Overview of the Interstellar Medium

1. Basics & Nomenclature

The *interstellar medium* is the medium between stars in galaxies. We will include the *circumgalactic medium* in our discussion, though usually that refers to diffuse gas which may be bound to the galaxy but is not intermixed with its main population of stars. Here we concentrate on the overall picture and the processes at play in determining the conditions of the gas.

The contents of the interstellar medium are: gas (ions, atoms, molecules); dust (small solid particles, mostly $< 1\mu$m; cosmic rays (ions and electrons, distinguished from the "gas" by its nonthermal energy distribution extending to as high as 10^{21} eV); radiation (from many sources); and dark matter. The interstellar medium is also threaded by magnetic fields.

The gas content can be divided into several classes, from hottest to coolest:

- Coronal gas at 10^5–10^6 K and typical density of $n \sim 0.005$ cm^{-3}, attributed to shockheating by supernova blast waves, and highly collisionally ionized. Observable through synchrotron in the radio, and UV and X-ray emission.
- HII gas at 10^4 K, with densities range from 0.3 (in the diffuse medium) to 10^4 cm^{-3} (in HII regions). Photoionized primarily by nearby hot stars. Observable through optical emission lines and thermal radio continuum.
- HI gas at a range of temperatures (100 K to 5000 K) and densities (30 to 0.5 cm^{-3}). Observable through embedded metal absorption lines and the 21 cm line.
- H_2 at 10 K to 50 K and in diffuse or dense regions with densities ranging from 100 to 10^6 cm^{-3}. Observable through CO rotational transitions, dust emission, and metal absorption lines.

The overall cycle of the interstellar medium is thought to be as follows. Gas flows into dark matter halos. Relative to the dark matter, gas can efficiently radiate energy and can fall deeper into the potential well. It loses angular momentum less efficiently and forms a rotating disk. The disk tends have a large fraction of neutral gas; as described below, the temperature at 5000 K of neutral gas is stable. Within the disk and perhaps at previous stages, perturbations in the gas can become unstable to cooling and can form molecular clouds. A small fraction of the mass in such clouds (around 1%) will form into stars. Hot, massive O and B stars, and later on evolved stars, can ionize the gas around them. Stellar winds, supernovae, and stellar mergers can cause gas to be returned to the interstellar medium, along with nucleosynthetic products of stellar processes. Blast waves from supernovae and perhaps winds from active galactic nuclei can remove gas from the galactic system, either temporarily in a fountain-like structure or permanently.

The multiphase interstellar medium is far from thermodynamic equilibrium, and is prevented from achieving equilibrium primarily through stellar processes, which produce ultraviolet radiation and input kinetic energy in a non-uniform fashion and on time scales much shorter than any equilibration time for the interstellar medium as a whole. Thus, the thermal state of the gas is determined by local conditions and a number of relevant heating and cooling processes. The relevant processes depend on the temperature and density of the gas as well as the radiation field.

1.1. Coronal gas

Diffuse hot gas, such as coronal gas (or gas in a dark matter halo surrounding a galaxy or cluster), can often be approximated with collisional ionization equilibrium. In this case the effect of ionizing radiation is ignored and the ionization fraction is only a function of temperature. Such gas experiences cooling due to collisional excitation followed by radiative deexcitation, and at low densities (below the critical density for the ions) collisional deexcitation may be ignored. At temperatures above 10^4 K, the ionized electrons of H dominate collisions. In this case cooling can be quantified by the cooling function:

$$\Lambda = n_e n_H f_{\rm c}(T; \vec{A}) \tag{1}$$

where $\vec{A}$ indicates the elemental abundances relative to H. At high temperatures ($10^{6.5}$–$10^{7.5}$ depending on abundance), this cooling is dominated by bremstrahlung and scales as $f_{\rm c} \propto T^{1/2}$. For low metallicity gas there are peaks at $\sim 2 \times 10^4$ K and $\sim 10^5$ K associated collisional excitation within H and He. For solar abundance gas, the addition of O and C cooling lead to a broad peak around $\sim 2 \times 10^5$ K and Fe and Ne dominate between 10^6 and 10^7 K.

1.2. Ionized gas

HII gas is ionized gas at around 10^4 K typically found around stars hot enough to emit photons blueward of the Lyman limit (912 Å, or 13.6 eV). The illustrative case of an HII region is a *Stromgren sphere*, which results from a spherically symmetric, uniform cloud of gas being ionized by such a star. If Q is the number of photons emitted by the star, and assuming Case B recombination (optically thick to photons slightly more energetic that the Lyman limit), then equilibrium between ionization and recombination dictates:

$$Q = \frac{4\pi}{3} R_S^3 \alpha_B n(H+) n_e = \frac{4\pi}{3} R_S^3 \alpha_B n_e^2 \tag{2}$$

where the recombination coefficient can be approximated as $\alpha_B = (2.56 \times 10^{-13})(T/10^4\ {\rm K})^{-0.83}$ cm^3 s^{-1}. The exercises below will show that these regions have sizes of a few parsecs and sharp boundaries.

The HII gas is usually primarily heated by photoionization. In ionization equilibrium the number density of ionizations equals the recombination rate $\alpha_B n_e n_H$. If the mean energy per photoelectron is $\phi k T_*$, where T_* is the effective temperature of the star then the heating rate is:

$$\Gamma = \alpha_B n_e n_H \phi k T_* \tag{3}$$

An exercise below demonstrates that ϕ is of order unity. The dependence of cooling on gas temperature is contained in α_B, which declines almost linearly with T.

As long as metals are present in the gas, HII regions are primarily cooled by collisional excitation of ions followed by radiative decay. The primary ions responsible are OIII, SIII, and to a lesser extent OII, NeII, and NII. Within the relevant range of gas temperatures for HII regions, collisionally excited cooling increases with T, since higher temperatures lead to stronger collisions and more excited ions. Cooling is an increasing function of metallicity due to the greater number of ions. Cooling is a decreasing function of density due to increased collisional deexcitation.

The decreasing heating and increasing cooling as a function of gas temperature lead to an equilibrium temperature at around 8,000 K for $n \sim 4000$ cm^{-3}, $T_* \sim 35,000$ K, and solar abundances. The equilibrium temperature can range between 5,000 and 15,000 K depending on metallicity, and is an increasing function of density. This temperature dependence and the resulting signatures in the collisionally excited lines are an important indicator of metallicity.

Similar regions are found around evolved stars whose hot stellar cores are exposed, on their path to becoming white dwarfs. Because of the smaller flux of these stars, these *planetary nebulae* are smaller than HII regions.

Ionized gas in HII regions is typically detected through recombination lines of hydrogen and collisionally excited lines.

Diffuse ionized H also exists throughout disk galaxies like the Milky Way in a warm phase. In the Milky Way its distribution can be constrained from the dispersion measures to pulsars, and it is distributed throughout the disk and has a vertical structure more extended than the HI disk. In other galaxies it can be observed through its collisionally excited line emission.

1.3. Neutral gas

Diffuse neutral gas in the disk exists in multiple phases. In many galaxies, including the Milky Way, it extends considerably further than the stars, up to several times further out in radius. Heating and cooling of this gas are complex processes. Heating is dominated by cosmic ray ionization and photoelectric heating by dust (which requires lower frequency photons than photoelectric heating by H). Cooling is dominated by collisional excitation lines [CII] 158 μm and [OI] 63 μm. [CII] becomes important above 100 K, and the cooling rate rises slowly until 10^4 K, when Lyman-α cooling rapidly becomes important. Under typical conditions, a stable thermal equilibrium is available at both 100–200 K (where [CII] 158 μm has a stronger flux) and at 5,000–6,000 K (where [OI] 63 μm has a stronger flux).

The neutral gas can best be traced through the 21 cm emission due to the hyperfine transition of H, between misaligned and aligned spins of the electron and proton. The energy of the system is lower by an amount equivalent to a 21 cm photon when the magnetic moments are aligned, and thus when the spins are mis-aligned. The Einstein A coefficient for the radiative transition from aligned to mis-aligned is 2.85×10^{-15} s^{-1}. In the exercises, we will show that under interstellar conditions without self-shielding these transitions lead to a 21-cm line luminosity directly proportional to the hydrogen mass of:

$$L = \left[\frac{3}{4}\frac{Ahc}{\lambda m_p}\right] M_H \tag{4}$$

Commonly the gas is sufficiently dense that self-shielding is important; this effect depends on the geometry and conditions of the gas but can easily be 20–30% overall for a galaxy.

1.4. Molecular gas

Molecular hydrogren populates the densest regions of the interstellar medium. H_2 can form in pristine gas but only through indirect mechanisms. In galactic environments, molecular hydrogren is formed through dust grain catalysis; two H atoms bound to the grain surface react to form H_2, and the released energy (4.5 eV) detaches them. H_2 is susceptible to photodissociation, through excitation to rotation-vibration levels that can decay into a dissociated state. Due to this effect, H_2 is present in the neutral medium in very small amounts. Molecular regions remain molecular due to self-shielding; deep in the cloud there is a large optical depth for the photons exciting to the rotation-vibration levels. H_2 emission is very weak, so molecular clouds are typically studied through the emission of other molecules, principally through radio-wavelength lines of CO calibrated relative to H_2 through virial masses of local clouds.

Molecular regions are the where star formation occurs, through further cooling and collapse of protostellar objects. These star forming regions lead to the dissociation and ionizing of the gas surrounding them (creating HII regions), as well as to supernovae which can shock heat the interstellar medium to create coronal phase gas.

1.5. Dust

Dust comprises of order 1% of the gas by mass. In the diffuse interstellar medium the gas can be shown to be depleted in a number of abundant elements, specifically C (about 30–40% depletion), and Mg, Si, and Fe (about 90% depletion). How depleted oxygen is is unclear. There is a tendency for higher depletion of elements with a high condensation temperature (approximately $T_c > 1000$ K). These depleted elements likely form the interstellar dust, whose presence was first detected through the extinction and reddening it causes. Analysis of the extinction leads the conclusion that the size of dust particles range from 0.01 to a few tenths μm. Warm dust emission in the infrared reveals the presence of small dust grains. Mid-infrared emission lines indicate the presence of polyaromatic hydrocarbons. A broad absorption band at 2250 Åmay also be due to aromatic carbon of some variety. A large number of diffuse interstellar bands are detectable whose origin is unknown.

1.6. Cosmic Rays

Cosmic ray particles are present in the gas, with a steeply declining spectrum in energy ($E^{-2.6}$). They are thought to be accelerated around shock fronts through the first-order Fermi process. Most of the particles are protons, but they come in many elements with a vaguely solar abundance ratios. They are overabundant in Li, B, and Be, probably because these can be formed through spallation of higher mass cosmic rays against protons, and in Mg, Si, and Fe, perhaps because dust plays some role in sourcing the cosmic ray distribution.

2. Commentary

The complexity of the interstellar medium and its physics are apparent even in this brief discussion. A course in extragalactic astrophysics can hardly do it justice given the phenomenology we need to cover about galaxies.

However, much of that phenomenology, and many of the theoretical predictions of galaxy evoution, are derived from an understanding of the interstellar medium. Particularly as observations of galaxies reach ever higher redshifts — and thus physical conditions with a smaller likelihood of a well-studied local analog — we all do well to keep this dependence in mind.

3. Key References

- *Physics of the Interstellar and Intergalactic Medium, Draine et al. (2007)*
- Leroy ARAA
- Kalberla ARAA

4. Order-of-magnitude Exercises

1. Estimate the cooling time of hot gas. The cooling time of hot gas (assuming constant density) can be estimated as $3nkT/2\Lambda$. At solar abundance, $n = 0.005$ cm^{-3}, and $T = 10^6$ K this is $\sim 2 \times 10^7$ yr; it varies roughly in proportion to metallicity and approximately as $T^{1.7}$.

2. Estimate the temperatures at which cooling due to [CII] 158 μm and [OI] 63 μm should start to become important.

3. Estimate the optical depth due to dust through the warm-phase neutral medium, for 100 pc and for 8 kpc.

4. We often see little reddening of the central star of an HII region. Assuming the extinction is less than 0.1 mag, what would that say about the dust fraction in HII regions relative to its presence in the neutral and molecular gas?

5. Dust emits a large proportion of its light around 100 μm in an approximately thermal distribution. What temperature is the dust?

5. Analytic Exercises

1. Derive Equation 6 for the luminosity of the HI 21-cm line, a hyperfine transition between $n = 1$ ground states of neutral hydrogen, the upper one with spins of the electron and proton aligned and the lower one with them misaligned.

   We proceed first by showing that the population levels of the hyperfine states are set entirely by the statistical weights of the states, and not by the details of the gas temperature and density. This is because collisions are far more common than radiative transitions, and the energy of collision is far greater than the hyperfine transition energy.

   Interstellar gas conditions vary, but it is sufficient for our purposes here to assume $n \sim 1$ cm^{-3} and $T \sim 10^4$ K. The rate of collisions between neutral atoms is:

   $$C = v\sigma n \sim 3 \times 10^{-10} \text{ s}^{-1} \tag{5}$$

   where $\sigma \sim 10^{-16}$ cm^2 and $v \sim \sqrt{kT/m_p}$. This rate $C \gg A$.

   The 21-cm line corresponds to $\Delta E = hc/\lambda =$. Each collision correponds to $E_c \sim kT =$. The Boltzmann factor $\exp(-\Delta E/kT)$ is therefore extremely close to unity for these two states.

   Together, these results imply that at any time the population of the two hyperfine states are simply their statistical weight. Spin-aligned states have a total angular momentum number $l = 1$, so the upper state has $g = 3$ ($m = -1$, 0, 1); spin-misaligned states have $l = 0$, so the lower state has $g = 0$ ($m = 0$). Thus 3/4 of the hydrogren is in the upper state.

   Putting this together we find that the luminosity is the number of hydrogen atoms N_H, times the fraction in the upper state 3/4, times the rate each upper state decays at, times the energy it emits when it does:

   $$L = \frac{3}{4} N_H \Delta E A = \left[\frac{3}{4}\frac{Ahc}{\lambda m_p}\right] M_H. \tag{6}$$

6. Numerics and Data Exercises

1. Something with CHIANTI database and chiantipy
2. Calculating ϕ For the process

$$X^{+r} + h\nu \rightarrow X^{+r+1} + e^{-1} + \text{ kineticenergy}, \tag{7}$$

the heating rate per unit volume is:

$$\Gamma = n\left(X^{+r}\right)\int_{\nu_0}^{\infty} \mathrm{d}\nu\sigma_{\mathrm{pi}}c\left(\frac{u_n}{h_\nu}\right)(h\nu - h\nu_0) \tag{8}$$

where $h\nu_0$ is the ionization energy. The number of ionizations per unit volume can be calculated similarly.

3. depletion onto dust
4. reddening in optical, NIR
5. Virial estimate of H2 masses
6. HII map exploration; dust, CO, HI emission

‘

REFERENCES

Draine, B. T., Dale, D. A., Bendo, G., et al. 2007, ApJ, 663, 866

This preprint was prepared with the AAS LaTeX macros v5.2.