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

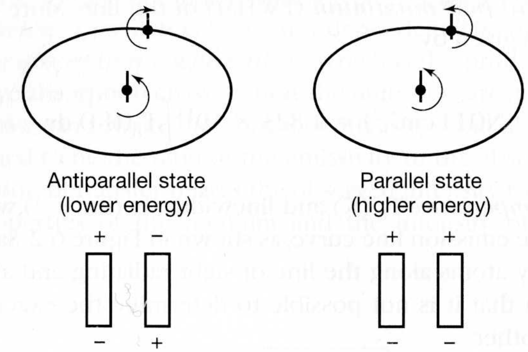

FIGURE 6.1 ***Hyperfine transitions in a hydrogen atom.***

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