Interstellar Astrophysics
Summary notes: Part 1

Dr. Paul M. Woods

Convention: Figure numbers refer to the chapter and figure number (N-n) in Freedman & Kauffman (8th or 9th ed.). Density units are expressed in cm^{-3}, as is the astronomical standard. $1\,\mathrm{cm}^{-3} = 10^{-6}\,\mathrm{m}^{-3}$.

1 Introduction & overview

In galaxies the space between stars is not completely empty but is found to be made up of relatively low density gas and microscopic dust particles. This medium between the stars is called the interstellar medium (ISM). The ISM makes up 75% of the baryonic matter of the universe, with the remainder in stars. It forms a crucial part of the cycle of matter in a galaxy, being the source of young stars, and the repository of ejected stellar material from old stars. Although we can try to recreate the conditions of the ISM in the laboratory, our best avenue of investigation is using telescopes to observe the light from the ISM.

Evidence for the ISM

Evidence for the ISM in our own galaxy (the Milky Way) comes from a variety of methods:

Direct imaging (at optical wavelengths) shows many regions of extended emission associated with glowing gas – e.g. the great nebula in Orion (M42) – see Fig. 18-1. Emission nebulae emit light with a characteristic emission line spectrum (showing lines of the Balmer series of hydrogen, together with lines of helium and some special emission lines of oxygen referred to as forbidden lines – see later). Fig. 18-2 shows some emission nebulae in the Orion region, which provide direct evidence for gas atoms in the ISM.

Diffuse emission nebulae are large, irregular patches of optically-emitting gas. They are spatially confined to the Galactic plane, with a scale-height of <50 parsecs. They are found near hot, luminous stars of spectral types O and B.

OB stars are hot stars (effective temperature > 20000 K) which emit copious amounts of ultraviolet radiation at wavelengths < 912 Å. Such photons can ionise hydrogen atoms and we refer to these regions as H II regions (signifying that the hydrogen in mainly ionised – H II rather than neutral H I). The H-Balmer lines are produced by cascades of electrons in H-atoms from levels above $n = 2$ following recombination (with electrons) of the H II gas – see Figs. 5-21, 5-24, 5-25 or 18-3 for this Balmer line emission process.

Typical emission nebulae have mass in the range 100–10000 $M_\odot$. Their diameters are large, typically several parsecs, and thus the gas densities are relatively low; typically 10^2–10^3 atoms per cm^3.

[NB. Planetary nebulae are technically H II regions - but they are much smaller and are formed by the ejection of gas from a low-mass star near the end of its lifetime. The ejected gas is excited by the UV radiation from the hot stellar remnant which is evolving towards the white dwarf stage. Gaseous masses of PN are small, typically about 0.5 $M_\odot$. They show similar emission line spectra as bone fide H II regions – e.g. hydrogen and helium recombination lines and forbidden lines from heavier elements.]

Further evidence for the existence of the ISM comes from detailed spectroscopy of stars used as background probes of ISM gas. At optical wavelengths, atomic absorption lines of calcium (Ca II 3968, 3933 Å) and sodium (Na I 5895 Å) are often seen, which appear stationary in binary star spectra (where the stellar lines are found to move in wavelength by the doppler motions of the orbiting stars) – showing that their origin is NOT in the star's atmosphere but in the intervening gas. In the ultraviolet and far-UV many more ISM absorption lines are seen from many different atomic species. These lines are called resonance lines – since they occur from electron transitions from the atomic ground states (see Fig. 5-25 and the later section of ISM elemental abundances).

Evidence for dust in the ISM

Direct imaging (e.g. Fig. 18-2) shows dark nebulae that are so opaque that they block out background visible light (either from background stars or emission nebulae gas) – e.g. the Horsehead Nebula in Orion. This is interpreted as obscuration by dust. Fig 18-4 shows regions of more concentrated obscuring dust patches on the sky called Barnard Objects (dimensions of a few arcmin) and even small dark regions (×10 smaller) are called Bok Globules (Fig. 18-9). These dark nebulae are relatively more dense that the general ISM diffuse clouds, having densities of 10^2–10^5 particles per cm^3 (made up of atoms, molecules and dust particles) and have low temperatures of 10–100 K. They are often found within H II regions.

Other evidence for dust comes from imaging of reflection nebulae (see Fig 18-5), which are patches of gas/dust in lower concentration than in dark nebulae. Nearby OB stars have their optical light scattered by the dust particles in these nebulae. The dust particles have diameters typically of about 500 nm, similar to the wavelength of visible radiation, and the dust scatter blue light more than red light - hence the bluish appearance of reflection nebulae (similar process gives the Earth's sky its blue colour).

Interstellar reddening and interstellar extinction also provide evidence for dust in the ISM. Fig. 18-6(a) shows the basic process by which light from a background star is caused to redden by scattering from the dust in the line of sight. Fig. 18-6(b) shows how more distant stars appear redder that nearer stars.

By comparing the detailed observed energy distributions (i.e., spectra over a wide range of wavelengths) from intrinsically identical stars, but at different distances (and thus different amounts of dust extinction) one can determine the detailed scattering/absorption properties of the dust to form the interstellar extinction curve – a plot of the amount of extinction versus wavelength. We will look at this in more detail later on.

Direct imaging at optical wavelengths of external spiral galaxies, viewed edge-on, shows the location of dust in these galaxies confined to the galactic plane and seen as dust lanes in these images (see Figs. 18-7 and 18-8).

Cool dust can emit infrared radiation and we can see this directly from IR satellite images of the Galaxy (e.g. Fig. 6-34(c) shows the *IRAS* satellite picture of the sky at 12–100 microns, showing the emission coming from dust radiating as a blackbody at temperatures of 100–300 K. See also Fig. 18-8).

Infrared spectroscopy (e.g. with the *ISO* satellite) of stars and other sources shows broad absorption bands, which can be identified with solid-state absorptions in dust particles like silicates.

1.1 The main phases of the ISM

Our current model of the ISM posits the existence of 4 main temperature components:

(i) A hot ionised medium (HIM) with low density ($n \sim 10^{-3}\,\mathrm{cm}^{-3}$) and high temperature $T \sim 10^6\,\mathrm{K}$. Believed to occupy about 70% of the volume of the ISM but little of its mass. It is believed to arise through the heating and energy input from overlapping supernovae explosions and their remnants. It is directly seen in X-rays.

(ii) A cold neutral medium (CNM) occupying a small volume fraction but most of the mass of the ISM, comprising the large diffuse interstellar gas clouds. Cloud densities are typically $n \sim 10^1$–$10^3\,\mathrm{cm}^{-3}$ and low temperatures, typically $T \sim$30–100 K.

(iii) two further interface regions between the HIM and CNM:

A warm ionised medium (WIM) with a temperature $T \sim 8000\,\mathrm{K}$ and density $n \sim 0.15\,\mathrm{m}^{-3}$ and H-ionised fraction $X_\mathrm{H} \sim$70% produced by photoionisation from nearby hot OB stars. A warm neutral medium (WNM) with similar $T \sim$8000 K and density, but with the hydrogen mainly neutral, with a small H-ionisation fraction of $X_\mathrm{H} \sim$10% maintained by X-rays penetrating into the inner regions from the HIM.

In temperature terms this 3-phase model of the ISM (cold, warm and hot) are in approximate pressure equilibrium: i.e., pressure $(P) = n\,k\,T \sim$ constant. Thus the coldest regions will tend to be the densest and vice versa.

Overall the mean density of the ISM in our Galaxy is about 10^2 particles cm^{-3} (averaged over all phases) but is highly clumped (with a filling factor of about 3%). The gas is mainly hydrogen (90%), helium (10%) and other atoms ("metals", like C, N, O,…Fe) <1% by number.

Dust grains are generally mixed with the gas atoms in the rough ratio of 10^{12} gas atoms for every dust grain. The dust grains have a power-law size distribution, with radii $a \sim 5\times10^{-9} - 2\times10^{-7}\,\mathrm{m}$, with smaller grains being more abundant.

The CNM is dominated by the diffuse clouds with $n \sim 10^1$–10^3 cm^{-3} and $T \sim$30–100 K, with individual cloud radii of a few parsecs. These clouds are cold enough that simple molecules can form in them, like H_2 and CO. However, most interstellar molecules are mainly found in the denser dark clouds (like Barnard Objects and Bok Globules) with densities $n \sim 10^3$–10^4 cm^{-3} and $T \sim$10 K. These clouds are deficient in atomic hydrogen (as deduced from the absence of H I 21 cm emission, with the H being mainly molecular). Still denser regions are Giant Molecular Clouds with $n \sim 10^7$ m^{-3} and $T \sim 50$ K, which are associated with sites of new star formation.