Astronomy 401/Physics 903
Lecture 9
Gas, Dust and Star Formation

In addition to stars, galaxies contain **gas** and **dust**, which are both very important to the formation of stars in galaxies. The gas and dust in galaxies is called the **interstellar medium (ISM)**. The ISM and the process of star formation are complex and inter-connected; they both affect each other.

Gas in galaxies is primarily hydrogen, and comes in three basic forms:

- **Molecular**: H_2—forms in cold, dense regions
- **Atomic/Netural**: "HI"—single atoms of neutral hydrogen
- **Ionized**: "HII"—ionized hydrogen

All forms coexist in galaxies.

Almost all galaxies have gas, but in amounts varying from nearly zero to being the dominant state of matter (i.e. nearly all gas, few stars). Ellipticals have less gas and spirals have more gas.

1 Phases of the Interstellar Medium

The following is a very rough breakdown of the typical phases of gas found in galaxies. All of these phases actually exist at a range of temperatures and densities, and are usually subdivided into additional phases. See Figure 1 for a more detailed breakdown of the ISM.

1.1 Molecular gas

- Very dense (10^8 to 10^{11} atoms m^{-3}) and cold ($T \sim 10 - 50$ K)
- Usually found in clumps called molecular clouds or Giant Molecular Clouds (GMCs)
- This is where stars form—gas that is dense and cold can collapse more easily to form stars
- Hard to detect because it has no easily observed emission lines. Usually detected indirectly by using carbon monoxide (CO) as a tracer, which has emission lines that can be detected at submillimeter wavelengths.
- Other, more exotic molecules also seen: H_2O, H_2CO (formaldehyde), H_2SO_4 (sulfuric acid), CH_4 (methane), NH_3 (ammonia), many others

1.2 Atomic gas

- Less dense, warmer than molecular gas. $n \sim 10^6$ atoms m^{-3}, $T \sim 8000$ K
- Easily detected through the 21-cm emission line with radio telescopes—the electron spin-flip transition between the ground state hyperfine levels of hydrogen, which produces a photon with wavelength 21.106 cm or frequency 1420.406 MHz
- Confined to a thin layer in the plane of disk galaxies

- Extends to much larger radii than starlight $\Rightarrow$ good for studying the dynamics of galaxies at large radii, through Doppler shifting of the 21-cm line

1.3 Ionized gas

- Hot ($T \gtrsim 10,000$ K)
- Heated by some combination of
  - ionizing radiation, emitted in the ultraviolet (UV), usually by very hot and short-lived stars. Hydrogen ionizing photons have energies greater than 13.6 eV, or wavelengths shorter than 912 Å (1 Å= 10^{-10} m, this is how astronomers measure wavelengths of optical light).
  - kinetic energy: shocks. These can come from supernovae or rapid mass loss in the late stages of stellar evolution
- Detected by recombination emission lines (free electrons recombining with nuclei), usually detected in the optical. One of the strongest and most common: Hα, the $n = 3$ to $n = 2$ transition, seen at 6563 Å.
- Three main physical components:
  - HII regions—compact, ionized regions near young stars (OB associations). These are bright spots in optical galaxy images.
  - Diffuse or Warm Ionized Medium—widely distributed, heated by “escaping” UV radiation
  - Hot Ionized Medium—usually in halo, heated by shocks

These phases are largely in pressure equilibrium with each other.

$P = nkT \Rightarrow$ if in equilibrium, $nT \sim$ constant, so high densities and low temperatures can be in balance with low densities, high temperatures.

The ISM is dynamic—phases change and evolve, largely in response to star formation.

And... the total amount of gas changes with time.

Sources (processes which add gas):

- Infall of fresh gas from outside the galaxy
- Return of gas from evolving stars (mass loss from stellar winds in the late stages of stellar evolution, supernovae)
- Accretion of other galaxies

Sinks (processes which remove gas):

- Gas condenses into stars
- Supernovae, stellar winds blow gas out of the galaxy
- Gas stripped by interactions with nearby galaxies

6 CHAPTER 1

Table 1.3 Phases of Interstellar Gas

Phase	T(K)	$n_{\rm H}$(cm^{-3})	Comments
Coronal gas (HIM) $f_V \approx 0.5?$ $\langle n_{\rm H}\rangle f_V \approx 0.002\,{\rm cm}^{-3}$ ($f_V \equiv$ volume filling factor)	$\gtrsim 10^{5.5}$	~ 0.004	Shock-heated Collisionally ionized Either expanding or in pressure equilibrium Cooling by: ◇ Adiabatic expansion ◇ X ray emission Observed by: • UV and x ray emission • Radio synchrotron emission
H II gas $f_V \approx 0.1$ $\langle n_{\rm H}\rangle f_V \approx 0.02\,{\rm cm}^{-3}$	10^4	$0.2 - 10^4$	Heating by photoelectrons from H, He Photoionized Either expanding or in pressure equilibrium Cooling by: ◇ Optical line emission ◇ Free–free emission ◇ Fine-structure line emission Observed by: • Optical line emission • Thermal radio continuum
Warm H I (WNM) $f_V \approx 0.4$ $n_{\rm H} f_V \approx 0.2\,{\rm cm}^{-3}$	~5000	0.6	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Pressure equilibrium Cooling by: ◇ Optical line emission ◇ Fine structure line emission Observed by: • H I 21 cm emission, absorption • Optical, UV absorption lines
Cool H I (CNM) $f_V \approx 0.01$ $n_{\rm H} f_V \approx 0.3\,{\rm cm}^{-3}$	~ 100	30	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • Optical, UV absorption lines
Diffuse H_2 $f_V \approx 0.001$ $n_{\rm H} f_V \approx 0.1\,{\rm cm}^{-3}$	~ 50 K	~ 100	Heating by photoelectrons from dust Ionization by starlight, cosmic rays Cooling by: ◇ Fine structure line emission Observed by: • H I 21-cm emission, absorption • CO 2.6-mm emission • optical, UV absorption lines
Dense H_2 $f_V \approx 10^{-4}$ $\langle n_{\rm H}\rangle f_V \approx 0.2\,{\rm cm}^{-3}$	$10 - 50$	$10^3 - 10^6$	Heating by photoelectrons from dust Ionization and heating by cosmic rays Self-gravitating: $p > p$(ambient ISM) Cooling by: ◇ CO line emission ◇ C I fine structure line emission Observed by: • CO 2.6-mm emission • dust FIR emission
Cool stellar outflows	$50 - 10^3$	$1 - 10^6$	Observed by: • Optical, UV absorption lines • Dust IR emission • H I, CO, OH radio emission

Figure 1: This table provides a detailed breakdown of the phases of interstellar gas. f_V is the volume filling factor, the approximate factor by which the volume of the Milky Way is filled by gas in a given phase. Relevant acronyms: hot ionized medium (HIM), warm neutral medium (WNM), cold neutral medium (CNM). Source: Draine, Bruce T. *Physics of the Interstellar and Intergalactic Medium*, Princeton University Press, 2010

- Metals in gas condense into dust

The phases of the ISM respond to the current state of star formation, and the rate of star formation responds to the state of the gas. Very useful to consider the **star formation rate (SFR)** in a galaxy.

$$\text{SFR} \equiv \text{mass in new stars formed per unit time, expressed in } \mathrm{M}_\odot \text{ yr}^{-1} \tag{1}$$

Within galaxies and from galaxy to galaxy, there is a close relationship between the density of the gas and the amount of star formation. Because most star formation takes place in disk galaxies, this can be expressed in terms of the surface denisties of star formation and gas (gas mass per unit area $\Sigma_{\rm gas}$, star formation rate per unit area $\Sigma_{\rm SFR}$). The relationship is called the Schmidt law:

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^a, \tag{2}$$

where a is an exponent that tells us about the efficiency of star formation (how good galaxies are at turning their gas into stars).