Stars and their evolution
The Hertzsprung-Russell (HR) Diagram
(Color-Magnitude Diagram)

Apparent and Absolute Magnitudes; Dust Extinction

The brightness of a star near any wavelength $\lambda$ is measured either by its apparent and absolute magnitudes: $m_\lambda$ and $M_\lambda$, respectively

\[
m_\lambda = -2.5 \log F_\lambda(r) + m_{\lambda o}
\]
\[
M_\lambda = -2.5 \log F_\lambda(10\text{pc}) + m_{\lambda o}
\]
\[
m_\lambda = M_\lambda + 5 \log \left( \frac{r}{10\text{pc}} \right)
\]

If dust is present along the line of sight:

\[
m_\lambda = M_\lambda + 5 \log \left( \frac{r}{10\text{pc}} \right) + A_\lambda
\]

Consider two different wavelengths, $\lambda_1$ and $\lambda_2$:

\[
(m_{\lambda_1} - m_{\lambda_2}) = (M_{\lambda_1} - M_{\lambda_2}) + (A_{\lambda_1} - A_{\lambda_2})
\]

Observed color index, $C_{12}$
Intrinsic color index, $C^0_{12}$
Color excess, $E_{12} = C_{12} - C^0_{12}$
Stellar Structure

Energy transport in a main-sequence (MS) star. The interior luminosity, $L_{\text{int}}$, is generated in the nuclear-burning region near the center and is equal to the surface value, $L^*$.

$$L^* = 4\pi R^*^2 \sigma_B T_{\text{eff}}^4$$

$L_{\text{int}} = L^*$

Pre-Main-Sequence

Energy transport in a pre-main sequence (PMS) star. There is typically no central nuclear burning region. The luminosity $L_{\text{int}}$ monotonically increases from zero at the center to $L^*$ at the surface.

Kelvin-Helmholtz time

$$t_{\text{KH}} = \frac{GM^*^2}{(R^* L^*)} = 3 \times 10^7 \text{yr} M^*^{-1} R^* L^*^{-1}$$

$L_{\text{int}} < L^*$
Pre-main-sequence evolution

Consumption of Nuclear Fuel

\[ E_{\text{tot}} = 0.007 \, f_H \times M_* \times c^2 \]

\[ t_{\text{ms}} \sim 5 \times 10^{-4} \, M_\odot \times c^2 / L_* \]

\[ = 1 \times 10^{10} \, \text{yr} \, (M_\odot,1/L_\odot,1) \]
Recycling of gas via star formation and stellar evolution

Winds from stars with $M \leq 3 \, M_\odot$ provide roughly 90 percent of the mass returned to the interstellar medium. Supernovae and the winds from massive stars account for the remainder. The latter two processes also yield the bulk of the heavy elements.

The Interstellar Medium
Elements in Interstellar Space

X = 0.70 (H); Y = 0.28 (He); Z = 0.02 (heavier elements)

<table>
<thead>
<tr>
<th>Element</th>
<th>Solar</th>
<th>Cosmic</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>3.6(-4)</td>
<td>2.1(-4)</td>
</tr>
<tr>
<td>N</td>
<td>9.3(-5)</td>
<td>6.6(-5)</td>
</tr>
<tr>
<td>O</td>
<td>7.4(-4)</td>
<td>4.6(-4)</td>
</tr>
<tr>
<td>S</td>
<td>1.9(-5)</td>
<td>1.2(-5)</td>
</tr>
<tr>
<td>Si</td>
<td>3.6(-5)</td>
<td>1.9(-5)</td>
</tr>
<tr>
<td>Fe</td>
<td>3.2(-5)</td>
<td>2.7(-5)</td>
</tr>
<tr>
<td>Na</td>
<td>1.9(-6)</td>
<td>...</td>
</tr>
<tr>
<td>Mg</td>
<td>3.8(-5)</td>
<td>2.8(-5)</td>
</tr>
</tbody>
</table>

Anders & Grevesse 1989; Asplund et al. 2005; Snow & Witt 1996

Depletion of refractory heavy elements in ISM gas (relative to solar abundances) is one piece of evidence for dust grains.

Phases of the Interstellar Medium

We describe the phases of the ISM with reference to the chemical state of hydrogen: ionized (HII); atomic (HI); molecular (H$_2$). We will also see that the atomic and ionized phases can be sub-divided via temperature.
Hydrogen, the most abundant element in the Universe, emits radio waves even in cold clouds. To understand this, we need to consider the structure of protons and electrons.

Particles such as protons and electrons possess spin. Because electric charges in motion generate magnetic fields, a proton or electron behaves like a tiny magnet with a north pole and a south pole.

As in the case of two magnets, the energy of a hydrogen atom is slightly different depending on whether the spins of $p$ and $e^-$ are in the same or opposite directions.

If the spin of the electron changes its orientation from the higher-energy configuration to the lower energy one (spin-flip transition), a photon is emitted.

The energy difference between the two spin configurations is only $\sim 10^{-6}$ as great as those between different electron orbits.

The corresponding wavelength is **21 cm** (radio).

The spin-flip transition was first predicted in 1944 by the Dutch astronomer Henrik van der Hulst. Harold Ewen and Edward Purcell first detected it.
Example 21cm spectrum

Evidence for a cold neutral medium (CNM) ~80K and a warm neutral medium (WNM) ~8000K. A range of velocities due to motions of gas within our Galaxy.

Atomic and Molecular Gas Tracers

HI gas: 21cm line

H₂ has no permanent dipole moment, so therefore we use other, trace molecules e.g. 2.6mm (rotational transition) of CO(1-0)

The above lines are at long wavelengths, so are not obscured by dust. But they may become obscured (optically thick) by atoms or molecules in the ground state of the transition (see later).
Ionized Gas (HII) Tracers

Radio continuum emission
(thermal bremsstrahlung)

Recombination lines,
e.g. Hα (Balmer series n=3-2)
but this is affected by dust obscuration.
Note Lyα is hardly able to penetrate neutral atomic gas.

Mean Molecular Weight, $\mu$

$\mu$ is the average mass of a particle of gas relative to the hydrogen mass $m_H$. In a gas of mass density $\rho$, the total number density of particles is:

$$n_{\text{tot}} = \frac{\rho}{\mu m_H}$$

Any one element contributes a number density of particles given by:

$$n_i = \frac{X_i f_i \rho}{A_i m_H}$$

$X_i =$ mass fraction of element $i$
$f_i =$ number of free particles (including electrons) per atomic nucleus
$A_i =$ atomic weight

$\mu = 2.4$ for molecular gas
$\mu = 1.3$ for HI gas
Phases of the Atomic ISM - thermal instability

HI is found both in discrete cold clouds (CNM) and as warmer, more rarefied gas (WNM). What is the origin and how is it maintained?

Thermal Pressure, \( P = n k_B T \)

Empirically: \( nT (\approx P/k_B) \sim 3 \times 10^3 \text{ cm}^{-3} \text{ K} \) \( \Rightarrow \) HI clouds (CNM): \( n=30 \text{ cm}^{-3}, T=80 \text{ K} \)

WNM: \( n=0.5 \text{ cm}^{-3}, T=8,000 \text{ K} \)

Consider a parcel of interstellar gas. Let's compress it at successively higher densities. At each step, the gas will assume an equilibrium \( T \) and \( P \) (found by equating the heating and cooling rates). At lower densities, starlight (FUV photoelectric via dust) heating (and Ly\( \alpha \) cooling): \( T \sim 10^4 \text{ K} \). At higher densities, \( H \) becomes an inefficient radiator (mostly being in the ground electronic state) \( \Rightarrow \) the gas cools \( \sim 100 \text{ K} \) mostly by radiating via the CII line (158 \( \mu \text{m} \)).

\[
\text{Thermal Pressure, } P = n k_B T
\]

Empirically: \( nT (= P/k_B) \sim 3 \times 10^3 \text{ cm}^{-3} \text{ K} \) \( \Rightarrow \) HI clouds (CNM): \( n=30 \text{ cm}^{-3}, T=80 \text{ K} \)

WNM: \( n=0.5 \text{ cm}^{-3}, T=8,000 \text{ K} \)

"Two Phase Model" of the ISM by Field, Goldsmith and Habing (1969)

---

### Phases of the ISM

<table>
<thead>
<tr>
<th>Phase</th>
<th>( n_{\text{tot}} ) (cm(^{-3}))</th>
<th>( T ) (K)</th>
<th>( M \times 10^9 M_\odot )</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>COLD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>molecular</td>
<td>&gt;300</td>
<td>10</td>
<td>2.0</td>
<td>0.01</td>
</tr>
<tr>
<td>Cold Neutral</td>
<td>50</td>
<td>80</td>
<td>3.0</td>
<td>0.04</td>
</tr>
<tr>
<td>WARM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warm Neutral</td>
<td>0.5</td>
<td>8 \times 10^3</td>
<td>4.0</td>
<td>0.30</td>
</tr>
<tr>
<td>Warm Ionized</td>
<td>0.3</td>
<td>8 \times 10^3</td>
<td>1.0</td>
<td>0.15</td>
</tr>
<tr>
<td>HOT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hot Ionized</td>
<td>3 \times 10^{-3}</td>
<td>5 \times 10^5</td>
<td>-</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Field, Goldsmith and Habing (1969); McKee & Ostriker (1977)
Map of the cold, dense interstellar gas surrounding the Local Bubble in the plane of the Galaxy. White areas represent regions of extremely low gas density (which are probably filled with plasma); dark areas reveal where large condensations of cold, dense gas occur. Notice that the local cavity is surrounded by many of these condensations, but this "wall" is broken in several places by low density interstellar tunnels that link the local cavity with other nearby bubble cavities such as the Pleiades and GSH 238+00+09.

**Galactic Context**

**Structure of the Milky Way**

- **Galactic coordinates**: $l$, $b$
- **NIR (COBE)**
- **optical**

Local thickness:
- O,B stars: 100 pc, similar to the HI gas
- G stars: 350 pc
- central bulge: 3 kpc
- stellar halo: > 3 kpc
The sky at 21 cm: the distribution of atomic gas in the Milky Way

The 21 cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy.

Vertical Distribution of Gas

See S&P Ch. 2 and HW1
The detection of 21-cm radio radiation was a major breakthrough that permitted astronomers to probe the Galactic disk.

If we look within the plane of our Galaxy from our position, hydrogen clouds at different locations (A, B, C, D, E) along our line of sight are moving at slightly different speeds relative to us (but note distance ambiguity).

As a result, radio waves from these various gas clouds are subjected to slightly different Doppler shifts. This permits radio astronomers to sort out the gas clouds and thus map the Galaxy.

This map, constructed from radio-telescope surveys of 21-cm radiation, shows the distribution of hydrogen gas in a face-on view of our Galaxy. The map suggests a spiral structure.

Details in the blank, wedge-shaped region at the bottom of the map are unknown. Gas in this part of the Galaxy is moving perpendicular to our line of sight and thus does not exhibit a detectable Doppler shift (Courtesy of G. Westerhout).
Radial distribution of gas in the Milky Way

- HI gas, or the WNM: \( n_H \sim 0.5 \text{ cm}^{-3}, T \sim 8 \times 10^3 \text{ K}, M \sim 4 \times 10^9 \text{ M}_\odot \)
- HI clouds: \( n_H \sim 10-100 \text{ cm}^{-3}, d \sim 1-100 \text{ pc}, T \sim 80 \text{ K}, M \sim 3 \times 10^9 \text{ M}_\odot \)
- \( \text{H}_2 \) gas: \( n_H > 300 \text{ cm}^{-3}, T \sim 10 \text{ K}, M \sim 2 \times 10^9 \text{ M}_\odot \)

Spiral Arms

Our Galaxy resembles M51, a slightly later-type than the Milky Way. The Milky Way is thought to comprise a large barred spiral galaxy of Hubble type SBbc (loosely wound barred spiral) with a total mass of about \( 10^{12} \text{ M}_\odot \), comprising 200-400 billion stars.
The age of the Galaxy is currently estimated to be about 13.6 billion years, which is nearly as old as the Universe itself (Pasquini et al. 2004).

The galactic disk has an estimated diameter of about 100,000 light-years. The distance from the Sun to the galactic center is estimated at about 27,700 light-years. The disk bulges outward at the center.

The distribution of mass in the Milky Way is such that the orbital speed of most stars in the galaxy does not depend strongly on its distance from the center. Away from the central bulge or outer rim, the typical stellar velocity is between 210 and 240 km/s.

The galactic disk is surrounded by a spheroid halo of old stars and globular clusters. While the disk contains gas and dust obscuring the view in some wavelengths, the halo does not. Active star formation takes place in the disk (especially in the spiral arms, which represent areas of high density), but not in the halo.
Map of M51 in the 2.6 mm line of $^{12}\text{C}^{16}\text{O}$ (contours) and the H$\alpha$ line at 6563 Å.

The arms in spiral galaxies represent a wave-like enhancement of density and luminosity rotating at a characteristic pattern speed. Both stars and gas in the underlying disk periodically overtake the arms and pass through them. More massive stars (lifetime $\sim 10^6$ yr) are concentrated on spiral arms, suggesting that spiral arms must produce a local rise in the star formation rate.

H$\alpha$ arms are displaced by about 300 pc downstream from those seen in CO $\Rightarrow$ cold gas entering the arms first condenses to form large cloud structures that later produce massive stars. The time lag is $\sim 3 \times 10^6$ yr.