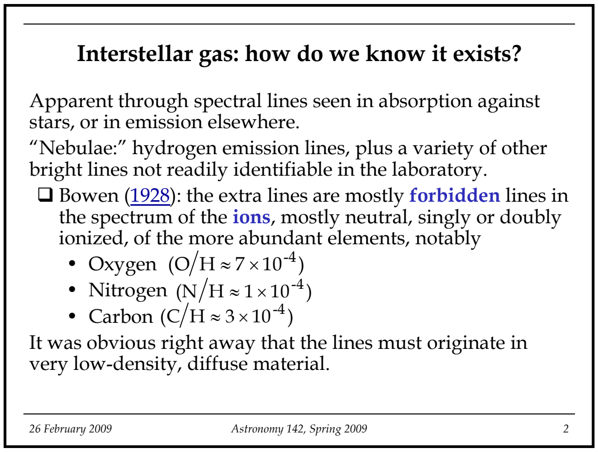
Today in Astronomy 142: interstellar gas

The Orion Nebula (M42 and NGC 1977), in spectral lines: blue = O^{++}, green = H, and red = S^{+}. By Russell Croman.



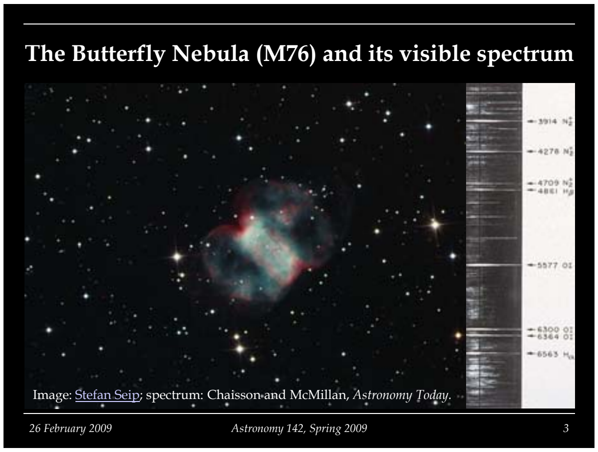
Interstellar gas: how do we know it exists?

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): the extra lines are mostly **forbidden** lines in the spectrum of the **ions**, mostly neutral, singly or doubly ionized, of the more abundant elements, notably
  - Oxygen $(O/H \approx 7 \times 10^{-4})$
  - Nitrogen $(N/H \approx 1 \times 10^{-4})$
  - Carbon $(C/H \approx 3 \times 10^{-4})$

It was obvious right away that the lines must originate in very low-density, diffuse material.



The Butterfly Nebula (M76) and its visible spectrum

Image: Stefan Seip; spectrum: Chaisson and McMillan, *Astronomy Today*.

Interstellar neutral atoms and molecules

- Late1930s: (McKellar, Swings) interstellar absorption by CN, CH, CH^+ detected at visible wavelengths.
- Early 1950s (Purcell, Oort): interstellar H detected via its ground-state hyperfine transition at $\lambda = 21.1$ cm.
- Early 1960s (Barrett, Weinreb): interstellar OH detected at $\lambda = 18$ cm.
- Late 1960s (Townes, Cheung): interstellar polyatomic molecules NH_3, H_2O discovered at $\lambda = 1$ cm.
- Early 1970s (Wilson, Penzias): interstellar CO discovered at $\lambda = 1$ mm.
- Mid 1970s (Gautier, Treffers): interstellar H_2 detected via vibrational emission at $\lambda = 2$ μm in molecular shocks.

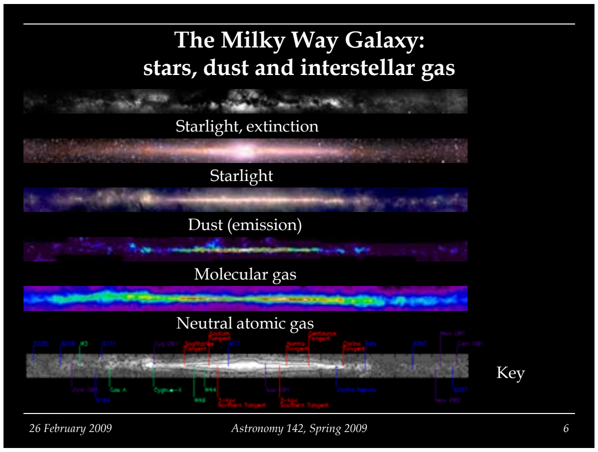
Interstellar gas: what is its role in the galaxy?

It is the reservoir of material for star formation and star death.

- Stars form by gravitational collapse of interstellar clouds.
- Dying stars return (fusion-processed) material to the interstellar medium, enriching it in heavier elements and providing material for new stars.

Many properties of interstellar gas clouds are measurable very precisely: density, temperature, pressure, element/molecule abundance….

- Useful complement to the information available from stars, for the purpose of study of structure, dynamics, evolution of galaxies.



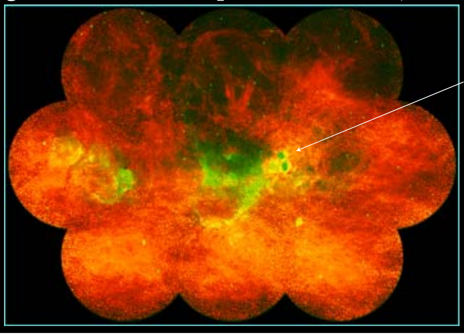
The Milky Way Galaxy: stars, dust and interstellar gas

Components of the interstellar medium (ISM)

Diffuse ISM: clouds of mass $10^3 - 10^6\, M_\odot$, size 10-100 parsecs, temperature 10-10,000K, and made of neutral atomic material, embedded in a much less dense, very hot (>100,000 K), ionized medium.

- Mostly in the form of dark clouds, with $n_{\mathrm{H}} = 0.1 - 10$ cm^{-3} T = 50-100 K (dark, because of the extinction by the dust they contain can be as high as $A_V \sim 3$).
- The neutral diffuse ISM fills 40-80% of the volume of our Milky Way Galaxy.
- There is about $10^9 - 10^{10}\, M_\odot$ of neutral diffuse ISM in the Galaxy.
- Spectral line tracers: the H I 21 cm line; the C$^+$ line at $\lambda = 157.7\ \mu$m.

H I 21 cm (red) and ionized gas (green) in a 5x7° region of the Galactic plane in Perseus (DRAO).



W3 (see the slide before last)

Components of the ISM (continued)

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 10-100 K, mass $10^3 - 10^6\, M_\odot$.

- As much mass (total in Galaxy) as the diffuse ISM, $10^9 - 10^{10}\, M_\odot$, but volume small in comparison.
- **Molecular cloud complexes** are usually physically connected to complexes of diffuse atomic clouds.
- The visual extinction through a molecular cloud is >>1.
- Best spectral line tracers: rotational lines of CO. (H_2 radiates too poorly and is excited too inefficiently.)
- 129 different molecular species have been detected so far in interstellar clouds, through their spectral lines. Smallest: H_2; biggest: $HC_{11}N$. (Al Wooten at NRAO keeps an updated interstellar-molecule website; check it out.)

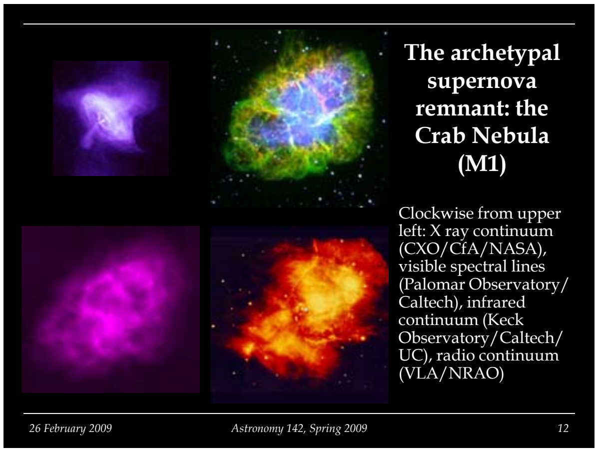
Components of the ISM (continued)

Ionized nebulae include **H II regions**, **planetary nebulae**, and **supernova remnants**.

- ☐ Hydrogen is fully ionized in ionized nebulae; other elements may be multiply ionized.
- ☐ These objects have negligible mass on the galactic scale, but they are very bright at visible wavelengths, and thus are the most easily-noticed components of the ISM.
- ☐ Spectral line tracers: hydrogen recombination lines, “forbidden” lines of relatively abundant ions and atoms (e.g. C, N, O).
- ☐ Planetary nebulae consist of gas ejected and ionized by stars with core masses below the Chandrasekhar mass that are becoming white dwarfs.

Components of the ISM (continued)

- ☐ H II regions are associated with young O stars in star formation regions.
  - Thus they always seem to occur on the edges of giant molecular cloud complexes. The **Orion clouds** (see below) are the nearest and best example.
- ☐ Electron densities are usually around $n_e = 10 - 10^4\ \mathrm{cm}^{-3}$, temperatures around 10,000K in H II regions and planetary nebulae.
- ☐ Supernova remnants are what their name implies. Their ionization traces the advance of the blast wave into the interstellar medium, rather than photoionization by stellar ultraviolet light.
  - The matter in SNRs tends to be in lower ionization states than that in H II regions and planetary nebulae.



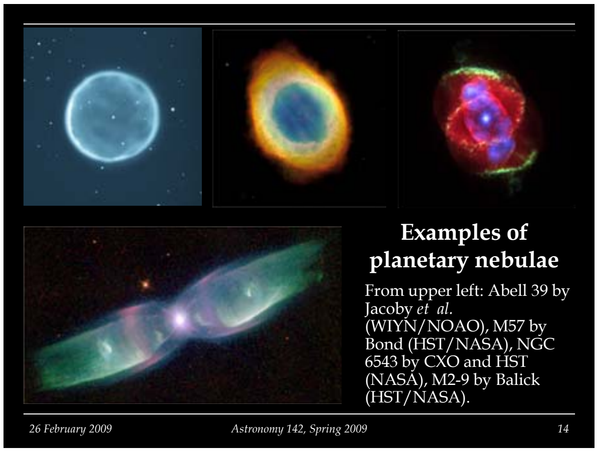
The archetypal supernova remnant: the Crab Nebula (M1)

Clockwise from upper left: X ray continuum (CXO/CfA/NASA), visible spectral lines (Palomar Observatory/ Caltech), infrared continuum (Keck Observatory/Caltech/ UC), radio continuum (VLA/NRAO)

The Crab Nebula seen from Mees Observatory by the students of AST 111

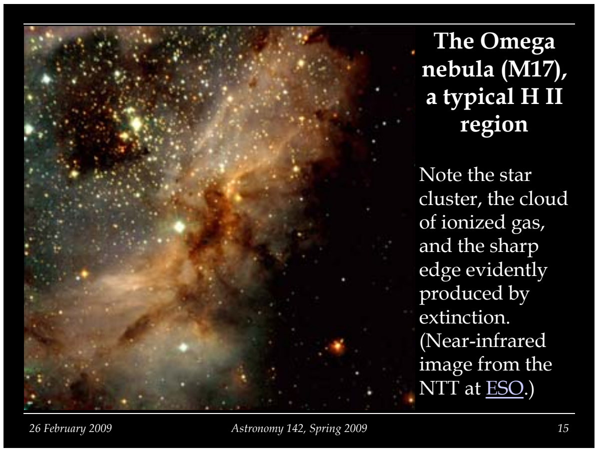
Observers:

Joe Bilyard, Mike Kass, Jason Kay, Eric Moreno, Diana Pogorzelski and Pratap Ranade, under Dan Licht's guidance.



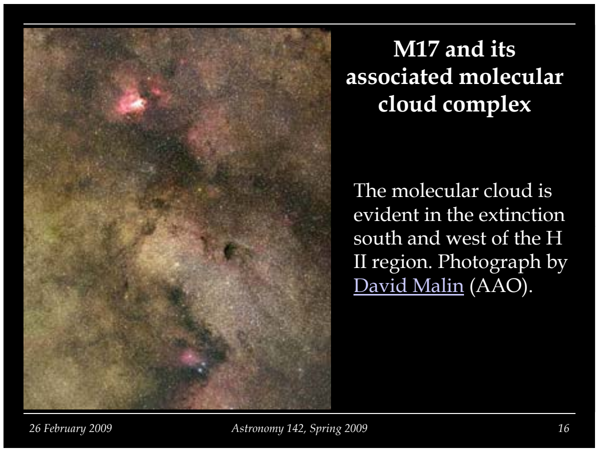
Examples of planetary nebulae

From upper left: Abell 39 by Jacoby *et al.* (WIYN/NOAO), M57 by Bond (HST/NASA), NGC 6543 by CXO and HST (NASA), M2-9 by Balick (HST/NASA).



The Omega nebula (M17), a typical H II region

Note the star cluster, the cloud of ionized gas, and the sharp edge evidently produced by extinction. (Near-infrared image from the NTT at ESO.)



M17 and its associated molecular cloud complex

The molecular cloud is evident in the extinction south and west of the H II region. Photograph by David Malin (AAO).

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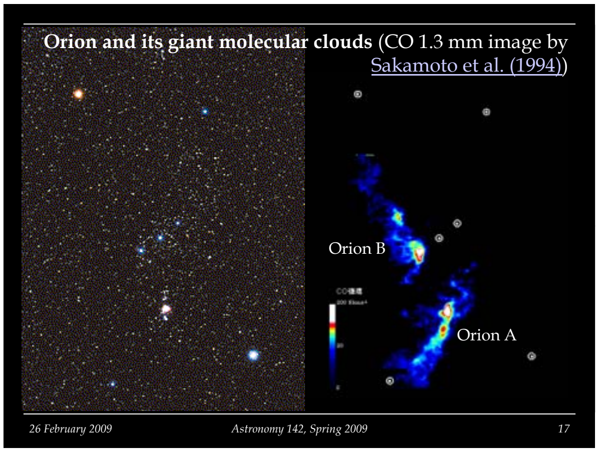

Orion and its giant molecular clouds (CO 1.3 mm image by Sakamoto et al. (1994))

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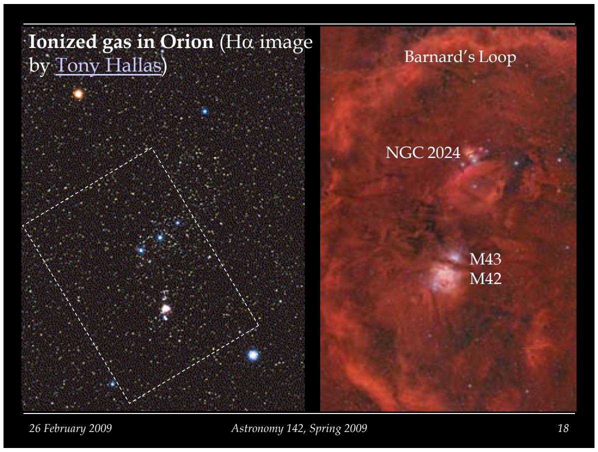

Ionized gas in Orion (Hα image by Tony Hallas)

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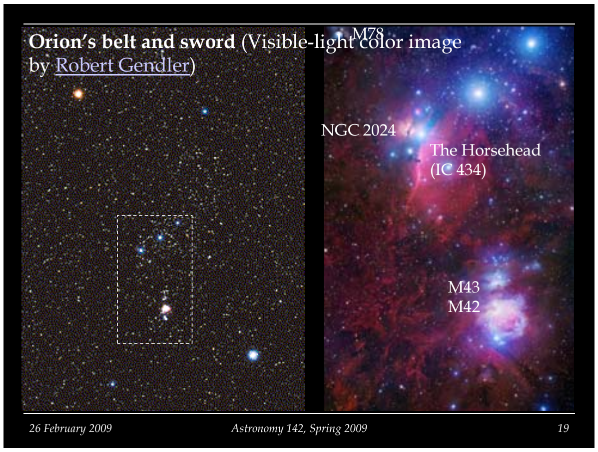
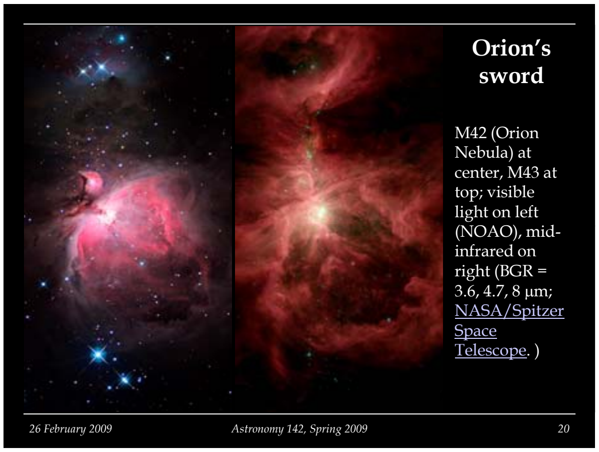
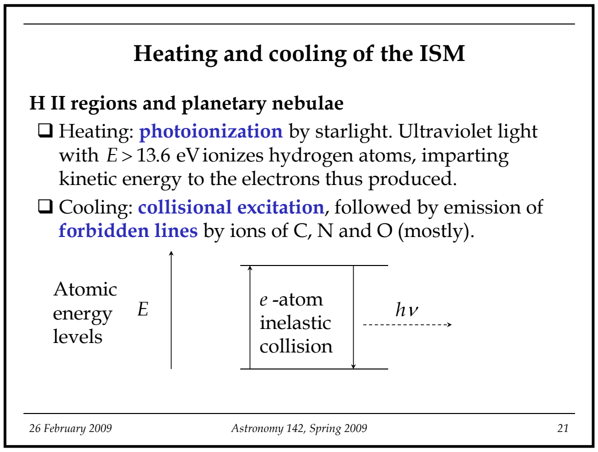


Orion's belt and sword (Visible-light color image by Robert Gendler)



Orion's sword

M42 (Orion Nebula) at center, M43 at top; visible light on left (NOAO), mid-infrared on right (BGR = 3.6, 4.7, 8 μm; NASA/Spitzer Space Telescope.)



Heating and cooling of the ISM

H II regions and planetary nebulae

- ❑ Heating: **photoionization** by starlight. Ultraviolet light with $E > 13.6$ eV ionizes hydrogen atoms, imparting kinetic energy to the electrons thus produced.
- ❑ Cooling: **collisional excitation**, followed by emission of **forbidden lines** by ions of C, N and O (mostly).

Heating and cooling of the ISM (continued)

Neutral, diffuse ISM

- Heating: ultraviolet light ($h\nu = 5 - 13$ eV) in background starlight (the interstellar radiation field), through the photoelectric effect on dust grains.
- Carbon can be ionized by $h\nu = 11$ eV photons; thus it is usually singly ionized in the diffuse ISM, even though hydrogen is neutral and atomic.
- Cooling: excitation of ionized carbon by collisions with H atoms and electrons, followed by radiation in the forbidden 157.7 μm line.

We aren’t sure what the heating mechanism in the hot diffuse ISM is.

Heating and cooling of the ISM (continued)

Molecular clouds

- Heating: not really sure, but it can’t be starlight directly. Best candidates are **turbulence** driven by stellar winds and outflows, and **cosmic rays**: ions accelerated to high energies in supernova remnants.
- Cooling: collisional excitation followed by radiation by the rotational lines of the more abundant molecules besides hydrogen (CO, OH, H_2O).
- Molecular clouds are frequently dense and cold enough to be **unstable** to collapse under their weight. As we will see, this gravitational instability of molecular clouds is the principal means by which stars are formed in our galaxy.

Molecular clouds: internal structure

- Molecular clouds are **clumpy**: they tend to consist of denser clumps in a range of sizes and masses, blending into a less-dense background.
- Molecular clouds are **cold**: they tend to have $T < 20$ K.
- Molecular clouds are **turbulent**: the random internal velocities are typically of magnitude 1 km/s, much larger than the typical molecular speeds in a quiescent gas in equilibrium at the same temperature.
- Molecular clouds (and clumps) generally **rotate** slowly.
- Molecular clouds are **magnetized**: they are threaded by the same magnetic flux as the same material was when it was diffuse and atomic; now it has been compressed to a much smaller size, and the fields are correspondingly larger.

Molecular clouds and star formation

As a result:

- ☐ Clumps get massive enough and cold enough that gas pressure can't hold up their weight, and they collapse.
  - They get hotter in their cores as they do so. If they are sufficiently massive and collapse to small enough scales, high enough temperatures are reached to ignite fusion - a star is formed.
- ☐ The clumps are constantly being rearranged, compressed or distended by turbulence.
- ☐ Collapse doesn't happen spherically symmetrically: collapse is easier along the axis of rotation for rotating clumps (because of centrifugal forces), and/or along ***B*** (because of $\boldsymbol{v}\times\boldsymbol{B}$ forces)

Collapse of a magnetized clump

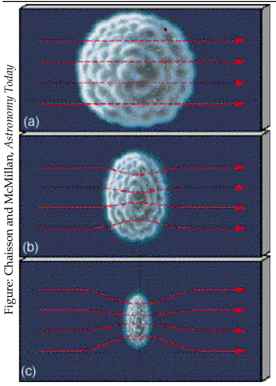


Figure: Chaisson and McMillan, *Astronomy Today*

The ions in a clump can collapse more freely along the field lines than in the other two directions (for which the $v \times B$ forces tend to make them spiral around the field lines). The concentration of ions is small in a molecular clump, but they still tend to drag the neutrals along. Thus the clump tends to collapse to a pancake perpendicular to the magnetic field.

Collapse of a clump: the Jeans mass

Consider a constant-density clump and its central pressure:

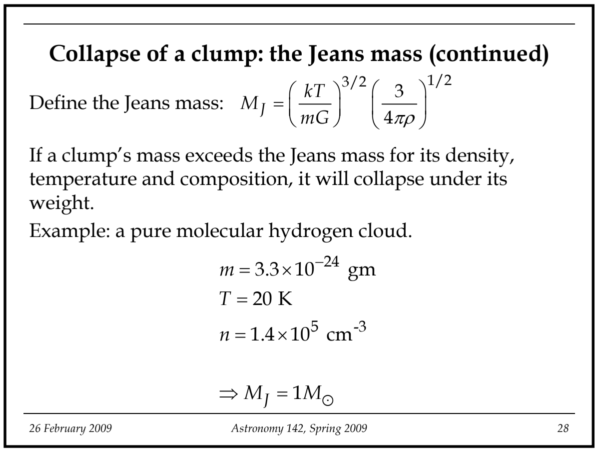
$$P_C \sim \frac{GM^2}{R^4} \qquad \text{from weight,}$$

$$= \frac{\rho k T}{m} \qquad \text{from the ideal gas law.}$$

Balance: $$\frac{GM^2}{R^4} = \rho \frac{GM}{R} = \frac{\rho k T}{m} \quad \Rightarrow \quad \frac{M}{R} = \frac{kT}{mG}$$

Uniformity: $$\rho = \frac{3M}{4\pi R^3} \quad \Rightarrow \quad R = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

Thus: $$M = \frac{kT}{mG}\left(\frac{3}{4\pi\rho}\right)^{1/3} M^{1/3} \quad \Rightarrow \quad M = \left(\frac{kT}{mG}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$



Collapse of a clump: the Jeans mass (continued)

Define the Jeans mass: $M_J = \left(\frac{kT}{mG}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$

If a clump’s mass exceeds the Jeans mass for its density, temperature and composition, it will collapse under its weight.

Example: a pure molecular hydrogen cloud.

$$m = 3.3\times10^{-24}\ \text{gm}$$
$$T = 20\ \text{K}$$
$$n = 1.4\times10^{5}\ \text{cm}^{-3}$$

$$\Rightarrow M_J = 1M_\odot$$