CHAPTER 6
Gas

Chapter Objectives: to describe the gas phases and distributions in different types of galaxies

Toolbox:	
phases of the ISM	hyperfine transitions
column density	metallicity

6.1 Radiation from Neutral Atomic Gas

The *interstellar medium* (ISM) is the material between the stars in a galaxy. It consists of intermixed gas and dust, with about 100 times more gas than dust by mass. The *phases* of the interstellar medium include a cold component, a warm component, and a hot component; the gas may be in the form of atoms, molecules, or ions. Some gas particles are diffusely distributed throughout the disk; others are clumped into big or small clouds. The average disk density is only about 1 atom per cubic centimeter.

Hydrogen atoms are the primary form of ordinary matter. They radiate strongly in the centimeter (radio) part of the electromagnetic spectrum, owing to electron jumps between split levels in the ground state. This split, or *hyperfine structure*, is caused by the slightly different energies an electron has depending on whether its spin is in the same direction as the proton spin or in the opposite direction, as shown in Figure 6.1. Slightly more energy is required for the electron to have the same spin (called the *parallel state*) than the opposite spin (*antiparallel state*): In the antiparallel state, the electron and proton, being oppositely charged, behave like the north and south pole of two magnets brought near each other. The parallel state is analogous to two north poles brought together; there is a slight repulsion, so this is a higher energy state.

A hydrogen atom that collides with another particle (or acquires sufficiently energetic radiation) can undergo a *spin-flip transition*, in which the electron flips its spin orientation and moves to the higher energy level of the ground state. The electron is very unlikely to flip back spontaneously to its original spin

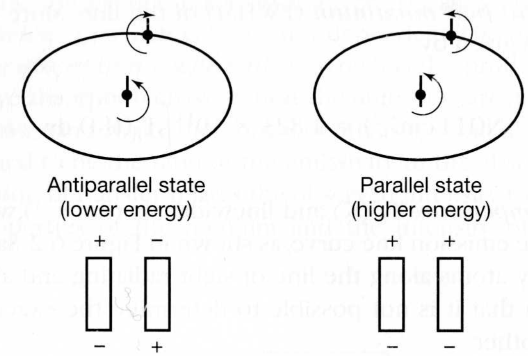

FIGURE 6.1 ***Hyperfine transitions in a hydrogen atom.***

orientation; on average in the interstellar medium, a spontaneous decay for any given atom occurs about once every 10^7 years. That same atom will be hit about every million years on average, and then the colliding particle will cause deexcitation and carry the extra energy away. Because there are so many hydrogen atoms, however, many are able to spontaneously decay, and when they do, they emit a photon with a wavelength $\lambda = 21$ cm (which corresponds to a frequency $\nu = c/\lambda = 1420$ Mhz).

Atomic clouds, called *H I clouds* because they are mostly neutral hydrogen, have temperatures of 80 K–100 K as a result of a balance between heating from incoming stellar radiation and cooling from cloud radiation. The dominant form of cooling comes from radiation by collisionally excited carbon atoms that are intermixed with the hydrogen atoms. In addition to atomic clouds, there is a pervasive distribution of warm intercloud neutral gas with temperatures of about 1000 K.

Gas emits all along a given line of sight, so that the total thickness or geometry of a radiating region is not always determinable. Instead of speaking of the number density, n (number per cubic centimeter), of material in a given direction, it is customary to speak of the *column density*, N (number per square centimeter), which is the material integrated along the line of sight of length L:

$$\boxed{N(\text{cm}^{-2}) = \int n\, dL}$$

The column density is measured in terms of the observed brightness of a region, which depends on the cloud temperature and the background source (if any) temperature, moderated by the optical depth at the wavelength of interest. The 21-cm emission is received over a range of frequencies (or velocities) because relative motions of material in the disk lead to Doppler-shifted emission.

If the atomic hydrogen line is not saturated (that is, if the gas is optically thin, as atomic hydrogen usually is), then the column density $N(H\ I) \propto T\,\Delta v$, where Δv

is the *full width at half maximum* (FWHM) of the line. More specifically, the column density is given by

$$N(\text{H I cm}^{-2}) = 1.823 \times 10^{18} \int T_B(\text{H I})\, dv$$

for *brightness temperature* T_B (K) and linewidth dv (km s^{-1}),which integrates the area under the emission line curve, as shown in Figure 6.2. Saturation means there are so many atoms along the line of sight radiating and absorbing at the same wavelength that it is not possible to determine the exact number, since they block each other.

In the limit of small (hν/kT), the exponential term in the Planck function (described in Chapter 3) can be replaced by 1 + (hν/kT) using the approximation $e^x = 1 + x$. For typical atomic cloud temperatures of 100 K, the exponential term is small (hν/kT = 6.86×10^{-4}), so the approximation is valid. The Planck function can be represented by the *Rayleigh-Jeans approximation*:

$$I_\nu = \frac{2kT_B\nu^2}{c^2}$$

The brightness temperature is defined by this equation. Thus, the brightness temperature registered by the radio telescope is directly related to the intensity of the source, which depends on the number of radiating atoms per unit solid angle.

The equation of transfer relates the observed intensity to the intensity coming from a source. There is absorption as well as emission by the gas, so the simple equation of transfer that we wrote in Chapter 4 must be modified to include the emission term if we are observing at a wavelength for which the gas emission can be detected (e.g., 21 cm). The *emissivity*, or energy emitted by the

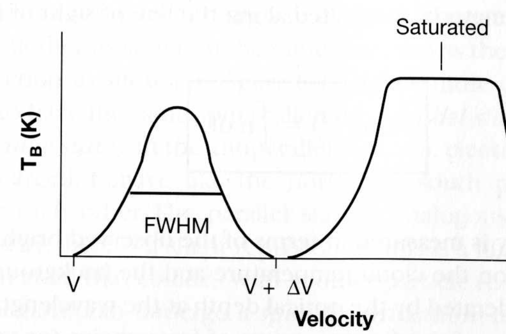

FIGURE 6.2 ***The column density is obtained by integrating the emission over the whole spectral line, shown on the left. If the line is saturated, as shown on the right, then the calculated column density is only a lower limit.***

radiation per unit volume per unit solid angle per second, is represented by the *emission coefficient*, j_ν, which is frequency-dependent. The *absorptivity* is represented by the *absorption coefficient*, κ_ν, which is the product of the gas density and effective absorption cross section; the units of κ_ν are inverse length. With this definition, we can rewrite the optical depth as $\tau_\nu = \int \kappa_\nu dl$. The *source function*, S_ν, is defined to be the ratio of the emissivity to the absorptivity: $S_\nu = j_\nu/\kappa_\nu$. Then the equation of transfer relates the observed intensity to the emission and absorption properties of the medium and the intensity of the background source by

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

The derivation of this equation is beyond the scope of this text, but it is detailed in references (e.g., Spitzer 1978, Scheffler and Elsasser 1987).

The gas is said to be in *local thermodynamic equilibrium* when the source function is given by the Planck function for the local gas temperature. If we substitute the brightness temperature for the intensity and integrate the equation of transfer over the optical depth, we get for a uniform medium

$$T_B = T_o(1 - e^{-\tau_\lambda}) + T_b e^{-\tau_\lambda}$$

where T_o is the excitation temperature of the gas, and T_b corresponds to the temperature of a background radio source.

Suppose there is a background radio continuum source along the line of sight to a cloud. Observing in a direction just off the background source at line center frequency makes visible the 21-cm emission from the cloud and its self-absorption along the line of sight; then the equation reduces to

$$T_{B_1} = T_o(1 - e^{-\tau_\lambda})$$

On the background source at a frequency to either side of the hydrogen line, continuum emission will be observed; the equation then reduces to

$$T_{B_2} = T_b$$

These equations, corresponding to observations on and off the background source and at frequencies to either side of line center and at line center, can be used to solve for the optical depth and the gas temperature of the cloud.

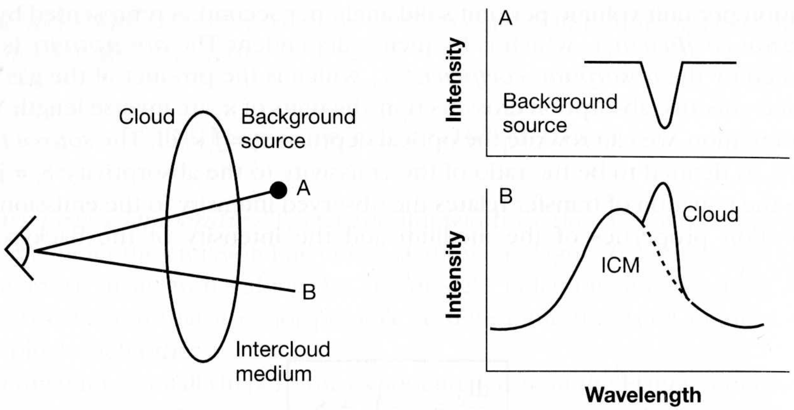

FIGURE 6.3 ***(left) Lines of sight through a cloud on and off a background source; (right) the corresponding line profiles.***

The appearance of 21-cm lines is represented in Figure 6.3. The top profile on the right shows absorption of the background continuum 21-cm radiation by a cold cloud. The bottom profile is a line of sight off the background source. The narrow line is from the cold cloud, and the broader shallower line is from a warm intercloud component of the ISM because the line width is proportional to the temperature of the region. The ICM (intercloud medium) does not show up in the absorption profile because the optical depth is proportional to the inverse temperature and so is small for the ICM.

6.2 Radiation from Molecular Gas

Molecules emit radiation as they rotate about their center of mass and oscillate about their average separation of nuclei. These motions are quantized. Molecular hydrogen, H_2, is the most abundant molecule; however, it is difficult to observe because it radiates very weakly at the typically low temperature of the interstellar medium. In general, the strongest radiation from an asymmetric molecule is *electric dipole radiation*, which results from two slightly separated charges with different masses. There is no electric dipole radiation from H_2 because it is a symmetric molecule, so the center of mass and the center of charge coincide. Instead, H_2 radiates weak *quadrupole emission* due to *rotational-vibrational transitions* at high temperatures. It is more practical to examine other molecules that are less abundant but radiate more strongly at low temperatures.

Carbon monoxide is a good tracer of molecular gas. There is only about one ^{12}CO molecule for every 10^4 H_2 molecules. The exact ratio of CO to H_2 varies and is a subject of considerable interest, since observations of CO are critical for determining the total mass content of a region if the gas is optically thin. The great strength of the CO line compensates for its low abundance relative to hydrogen; CO is the most widely observed molecule in our Galaxy and in other galaxies

because of its intense 1–0 transition rotation line. The most abundant form of CO consists of the most common isotopes of C and O—that is, ^{12}C and ^{16}O—and is usually just written as ^{12}CO. This molecule has a rotationally excited state that radiates at 2.6 mm from the J = 1 to 0 transition, where J is the *rotational quantum number*. The next excited rotational state leads to a 1.3-mm emission line from the transition J = 2 to 1. The frequency-integrated intensity of the emission is related to the number of molecules radiating per solid angle, so it (indirectly) measures the mass content of a region if the gas is optically thin. There are also other less-abundant isotopes, such as ^{13}CO (a factor of 40 less abundant) and $^{12}C^{18}O$ (a factor of 500 less abundant).

In the solar neighborhood, the column density of CO is empirically related to the temperature (K) and linewidth dv (km s^{-1}):

$$N(H_2\,cm^{-2}) \approx 2.8 \times 10^{20} \int T_R^*(CO)\, dv$$

The equation is similar to the equation for N(H I). Here T_R^* is the equivalent Rayleigh-Jeans temperature; since the Rayleigh-Jeans approximation is not valid for the 2.6-mm CO line (i.e., $h\nu/kT = 0.55$, which is not $<<1$), a correction factor relates the excitation temperature of the gas to the Rayleigh-Jeans temperature.

Less abundant molecules are useful for tracing dense regions, because their low abundance is not likely to give a saturated line. The weak line $^{12}C^{18}O$ requires high column densities in order to be observable, whereas CS requires high densities for excitation.

The low temperatures in molecular clouds are a result of *self-shielding* and dust shielding against outside stellar radiation. Typically, a molecular cloud has an overlying atomic layer in which the starlight at the H_2 photodissociation frequencies is absorbed. Cosmic rays are the dominant source of heating in molecular clouds, because they are able to penetrate the clouds; this energy input is balanced by losses from radiating molecules.

6.3 Radiation from Ionized Gas

Interstellar gas may exist in an ionized state at low density and high temperatures. Around O stars, the gas is heated to temperatures between about 7000 K and 14,000 K due to the ultraviolet radiation. This ionized gas is known as an *H II region*; an example in our Galaxy is shown in Figure 6.4. H II regions are also referred to as *Strömgren spheres* after the astronomer who developed the theory to explain the ionization process in the interstellar medium.

In a steady state, the rate of ionization of hydrogen atoms equals the rate of recombination. The number of ionizing photons per unit time, N_{uv} (a function of stellar type), is equal to the integral of the recombination rate, $n^2\alpha$, over the volume of a sphere:

FIGURE 6.4 ***H II region M17 in the Milky Way. (Image from the STScI Digital Sky Survey.)***

$$N_{uv} = 4\pi \int r_S^2 \, n(r)^2 \, \alpha \, dr$$

where α is the *recombination coefficient* for hydrogen and depends on the temperature of the region (details may be found in references such as Osterbrock 1974). The integrated equation may be rewritten to solve for the Strömgren radius, r_s, describing the extent of the ionization:

$$r_S = \left(\frac{3}{4\pi\alpha}\right)^{1/3} N_{uv}^{1/3} \, n^{-2/3}$$

(in this equation, the density is assumed to be constant, although generally it is nonuniform). Different atoms have different ionization energies and recombination coefficients; thus, an H II region may have a Strömgren sphere of ionized helium with a smaller size than the Strömgren sphere of ionized hydrogen.

For purposes of understanding galaxy radiation, one of the key aspects of H II regions is that they produce strong Hα emission (see Chapter 3) because of the recombination and cascade of electrons in hydrogen atoms. Thus, a filter that isolates the Hα line is useful for examining regions of star formation in a galaxy, as shown in Figure 6.5. We will return to this point in Chapter 10 when we examine star formation in more detail.

In addition to the ionized gas around young hot stars, there is a fairly uniform distribution of warm intercloud ionized gas of ~8000 K. There is also a hot component of interstellar matter, with T ~ 10^5 K–10^6 K. This gas is sometimes called the *coronal gas* because its temperature is the same as that of the Sun's corona. Because of its high temperature, the coronal gas has a high kinetic energy. Consequently, it fills a larger volume of galactic space than does cold, low energy gas. The hot component is observed through absorption lines of highly ionized

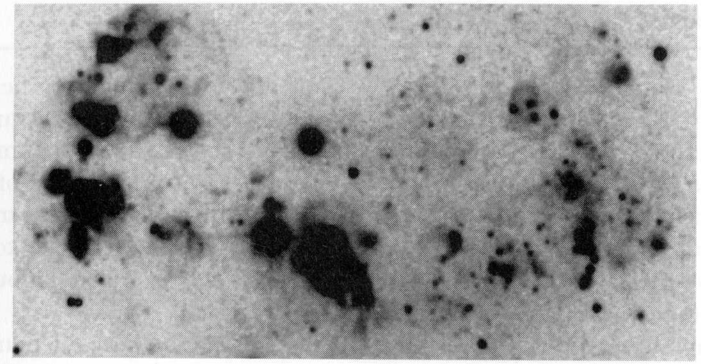

FIGURE 6.5 ***Hα image of a portion of the nearby galaxy Holmberg II. Note the shells of ionization that appear as loops. (Imaged with the KPNO 0.9-m telescope***

atoms such as C IV, Si IV, N V, and O VI along the lines of sight to stars. The strengths of these lines increase with the distances to the stars. The highly ionized regions are uniformly distributed but clumpy, with typically three hot gas regions along a 1-kpc line of sight. The hot gas may result from supernova remnants or from thermal evaporation of cold clumpy gas in even hotter material. A model for this distribution is shown in Figure 6.6.

X-ray emission in galaxies is observed in early Hubble types. X-rays radiate from hot gas in the bulge shed by stars; the gas is hot because of the high-velocity dispersion of the bulge. If the velocity dispersion is less than ~200 km s^{-1}, the temperature of the gas falls below 5 × 10^6 K and will not be detected.

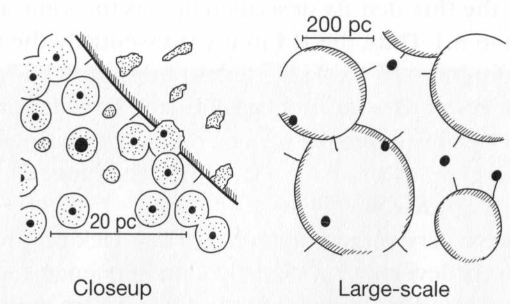

FIGURE 6.6 ***Distribution of the hot interstellar medium according to the supernovae model (McKee and Ostriker 1977). The hatched areas in both diagrams represent regions of 10^5 K–10^6 K around OB stars and supernovae. (left) A supernova wave is moving across the diffuse clouds, which have 80 K cores (the solid dots); the dotted transition areas are 8000 K envelopes. (right) A larger view: the large circles are supernova remnants, and the small circles are clouds larger than 7 pc.***

6.4 Total Gas Mass

The total gas mass in a galaxy can be determined from the integral of the column density over the area of the galaxy. The column density (number per square centimeter) is converted to a mass column density (grams per square centimeter) by multiplying it by the mass per H atom, 1.67×10^{-24} g (or, for a ratio of H:He = 10:1, the average mass per atom is 2.3×10^{-24} g). The total molecular mass may be similarly estimated on the basis of CO emission. In our Galaxy, the total molecular gas mass is about $4 \times 10^9\ M_\odot$, which is ~2% of the luminous mass, whereas the total H I mass is $5 \times 10^9\ M_\odot$.

All spiral galaxies have H I emission, but the amount varies depending on Hubble type and galaxy luminosity. H I has been detected in ~20% of S0s sampled. In these galaxies, the H I gas often is in a ringlike distribution. Sometimes it is concentrated toward the galaxy center, which is very different from the distribution in spiral galaxy disks. Only about 2% of E galaxies have detectable H I, and this gas is probably from the capture of other galaxies or their gas.

An empirical index of H I richness, called the *H I index*, has been developed by de Vaucouleurs:

$$\text{H I index} = 16.6 - 2.5\log S_H^\circ - B_T^\circ$$

where S_H° is the 21-cm flux density in units of 10^{-28} watts per square meter over all velocities, corrected for self-absorption of 21-cm radiation due to the galaxy's inclination (see RC2); B_T° is the total apparent B magnitude corrected for inclination (see Chapter 4), and 16.6 is selected so that the H I index is approximately 1 for spirals. A watt is a unit of power, specifically joules per second (a joule = 10^7 erg), so the flux density described here is the same as flux described in Chapter 3, Section 3.1. Thus, the H I index is essentially the ratio (expressed as a magnitude difference) of a galaxy's 21-cm brightness to its optical brightness. The H I index is small for gas-rich galaxies and large for gas-poor galaxies. The index is useful for illustrating the general relation between atomic hydrogen content and Hubble type, as shown in Figure 6.7. The range of H I indices for a given Hubble type is approximately ±0.4.

Some galaxies have very smooth spiral arms that lack bright star-forming regions; van den Bergh developed a classification sequence for these galaxies, which he called *anemic*. His designations Aa through Am are analogous to the Hubble sequence Sa through Sm for normal spirals. The anemics apparently are H I gas-poor for their Hubble type. An example is NGC 4569, shown in Figure 6.8; its H I index is 3.9, compared with the normal value of ~2.7 for this Hubble type.

The amount of CO emission also varies with galaxy type. Elliptical galaxies with strong far-infrared emission have been detected in CO, with inferred gas masses of 2×10^6 to $10^9\ M_\odot$. Field ellipticals have a higher CO detection rate than ellipticals in groups. About 25% of S0 galaxies and 50% of S0a and Sa galaxies have been detected in CO, with corresponding H_2 masses of $\sim 10^7$ to $10^9\ M_\odot$.

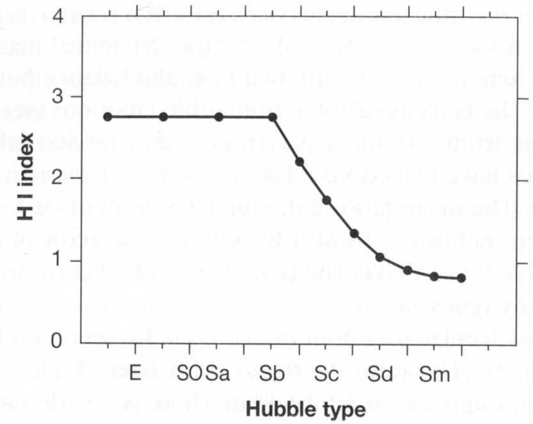

FIGURE 6.7 ***Hydrogen abundance relative to blue luminosity as a function of Hubble type, based on the de Vaucouleurs H I index.***

Irregular galaxies are H I-rich but underabundant in CO compared with their CO linewidth. This underabundance could result from less C or less O, from more CO destruction because of relatively less dust than in spirals, or because the CO excitation temperature is less than in spirals.

The gas mass in a galaxy may be compared with the mass of stars. The H I mass to blue luminosity ratio, M_{HI}/L_B, increases from ~0.06 for Sa galaxies to ~0.3 for Sc galaxies. In S0 galaxies, the ratio is $0.03 < M_{HI}/L_B < 1.4$, whereas in elliptical galaxies, which are very gas-poor, the ratio is $M_{HI}/L_B < 0.03\ M_\odot/L_\odot$. The ratio of molecular mass to blue luminosity, $M(H_2)/L_B$, is about the same for Sa through Sc galaxies and decreases by a factor of 3 for Scd through Sdm types.

FIGURE 6.8 ***NGC 4192 (left) is an Sb II galaxy; NGC 4569 (right) is an Ab II galaxy. Note the smoothness of the anemic galaxy arms compared with those of the normal spiral. (Images from the STScI Digital Sky Survey.)***

The fraction of the total gas in galaxies (H I + H_2) relative to the total galaxy mass can be expressed as M_{gas}/M_{dyn}. M_{dyn} is the dynamical mass inferred from kinematic measurements; it is determined from the balance between the gravitational force and the centrifugal force from orbital motions (see Chapter 7). The gas fraction ranges from ~4% for Sa galaxies to ~25% for Scd galaxies. Evidently, early-type galaxies have locked up a larger fraction of mass in stars than have late-type galaxies. The mean ratio of the total gas content (H I + H_2) to area inside the Holmberg radius is ~17 M_o/pc^2, with only a factor of 2 increase from early to late Hubble types; that is, late types have only slightly greater gas surface densities than early types.

The ratio of molecular to atomic mass, H_2/H I, averages 1.0±3.3 for spiral types Sa through Sd. The ratio decreases with later Hubble type: M_{H_2}/M_{HI} = 4.0±1.9 for S0/Sa, and 0.2± − 0.1 for Sd/Sm. There is a wide range within each type, as illustrated in Figure 6.9. By comparison, the few ellipticals measured to date have M_{H_2}/M_{HI} ratios of 0.4±0.6.

In general, the phase of the gas varies systematically along the Hubble sequence; later types have lower average molecular gas fractions. Variations in the ratio H_2/H I can result from changes in the efficiency of H_2 cloud formation, the rate of cloud disruption, the rate of molecule formation, or the metallicity.

There is an increase in H I and H_2 masses with increasing dust content in galaxies; typically the gas-to-dust mass ratio is ~100. IRAS observations of radiation at 100μ are used to infer dust masses. The dust mass per blue luminosity, M_{dust}/L_B, is a factor of 10 larger in Sa compared with S0a galaxies. Recent studies indicate that there may also be cold dust that does not radiate at wavelengths detectable by IRAS; as much as 90% of dust may be hidden in this way. Ellipticals have gas-to-dust mass ratios as high as 700, probably due to cold dust.

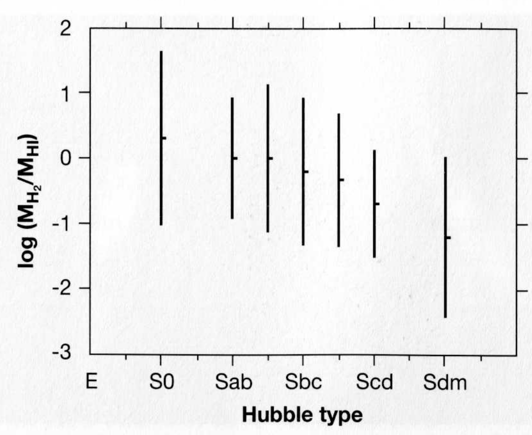

FIGURE 6.9 ***Ratio of molecular to atomic gas mass as a function of Hubble type. (Based on Young and Scoville 1991.)***

6.5 Distribution of Clouds

We will now examine the distributions of the different phases of the interste medium in galaxies. Atomic clouds typically have densities of a few ten atoms per cubic centimeter and temperatures of ~100 K. There is a large ra of cloud sizes; the smallest observed atomic clouds are *diffuse clouds,* which a few parsecs in size with ten to a few hundred solar masses. Diffuse clouds spread rather uniformly throughout the midplane of the disk, with a vertical tribution spanning about 100 pc. The largest atomic clouds have masses ~1 10^7 M_o and 0.5 kpc sizes. They are sometimes regularly spaced along spiral ar with separations that scale with the size of a galaxy, typically ~0.2 R_{25} = 1–4 k

The smallest isolated molecular clouds are *Bok globules*, which are sma and denser than diffuse atomic clouds of the same mass (see Figure 6. Slightly larger clouds are referred to as *dark clouds*; the largest aggregates are *ant molecular clouds* (GMCs), with masses up to 10^6 M_o and sizes up to ~ pc. Average densities are ~100 per cubic centimeter in molecular clouds creasing to ~10^5 per cubic centimeter or more in the dense cores. Figure 6 shows a CO intensity contour map in the region W3/W4/W5 in the Milky W

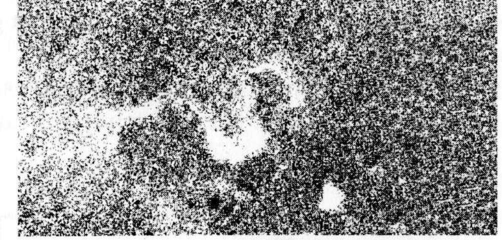

FIGURE 6.10 ***A filamentary Bok globule, Lynds 66, commonly known as the Snake. (Image from Schneider and Elmegreen 1979.)***

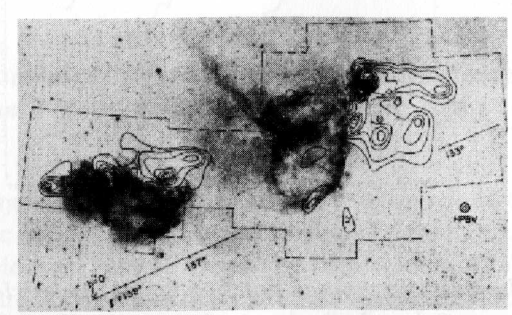

FIGURE 6.11 ***Molecular clouds in W3/W4/W5 in the Milky Way, as traced by temperature contours. (From Lada et al. 1978.)***