Interstellar Gas, Star Formation, & The Milky Way

Interstellar Atoms and Molecules
Molecular Clouds
Gravitational Collapse
Free-Fall Timescale
Pre-MS Stars and the Hayashi Track
The Shape of the Galaxy
Stellar Populations and Motions
Stars as a Gas

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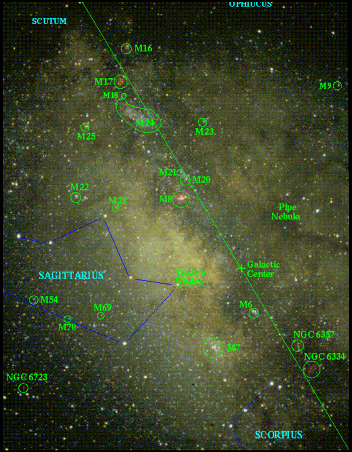
Interstellar gas, star formation, & the Milky Way

- Interstellar atoms and molecules
- Molecular clouds and gravitational stability
- Collapse of a spherical cloud: free-fall time
- Synopsis of star formation
- The initial mass function
- Formation of protostellar disks and jets
- Pre-MS stars and the Hayashi track
- The shape of the Galaxy
- Stellar populations and motions
- Stars as a gas: Scale height, velocities, and the mass per unit area of the disk

Reading: Kutner Sec. 16.4, Ryden Sec. 19.1–19.3, Shu Ch. 12



Wide-angle photo and overlay key of the Sagittarius region of the Milky Way (from Bill Keel, U. Alabama).

Role of interstellar gas in the galaxy

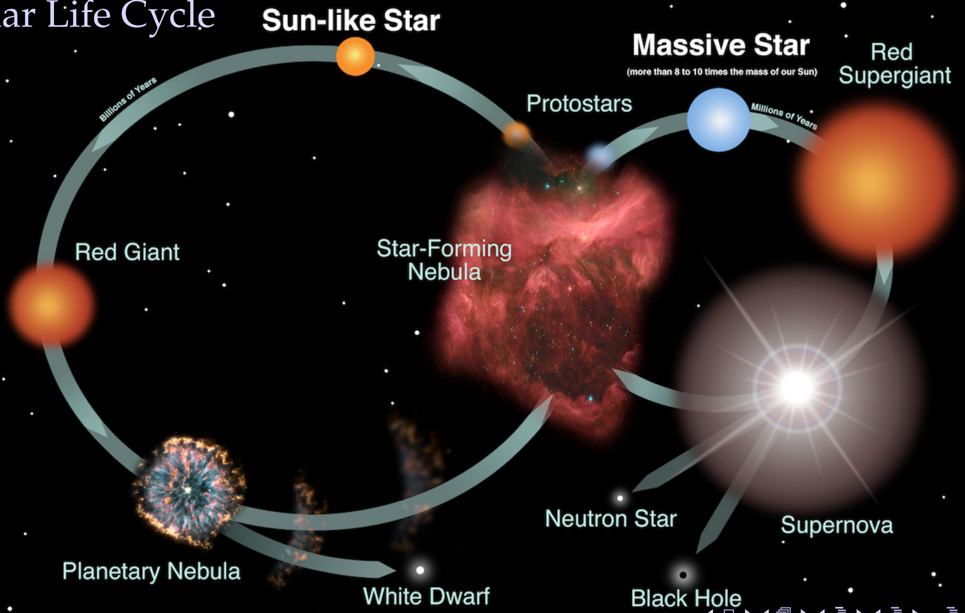
Interstellar gas is the reservoir of material for star formation and stellar death.

- 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



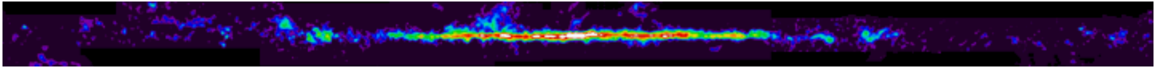
Milky Way stars, dust, and interstellar gas

Starlight, extinction

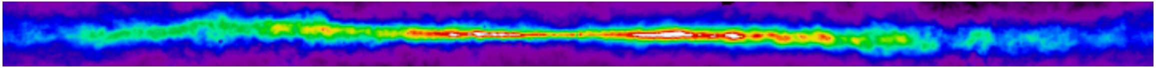
Starlight

Dust (blackbody emission)

Molecular gas



Neutral atomic gas

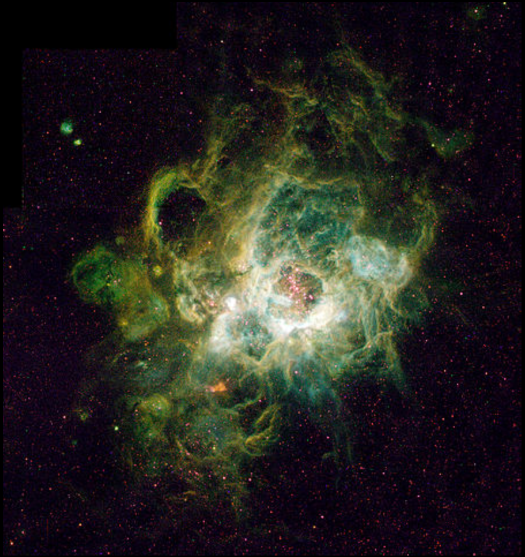


The components of the ISM

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

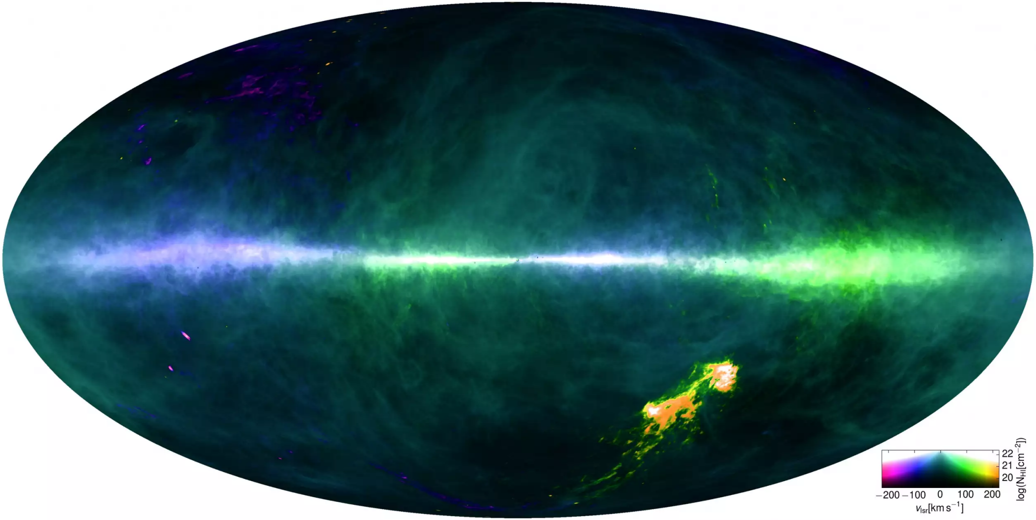
The diffuse ISM is typically subdivided into four parts:

Component	Hydrogen number density, n [cm^{-3}]	Temperature, T [K]	Volume filling fraction, ϕ	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 μm.

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 HII 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 HII 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 $n_e = 10 - 10^4$ cm^{-3}. Temperatures are about 10^4 K in HII 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.

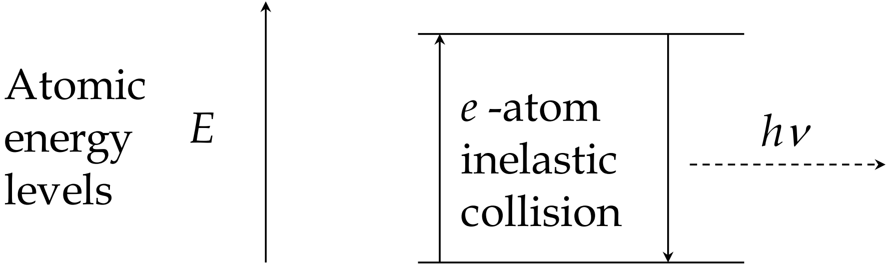
- The matter in SNRs tends to be in lower ionization states than in HII regions and planetary nebulae. This is a characteristic of collisional ionization, as opposed to photoionization.

Heating and cooling of the ISM

Warm ionized medium, HII regions, and planetary nebulae

Heating **Photoionization** by starlight; UV light with $E > 13.6$ eV ionizes hydrogen, imparting kinetic energy to the electrons produced.

Cooling **Recombination** of H or **collisional excitation** by free electrons, followed by emission of forbidden lines by ions of C, N, O, and S (mostly). The more metals, the more efficiently the cooling.



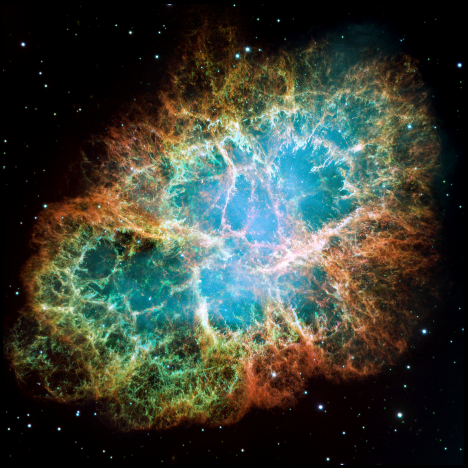
Heating and cooling of the ISM

Supernova remnants

Heating Viscous dissipation in the deceleration of the supersonic blast wave, i.e., shock heating.

Cooling Same as for photoionized regions, except

- There are fewer high-ionization species in SNRs than in the other ionized media.
- There are additional abundant, low-ionization species, like Si and Fe, that are liberated into the gas phase if the blast wave is fast enough to destroy dust grains.



The Crab Nebula, the archetype SN remnant, in the visible (HST)

Heating and cooling of the ISM

Warm and cold neutral medium

Heating UV light ($h\nu = 5 - 13$ eV) in background starlight, known as the interstellar radiation field (ISRF).

- Heating occurs via the photoelectric effect on dust grains and photoionization of C.
- Carbon can be ionized by $E = h\nu = 11$ eV photons and thus is usually singly ionized (C II) in the diffuse ISM even when hydrogen is neutral and atomic.

Cooling Excitation of excited carbon (C II) by collisions with H atoms and electrons, followed by radiation in the forbidden 157.7 μm line.

Heating and cooling of the ISM

Molecular Clouds

Heating :

Outer layers: Photoelectrons produced by starlight on dust grains and low-ionization elements.

Interior: Cosmic rays: ions accelerated to high energies ($\sim 10^{15}$ eV) in supernova remnants.

Cooling: Collisional excitation by H_2 followed by radiation in the rotational lines of the more abundant molecules like CO, OH, H_2O.

- Molecular clouds are frequently dense and cold enough to be unstable and collapse under their own weight.
- As we will see, the gravitational instability of molecular clouds is the principal means by which stars are formed in the 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 ~ 1 km/s, much larger than the average molecular speeds in a quiescent gas in equilibrium at the same temperature. It has therefore been mechanically stirred up, by supernova blasts, stellar winds, and the galaxy's differential rotation.
- Molecular clouds (and clumps) generally **rotate**, or tumble, slowly.
- Molecular clouds are **magnetized**: they are threaded by the same magnetic flux present when the material was diffuse and atomic. Now it has been compressed to a much smaller size, and the fields are correspondingly larger. The field lines are often sheared and twisted by motion of the ionized material in which it is threaded.

Molecular clouds & star formation

As a result:

- Clumps get massive enough and cold enough that the gas pressure cannot hold up their weight, and they collapse.
  - As clumps collapse they heat in their cores.
  - If they are sufficiently massive and collapse to a small enough scale, temperatures can reach the fusion ignition point and a star is formed.
- The clumps are constantly being rearranged, compressed, or distended by turbulence.
- Collapse does not happen with spherical symmetry; often collapse is easier along the axis of rotation because of centrifugal forces.

Collapse of a clump: the Jeans mass

Consider a uniform-density clump and its central pressure:

$$P_c \approx \frac{GM^2}{R^4} \qquad \text{from weight}$$
$$= \frac{\rho k T}{\mu} \qquad \text{from ideal gas law}$$

Balancing the pressure gives

$$\frac{GM^2}{R^4} = \rho \frac{GM}{R} = \frac{\rho k T}{\mu} \implies \frac{M}{R} = \frac{kT}{\mu G}$$

and assuming the mass is uniformly distributed gives

$$\rho = \frac{3M}{4\pi R^3} \implies R = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

$$\therefore M = \frac{kT}{\mu G}\left(\frac{3}{4\pi\rho}\right)^{1/3} M^{1/3} \implies \boxed{M = \left(\frac{kT}{\mu G}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}}$$

Collapse of a clump: the Jeans mass

Define the **Jeans mass**, M_J, as the critical mass for collapse:

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

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

For a cloud of H_2:

$$\begin{aligned} \mu &= 3.3 \times 10^{-24}\ \text{g} \\ T &= 20\ \text{K} \\ n &= 1.4 \times 10^{5}\ \text{cm}^{-3} \\ \therefore M_J &= 1 M_\odot \end{aligned}$$

Spherical free-fall time: Derivation

Follow a test particle that starts from rest at distance r_0 from the center of the cloud at time $t = 0$. How long until it reaches the center, i.e., until the clump collapses to a point?

$$F = ma$$

$$-\frac{GMm}{r^2} = m\frac{d^2r}{dt^2}$$

This is a **1D, nonlinear 2nd-order differential equation**. M is the mass interior to r and is constant. Multiplying both sides by $\frac{dr}{dt}$ and integrating over t:

$$\int_0^t dt' \frac{dr}{dt'}\frac{d^2r}{dt'^2} = -GM\int_0^t \frac{1}{r^2}\frac{dr}{dt'}dt'$$

Note that $v = \frac{dr}{dt}$ and $dv = \frac{d^2r}{dt^2}dt$ and start solving.

Spherical free-fall time: Derivation

$$\int_0^t \frac{dr}{dt'}\frac{d^2r}{dt'^2}dt' = -GM\int_0^t \frac{1}{r^2}\frac{dr}{dt'}dt'$$
$$\int_0^v v'\,dv' = -GM\int_{r_0}^r \frac{dr'}{r'^2}$$
$$\frac{1}{2}v^2 = \frac{GM}{r} - \frac{GM}{r_0}$$

Substitute back $v = \frac{dr}{dt}$:

$$\frac{1}{2}\left(\frac{dr}{dt}\right)^2 = \frac{GM}{r} - \frac{GM}{r_0}$$
$$\frac{dr}{dt} = -\sqrt{\frac{2GM}{r} - \frac{2GM}{r_0}}$$

choosing the negative root so that the particle moves to smaller r.

Spherical free-fall time: Derivation

Now insert $M = \frac{4}{3}\pi r_0^3 \rho_0$:

$$\frac{dr}{dt} = -r_0 \sqrt{\frac{8\pi G\rho_0}{3}\left(\frac{r_0}{r} - 1\right)}$$

Make a geometric u substitution $r = r_0 \cos^2 u$:

$$\frac{dr}{dt} = r_0 \frac{d}{dt} \cos^2 u = -2r_0 \cos u \sin u \frac{du}{dt}$$

$$\implies \frac{du}{dt} = \frac{1}{2\cos u \sin u} \sqrt{\frac{8\pi G\rho_0}{3}\left(\frac{1}{\cos^2 u} - 1\right)}$$

$$= \frac{1}{2\cos^2 u \sin u} \sqrt{\frac{8\pi G\rho_0}{3}\left(1 - \cos^2 u\right)}$$

$$= \frac{1}{2\cos^2 u} \sqrt{\frac{8\pi G\rho_0}{3}}$$

Spherical free-fall time: Derivation

Separate variables and integrate:

$$\int_{u_0}^{u} \cos^2 u' du' = \frac{1}{2}\sqrt{\frac{8\pi G\rho_0}{3}} \int_0^{t_{\rm ff}} dt \quad \text{where}$$

$$\begin{array}{llll} t = 0 : & r = r_0 & r_0 = r_0 \cos^2 u_0 & \Longrightarrow \; u_0 = 0 \\ t = t_{\rm ff} : & r = 0 & 0 = r_0 \cos^2 u_0 & \Longrightarrow \; u_0 = \frac{\pi}{2} \end{array}$$

$$\Longrightarrow \int_0^{\pi/2} \cos^2 u' du' = \frac{1}{2}\int_0^{\pi/2} \left[1 + \cos 2u'\right] du' = \frac{1}{2}\sqrt{\frac{8\pi G\rho_0}{3}} \int_0^{t_{\rm ff}} dt$$

$$\left[\frac{u}{2} + \frac{\sin 2u}{4}\right]_0^{\pi/2} = \frac{\pi}{4} = \frac{t_{\rm ff}}{2}\sqrt{\frac{8\pi G\rho_0}{3}}$$

$$\boxed{t_{\rm ff} = \sqrt{\frac{3\pi}{32 G\rho_0}}}$$

Time scale of spherical gravitational collapse

For spherically symmetric collapse in free fall, we see that

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32G\rho_0}} = 10^{12}\ \mathrm{s} = 30\ \mathrm{kyr} \qquad \rho_0 = \mu n = \text{initial mass density}$$

for $\rho_0 = 4.6 \times 10^{-19}\ \mathrm{g/cm^3}$.

- This is very fast by astrophysical standards. We should therefore have to get very lucky to catch a star in the act of formation.
- The result applies to a spherically symmetric collapse, and we know the collapse cannot really be very spherical (as angular momentum is conserved) so this is offered only as a crude estimate.