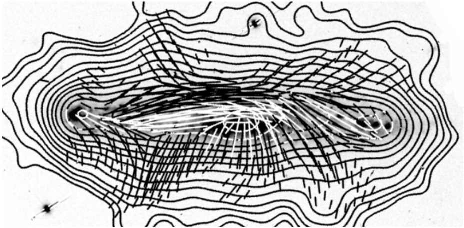
*Stellar dust grain polarization in the Galaxy (ESA & the Planck Collaboration).*

# Polarization of light by dust grains




*Model of the Galactic magnetic field (Jansson & Farrar 2012)*





*Top: Observed magnetic field of NGC 891 (Krause 2011)*

*Bottom: Observed magnetic field of NGC 5775 (Soida et al. 2011)*

# Nomenclature of spectral lines

Much of the evidence for the presence of interstellar gas comes from the detection of **atomic** and **molecular** emission and absorption lines.

In astronomy, the ionization states of atoms are indicated with Roman numerals.

- Neutral hydrogen (H) is denoted H I ("H-one").
- Ionized hydrogen (a free proton) is H II ("H-two"); compare to the usual chemical notation $H^+$.
- Do not confuse H II with $H_2$, which is molecular hydrogen.

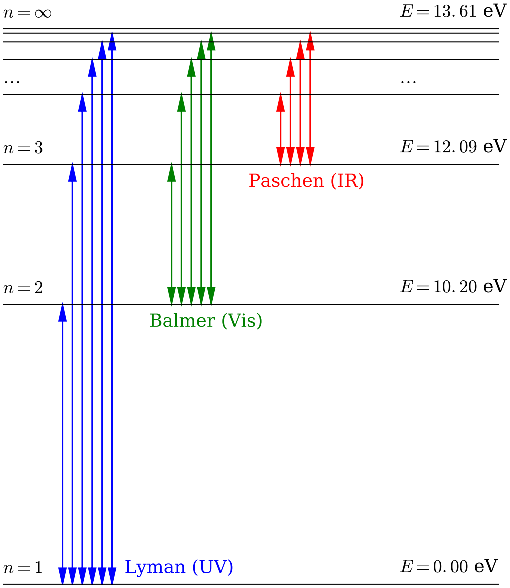
Other examples: Doubly-ionized oxygen ($O^{++}$) is O III. In the $10^6$ K solar corona, it is common to observe Fe IX and Fe X (iron atoms that have lost 8 or 9 electrons).

# Spectrum of Hydrogen

Recall that electron transitions in H give rise to radiation of discrete wavelengths.

Lyman: transitions to $n = 1$
Balmer: transitions to $n = 2$
And so on.

Lines within a series are sometimes labeled by Greek letters. E.g., the $n = 2 \to 1$ transition is called Lyman-$\alpha$, $n = 3 \to 1$ is Lyman-$\beta$, etc.

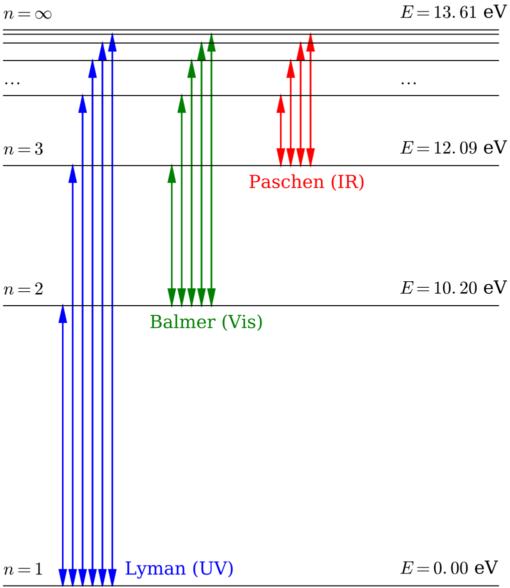


# Astronomically significant Hydrogen lines

The Lyman-$\alpha$ line (121.567 nm) is commonly used in cosmology since it is redshifted into the visible spectrum at cosmologically-important distances.

H$\alpha$ is the 656.28 nm line in the $n = 3 \to 2$ Balmer transition. It shows up a lot in HII regions due to **atomic recombination**.

The 21 cm HI line is due to an electron transition in the hyperfine levels of the 1s ground state. It is a tracer of **neutral hydrogen**.



# Fine and hyperfine structure in the spectrum

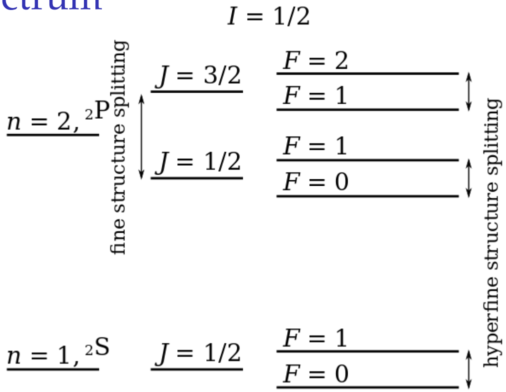
When you look with increasing precision at the H spectrum, you find that the energy levels are **split** into sub-levels.

In QM, we approximate the interactions inside the atom to varying degrees of accuracy.

Lowest order approximation  Coulomb force

"Fine structure"  corrections for relativistic motion of the electron.

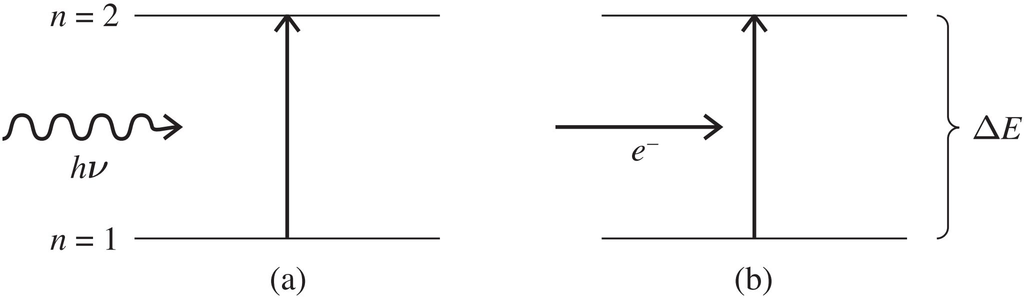
"Hyperfine structure"  interactions between electron orbital angular momentum and nuclear spin angular momentum (**spin-orbit coupling**)




*The dominant interaction in the hydrogen atom (Coulomb attraction of e and p) gives rise to the energy levels. Sub-dominant interactions cause splitting of the levels, observed as "fine" and "hyperfine" structure.*

# Atomic excitation

Atoms can be excited via one of two methods:

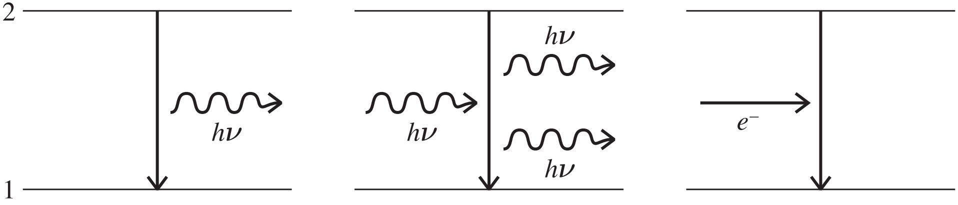



**Photoexcitation** (or absorption) occurs when the atom absorbs a photon with an energy exactly equal to the difference between energy levels.

**Collisional excitation** occurs when the atom collides with another particle (normally a free electron). Some of the free particle's kinetic energy will transfer to the internal energy of the atom.

# Atomic de-excitation

Atoms can drop down to lower energy levels via one of three methods:




(a) (b) (c)

**Spontaneous emission** occurs when the atom releases a photon with energy equal to the difference between energy levels (the inverse of photoexcitation).

**Stimulated emission** occurs when the atom encounters a photon with energy equal to the difference between the energy levels.

**Collisional de-excitation** occurs when the atom's de-excitation is triggered by a collision with another free particle.

# Atomic de-excitation

- Spontaneous emission is directly related to the instability of the excited states.
- In stimulated emission, the emitted photon has the same phase and direction as the stimulating photon, thereby amplifying the original photon signal. The rate of stimulated emission is proportional to the intensity of the radiation field at the relevant frequency.
- No photon is emitted in collisional de-excitation, as the free particle carries away the energy difference as additional kinetic energy.

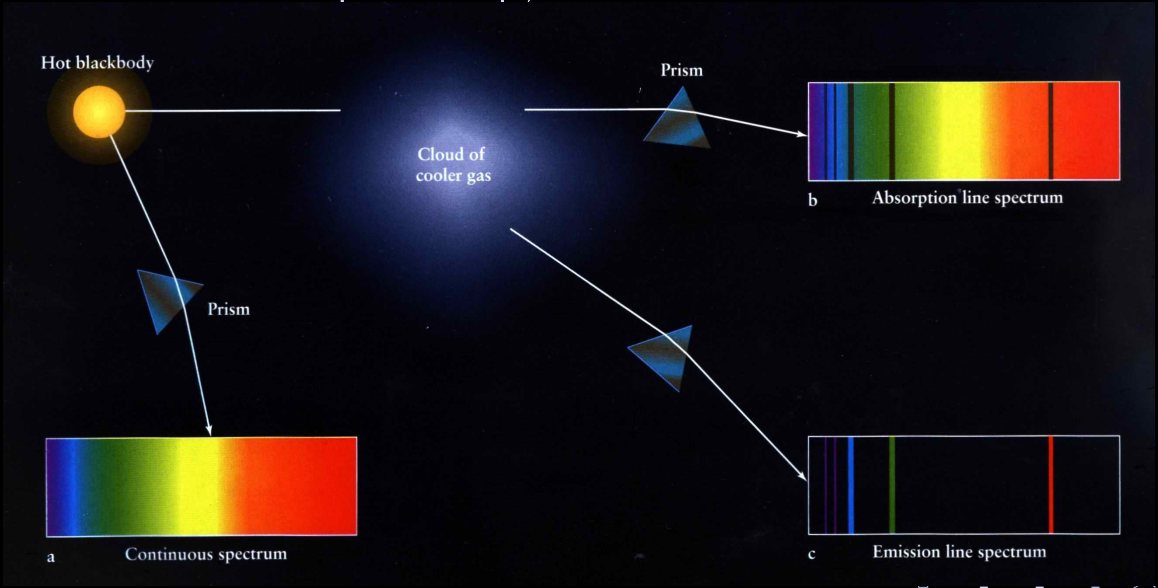
# Ionizing gas in the interstellar medium

When an atom absorbs a photon with energy greater than the ionization potential for its electron(s), the electron will be stripped from the atom. Photoionization results in the now free electron having a kinetic energy equal to the energy difference of the incoming photon and the ionization potential.

Collisional ionization can also occur, when a free electron with total kinetic energy greater than the ionization potential collides with the atom. The final speeds of the two free electrons is based on conservation of energy and momentum.

Free electrons can be captured by the ions, with a photon carrying away the excess energy. Recombination can result in the electron being located in any of the available energy states (ground or excited).

# Kirchoff’s Laws of Spectroscopy



# Evidence for interstellar gas

Apparent through spectral lines seen in absorption against stars or in emission elsewhere.

"Nebulae:" hydrogen emission lines, plus a variety of other bright lines not readily identifiable in the laboratory.

- Bowen 1928: extra lines are mostly **forbidden** lines in the spectrum of the **ions**, mostly neutral, singly-, or doubly-ionized, of the more abundant elements:
  - Oxygen ($O/H \approx 5 \times 10^{-4}$)
  - Nitrogen ($N/H \approx 2 \times 10^{-5}$)
  - Carbon ($C/H \approx 3 \times 10^{-4}$)

It was obvious right away that the lines must originate in very low density diffuse material, which is difficult to reproduce in labs on Earth. Best vacuum on Earth is now $\sim 10^3$ cm$^{-3}$; in space $\sim 0.1 - 1$ cm$^{-3}$.

# Forbidden lines

What are **forbidden lines**? And how can we see them if they are forbidden? In short, the term is a bit of a misnomer.

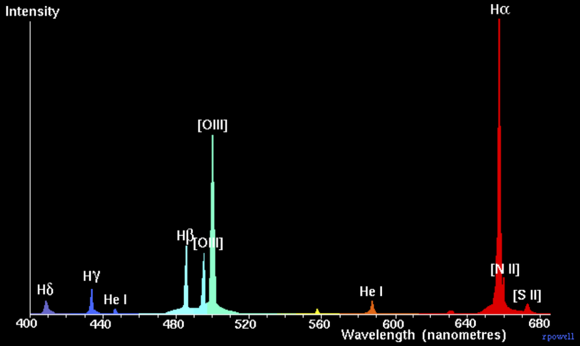
- Atomic and molecular transitions are governed by selection rules that tell us what changes in quantum states are allowed during the transition. The selection rules are determined by the physical process governing the transition.
- But we approximate these interactions to varying degrees of accuracy, with the lowest-accuracy ("first-order") effects dominating and then sub-dominant "higher-order" effects added as corrections.
- Selection rules that apply to first-order effects may forbid certain transitions, but the higher-order interactions may allow the transitions (albeit at low rates). These are the "forbidden transitions" which produce **forbidden lines**.

# Planetary Nebula NGC 7662 & its visible spectrum

## NGC 7662: the Snowball Nebula (or “Blue Snowball Nebula”)

Almost all of the emission is in the form of spectral lines: H and He recombination lines and forbidden lines of heavier elements.

*Color image taken at Mees Observatory.*




*Visible spectrum from Pic du Midi Observatory.*

# Role of interstellar gas in the galaxy

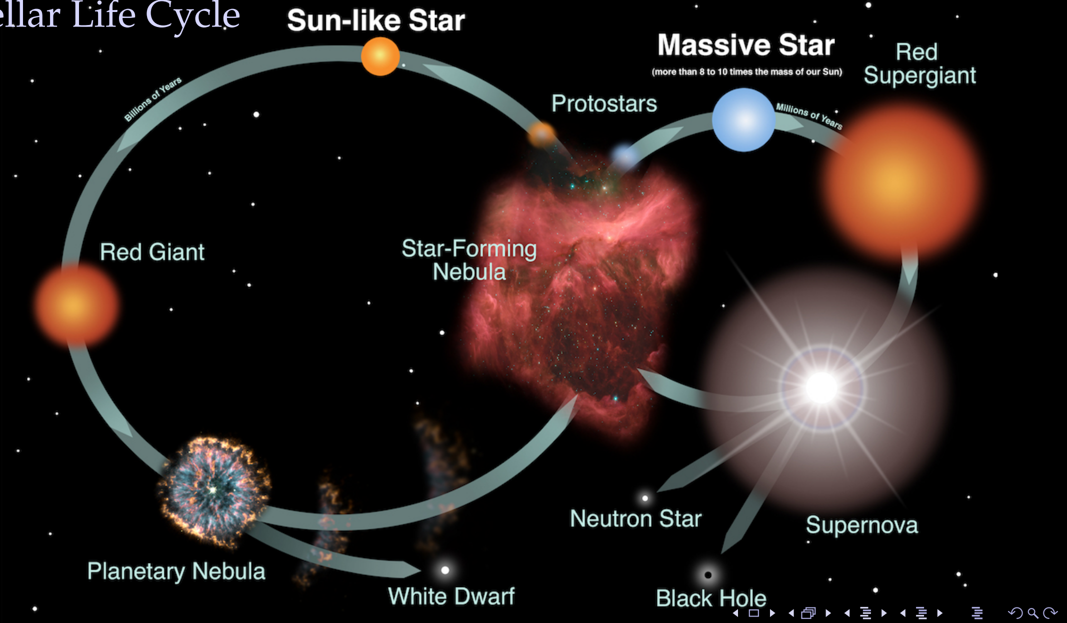
Interstellar gas is the reservoir of material for star formation and stellar death.

- Stars form by gravitational collapse of interstellar clouds.
- Dying stars return fusion-processed material to the ISM, enriching it in heavier elements and providing material for new stars.
  - Via stellar winds for most stars, supernovae for the most massive.
  - In particular, interstellar dust is produced in stellar winds from refractory elements (Mg, Si, Fe,. . . ) and their oxides.

Many properties of interstellar gas clouds are measurable with high precision: density temperature, pressure, elemental/molecular abundance, etc.

- For the purpose of studying galactic structure, dynamics, and evolution, the gas in the ISM is a useful complement to the information available from stars.

# The Stellar Life Cycle



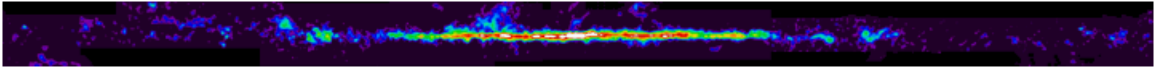
# Milky Way stars, dust, and interstellar gas

Starlight, extinction

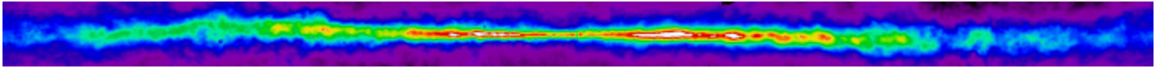
Starlight

Dust (blackbody emission)

Molecular gas



Neutral atomic gas

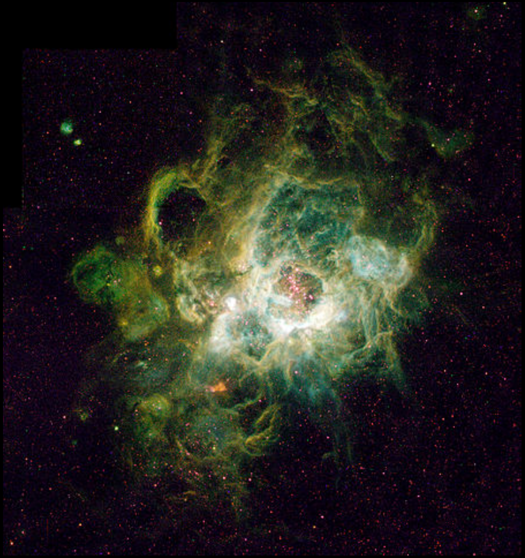


# The components of the ISM

**Diffuse ISM** neutral atomic clouds embedded in ionized medium

**Dense ISM** neutral molecular clouds

**Ionized nebulae** H II regions, planetary nebulae, SN remnants



*H II region NGC 604 in Triangulum (NASA/HST).*

# The components of the ISM

## Diffuse ISM

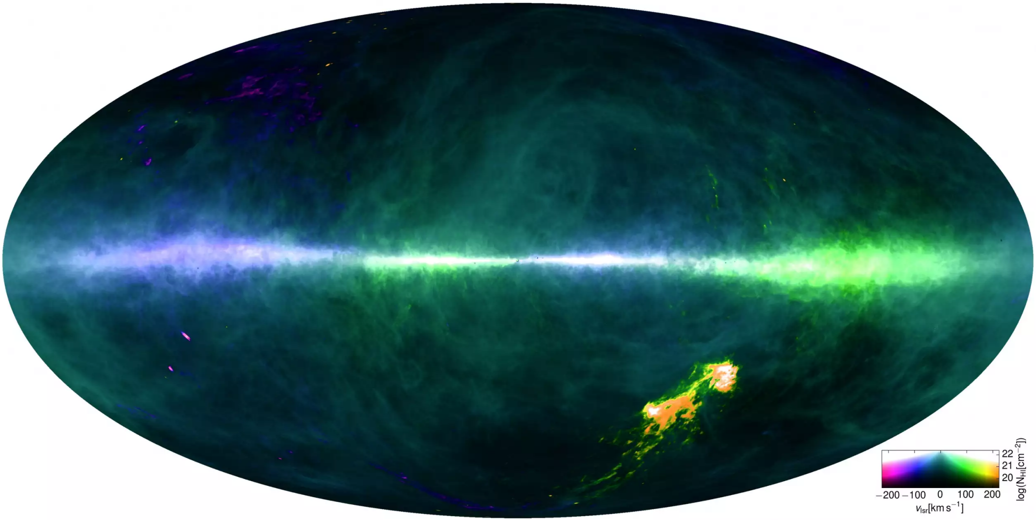
The diffuse ISM is typically subdivided into four parts:

| **Component** | **Hydrogen number density, $n$ [cm$^{-3}$]** | **Tempera-ture, $T$ [K]** | **Volume filling fraction, $\phi$** | **Mass, $M$ [$10^9 M_\odot$]** |
|---|---|---|---|---|
| Hot ionized medium (HIM) | 0.004 | $\gtrsim 5 \times 10^5$ | 0.5 | 0.1 |
| Warm ionized medium (WIM) | 0.02 | $10^4$ | 0.1 | 1.4 |
| Warm neutral medium (WNM) | 0.6 | 6000 | 0.4 | 1.6 |
| Cold neutral medium (CNM) | 30 | 70 | 0.01 | 2.4 |

- Mixed in with the gas is the interstellar dust, 1% by mass.
- The best spectral line tracers: HI 21 cm line; forbidden $C^+$ line at 157.7 $\mu$m.

# The neutral diffuse ISM in the Milky Way

## H I 21 cm image of the sky by the MPIfR/Parkes HI4PI survey



# The components of the ISM

## Dense ISM

H — neutral and mostly molecular instead of atomic — in the form of clouds with densities $n_{H_2} = 10 - 10^6$ cm$^{-3}$. Temperature is $10 - 100$ K, mass is $10^3 - 10^6 M_\odot$.

- As much mass (total in Galaxy) as the diffuse ISM, $10^9 - 10^{10} M_\odot$ but volume is small in comparison.
- **Molecular cloud complexes** are usually physically connected to complexes of diffuse atomic clouds.
- The visual extinction through a molecular cloud is $\gg 1$. (It is also 1% dust by mass.)
- Best spectral line tracers are rotational lines of CO. The most abundant molecule, $H_2$, radiates too poorly and is excited too inefficiently to be an effective tracer.
- 298 molecular species have been detected so far in interstellar clouds. Smallest molecule: $H_2$; largest: $C_{70}$ fullerene.
    - See Brett McGuire's list of reported ISM molecules

# The components of the ISM

## Ionized nebulae

Include H II regions, planetary nebulae, and supernova remnants.

- Hydrogen is fully ionized in ionized nebulae; other elements may be multiply ionized.
- The ionization is by stellar UV photons for H II regions and planetary nebulae, and by collisions with atoms in the SN blast wave for supernova remnants.
- These objects have negligible mass on the galactic scale but they are very bright at visible wavelengths and are therefore the most easily noticed components of the ISM.
- Spectral line tracers: hydrogen recombination lines, "forbidden" lines of relatively abundant ions and atoms (C, N, O, etc.).
- Electron densities are usually around $n_e = 10 - 10^4 \text{ cm}^{-3}$. Temperatures are about $10^4$ K in H II regions and planetary nebulae.

# The components of the ISM

## Ionized nebulae

**Planetary nebulae** consist of gas ejected and ionized by stars with core masses below the SAC mass that are becoming white dwarfs.

**HII regions** are associated with young, massive O-type stars in star-forming regions.

- They always seem to occur on the edges of giant molecular cloud complexes. The **Orion clouds** are the nearest and best example.

**Supernova remnants** are what their name implies. Their emission traces the supersonic advance of the blast wave into the ISM rather than photoionization by UV starlight.

- The matter in SNRs tends to be in lower ionization states than in HII regions and planetary nebulae. This is a characteristic of collisional ionization, as opposed to photoionization.

# HII region: the Omega Nebula (M17)

BVRH$\alpha$ image from the Wide Field Imager on the MPG/ESO 2.2-m telescope at ESO's La Silla Observatory in Chile.

Note the star cluster, the cloud of ionized gas, and the sharp edge evidently produced by extinction.

# M17 and its associated molecular cloud complex

M17 is the bright red spot in the left center of the image. The emission is caused by HII.

The molecular cloud is evident in the extinction above and to the right of the HII region (David Malin, AAO).

Center: open cluster M18 and Sagittarius Star Cloud M24.

Right: emission nebula IC 1283 (red) and reflection nebulae NGC 6589 and NGC 6590 (blue).