THE INTERSTELLAR MEDIUM

Summer Student Lecture, NRAO, summer 1984 by F.O. Clark

Let us begin with a broad overview of where the interstellar medium is found. Remember that broad generalities always have exceptions! Interstellar material is generally found only in spiral galaxies, which tend to rotate fairly rapidly (well every 10**8 years or so!), and is generally not found in elliptical galaxies, which rotate much more slowly than spiral galaxies, if at all.

I. GAS

This interstellar material is comprised of hydrogen gas in various forms, with a little helium, and, for all practical purposes, nothing else but a little contaminant, as illustrated in the table below (note by number!).

"COSMIC" ABUNDANCE OF THE ELEMENTS

H	10,000
He	1,000
O	6.3
C	4
N	1
Ne	0.4
Mg	0.32
Si	0.32
Fe	0.25
S	0.16
Li	0.16
Ca	0.025
Al	0.025
P	0.0025

(Spitzer-Phys. Processes in the Interstellar Medium 1978, p4)

This material was difficult to detect before the advent of spectroscopy, which allows the observation of individual spectral lines from the gas. This material is not uniformly distributed within a galaxy, but tends to be restricted to the plane of the galaxy defined by the rotation axes. The "spiral arms" are discernable in the gas as well. A figure from Mihalas and Binney (Galactic Astronomy, 2nd ed. 1981 -MB) clearly shows the spiral arms of the nearby galaxy M81, as viewed with a spectral line of

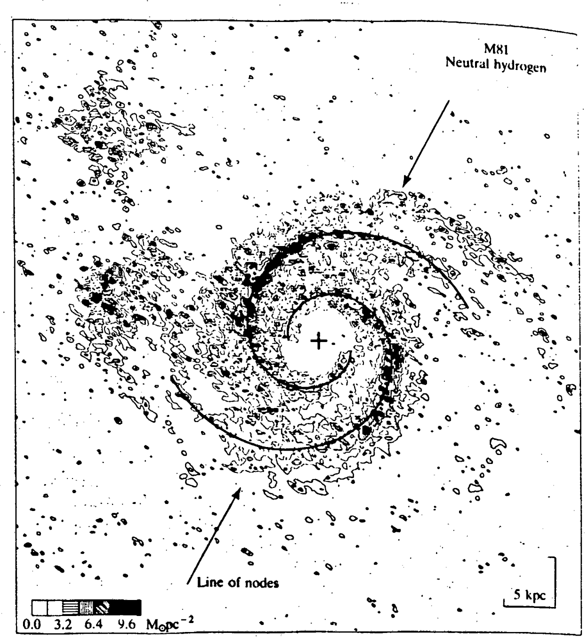

Figure 9-10. Contour map of the H I column density in M81 as observed with the Westerbork Aperture Synthesis Telescope, deprojected to a face-on view. Densities are given in $\mathcal{M}_\odot$ pc^{-2}. The spiral pattern has two principal arms that are well fitted by a logarithmic spiral with a pitch angle of 15°. [From (R3), by permission.]

hydrogen, the 21cm "spin flip" transition.

However, the interstellar medium in our galaxy and others has attributes other than spiral structure. The stellar distribution in our galaxy is strongly peaked in the nucleus, and decreases with increasing radius. This must be described with an ellipsoidal distribution. However, an isothermal spherical distribution of stars would decrease as R**-2. It is difficult to actually detect stars in our galaxy, at least away from the sun, due to the presence of another constituent of the interstellar medium, dust (IRAS is changing all of this, but the data analysis is slow). More about dust later. However, we can observe other galaxies, and adjacent is a figure illustrating surface brightness (which you may assume is somehow related to the number of stars!) as a function of radius (from MB again).

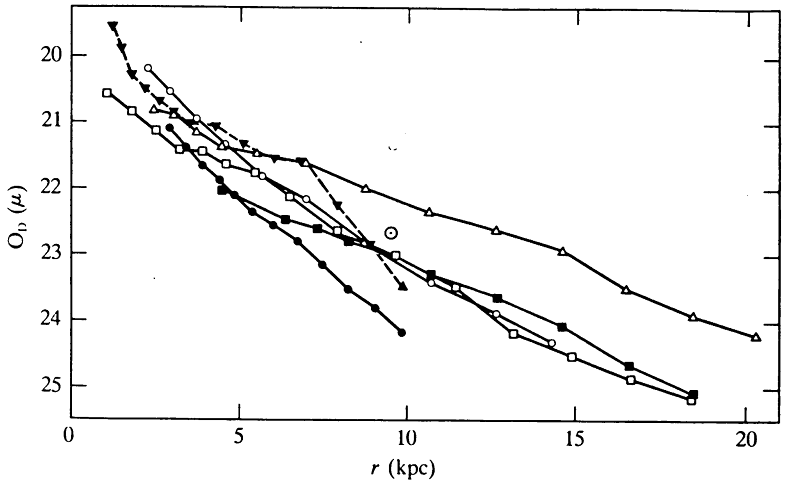

Figure 5-22. Orange surface brightness versus radius for six spiral galaxies [NGC 3031 (●), NGC 4255 (○), NGC 4321 (△), NGC 5194 (▼), NGC 5364 (■), and NGC 5457 (□)]. The solar symbol ⊙ indicates the estimated surface brightness of our Galaxy near the Sun. Notice that the outer parts of the profiles tend to be fairly straight in accord with equation (5-6). [From (S5) by permission. Copyright © 1976 by the American Astronomical Society.]

Clearly there are lots more stars near the center of galaxies, and fewer near the edges. Now, let us return to the gas and compare it to the stellar component. You now are in for a surprise (unless you have read widely, or had a course on the interstellar medium), as the gaseous distribution, while exhibiting the spiral pattern, does not mimic the stellar distribution at all! First, the distribution of gas has a minimum at the galactic center, where the stellar distribution peaks! A figure is shown which illustrates the distribution of hydrogen in our galaxy, the milky way (from MB), and a minimum is noted at the galactic center.

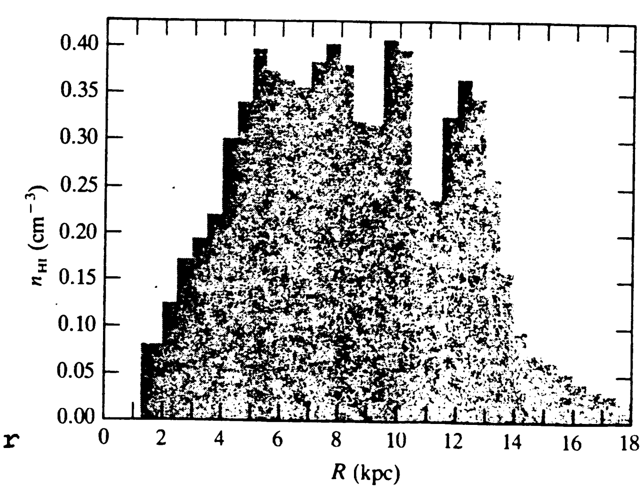

Figure 9-7. The radial density profile of neutral hydrogen in our Galaxy. [From (**B19**), by permission.]

The 21 cm line of hydrogen was observed to produce the above graph. This spectral line occurs when the spins of the p+ and e- "flip" from the higher energy aligned state to the lowest energy opposed state. This involves extremely low energy E/k = 0.07K! Further, this transition occurs extremely infrequently, only every 3.5 10**14 seconds, or every 10**7 years or so. However, the universe is all hydrogen, and there is enough HI to produce strong radio signals at 1420 MHz which can be observed from all over the galaxy. The 21cm line is completely thermal, Aul = 2.9 10**-15 s-1 << Cul (Einstein coefficient of spantaneous emission is much less than the collisional rate), or another way of stating the same thing is that the Tk of the gas is 100K, while the energy separation of the states involved is only 0.07K. The width of the HI lines is primarily determined by the doppler width of the gas due to its kinetic temperature and mass motions. The HI emission is often optically thin which allows the mass of the emitting region to be estimated.

Not all galaxies exhibit a minimum at the galactic nucleus, however, as the figures to the right illustrate for the hydrogen distribution in several nearby galaxies, some of which do not have nuclear HI minima.

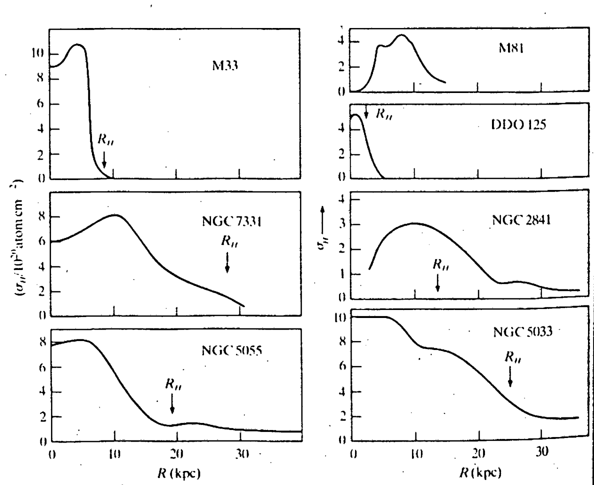

Figure 9-9. The azimuth-averaged, neutral hydrogen surface densities in eight Sa–Sm galaxies. [From data published in (B14) and from (N1), (R3), and (T2), by permission.]

The gas in the interstellar medium occupies several regimes, four of which will be considered here: 1. "corona", 2. intercloud region, 3. diffuse clouds, and 4. molecular clouds, where the nomenclature of Spitzer (2nd ed.) has more or less been used. The hydrogen gas distribution discussed earlier refers primarily to the "diffuse cloud" regime.
There are many ways of analyzing these regions, and they will only be outlined here. An interesting way of approaching this problem is to outline the characteristics of the three regimes and then consider whether they are in presssure balance. You probably recall the "ideal gas law" from somewhere in the dim dark reaches of your education. One way of writing this relation is: P = nkT, where P is pressure, n is particle number density cm-3, k is Boltzmann's constant, and T is kinetic temperature. The kinetic temperature is a parameter which describes the random motions of the atoms and molecules of the gas. The three regimes may be crudely characterized as follows:

The Interstellar Medium
(Horoscopes for Everyone!)

	density (cm-3)	temperature (K)	n*T
1. "Corona"	0.001	10**6	10**3
1. Intercloud Medium	0.3	6,000	1.8x10**3
2. Diffuse Clouds	20	100	2x10**3
3. Molecular Clouds	>1,000	15	1.5x10**4

The table above indicates that the first three components are approximately in pressure equilibrium, although the molecular clouds are not in pressure equilibrium with their surroundings, and a more sophisticated analysis must be used. One could humorously conclude that the molecular clouds should explode back into the intercloud medium! If the various regimes are changing only "slowly" in time (watch out maw, we mean >10,000 years here!), then they may be in "virial equilibrium", or close to it. This relation essentially states that:

$$E(g) + E(v) + E(nkT) + E(B) \sim 0$$

Where the first term represents gravitational energy, the second kinetic energy of motion, third gas pressure, and the fourth magnetic energy (see Spitzer, 2nd ed. p217). There are also magnetic surface terms not included here, and these all equal 1/2 the second time derivative of the moment of inertia of the system! However, for most objects, the above terms give an idea of the physical state of things, and when this analysis is done, most molecular clouds are found to be close to an equilibrium state. The gravitational term acts to hold the cloud together, motion and gas pressure to push it apart, and the magnetic term acts as a vector constraint on the system, if the material is ionized to a sufficient extent. Obviously, the above table of gas pressures suggests that either (or both) gravitational or magnetic effects are important in molecular clouds.

Lets examine the individual terms of the virial equation for a molecular cloud, B361, which refers to object #361 in an old optical atlas by EE Barnard (some say "EE" stood for eagle eye). B361 appears to be rotating (Milman 1977 Ap.J. 211, p128; Clark & Johnson 1982 Ap.J. 263, p160). Ignoring the surface terms (primarily because not enough is known about the system to evaluate them!):

$$\mu n(r)v^2 + 3n(r)kT_k + B^2/8\pi = \mu n(r)\mathbf{r}\cdot\nabla\phi\Big|$$

where the first term represents internal turbulent and rotational effects, the second ideal gas law, the third magnetic pressure; and all are equated to the gravitational energy density. Note that rotation and magnetic effects will decidely not enter as scalar quantities in actuality! Separate the first term into rotation and turbulent effects, and evaluate in terms of observed quantities:

$$3.09\times10^{-14}n(r)(\sin i)^{-2} + 3.35\times10^{-14}n(r)v_t^2\Big| + 3.5\times10^{-15}n(r) + 0.04B^2 = \mu n(r)\mathbf{r}\cdot\nabla\phi\Big|$$

The gas density for this object follows very closely the isothermal law, n(r) ~ r**-2 (note that Clark & Johnson assumed that this law was r**-3.4) and these terms may be evaluated to:

```
     rot                    turb        nkT          mag
3.1*10-11 sin**2(i) + 3.4*10-11 + 3.5*10-12 + .04 B**2
           = 1.7*10-11 (gravity)
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A few things become clear from these numbers. The gas pressure term is negligible by an order of magnitude. The "turbulent" (based on line profile width) and rotational terms are comparable, and a magnetic field of 20 uGauss would have non-negligible effects (see below). Yes, the gravitational term came out 2 times smaller than the other important terms, but it depends on the square of the density, which is uncertain of order 2 which easily gives a factor of 4 more in the gravitational term. The results were purposely given as they came out, with no attempt to make them "pretty". B361 is typical of lower mass (1-10 M) molecular clouds, the rotational velocity gets smaller at smaller radii, and the smaller radii observations typically yield a "quiescent" core. Obviously gravity is important in binding these objects. Once stars form, they often exhibit "bi-polar flows" which blow large cavities in the cloud. More massive molecular clouds (100-1000 M) appear to form more massive stars, usually in clusters, which not only exhibits the disruptive flow early on, but also ionize the surrounding gas in an "HII" region, or ionized hydrogen region. HI means one particle (hydrogen atom), HII means two particles (p+ and e-), obviously there is no HIII, but there is HeIII!

II. Magnetic Fields

The galaxy has a large scale magnetic field of about 3 microGauss, which affects the interstellar gas as long as it is partially (or fully) ionized. It is presently thought that sufficient ionization is present for some coupling between the gas and field below densities of perhaps 10**6 or 10**7 cm-3, which occur in the dense cores of molecular clouds. The field apparently is carried with the gas as it reaches higher densities, and thus the field strength is higher in denser regions. Just how much higher is a subject of conjecture. The field is difficult to measure in the denser regions. Zeeman effect measurements of OH and HI (atomic hydrogen) suggest little field increase. Check the recent literature if interested (search on names of Heiles, Crutcher, and Troland). The field probably increases with increasing density as the calculations of Mouschovias (magnetism explains everything in the universe!) indicate, B ~ n**1/2. Consider B361 again. The rotation is observed to actually decrease at smaller radii, which clearly is the opposite sense expected from conservation of angular momentum. Something is redistributing angular momentum, probably a magnetic field. Previously it was shown that a 20 uGauss field would affect the cloud. Using Mouschovias' law this would require about a 100 increase in density over the average galactic density, of perhaps 0.1 cm-3. since the relevant density of B361 in the region of interest is ~10-3, this criterion is easily met, and magnetic fields are likely acting to redistribute angular momentum in the galactic gas. Other indirect field measurements include the observation of retrograding cloud cores and fragments (Young et al. 1981 Ap.J. 251, L81, Clark & Johnson 1981 Ap.J. 247, 104) also predicted by the models of Mouschovias.

III. Dust

There is another component of the interstellar medium alluded to above, namely the "dust". It is well known that something in the interstellar medium not only absorbs light, but also reddens it, that is absorbs blue more than red. These evil characteristics, that prevent us from seeing our own galactic center in visibile light, are attributed to "dust". Dust, in some sense, is little more than an agglomeration of big molecules. Much of the present dust content may have formed near red giants as they lose enriched material back into the interstellar medium. Some dust may form or at least grow in dense cloud cores, and there are likely to be other sources. The extinction curve due to dust is shown below. One would think that the big feature near 2150 A would allow ready identification of the composition, but this is not so simple. There are other infrared features, however, which have been attributed to graphite, silicates, and small oxides. The dust exhibits a range of sizes, and objects the size of a car, football field, or even a radio telescope would exhibit no detectable characteristic (unless optically thick!). There is a recent article (last months I believe) in Scientific American by Mayo Greenburg on the dust grains. The dust distribution generally seems to track that of the gas, at least in our galaxy, and occurs in a MASS ratio of about 1/100 of the mass in gas.

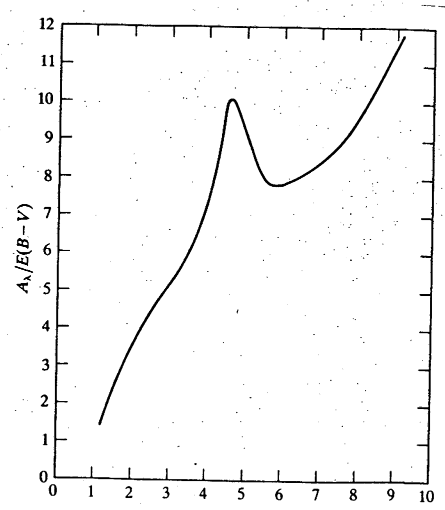

Figure 3-28. The mean interstellar absorption curve in the visual and ultraviolet [normalized to $E(B-V)=1$] as determined from OAO-2 observations. [From (B8), by permission. Copyright © 1972 by the University of Chicago.]

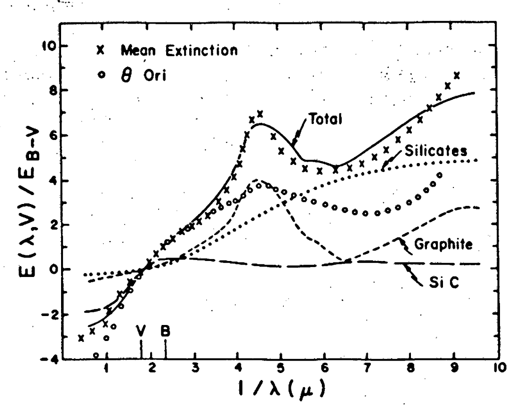

Figure 7.2 Dependence of selective extinction on wavelength. The ratio of $E(\lambda, V)$ to E_{B-V} is plotted against the reciprocal wavelength in microns. The crosses give the mean observed extinction for normal stars [2]; in the ultraviolet these are based on 14 observed stars, excluding 3 abnormal ones; the circles give observed values for $\theta^1+\theta^2$ Ori, showing abnormal extinction. The other curves are computed theoretically [16] for grains of three different types (see text), with the sum of the three shown by the solid line.

Another property of the interstellar medium likely attributable to the grains is the set of interstellar "diffuse bands". These bands are still of unknown origin, but seem to track the dust, and likely are due to the molecular properties of the surface of the dust grains ("Interstellar Grains". ed. Greenberg & Roark, 1967, NASA). There are a large number of these weak broad features known, for example 4430, 4760, 4890, and 6180 A. A few are illustrated in the figure (from ref. above). In a recent article Gammelgaard attributes 6 diffuse bands, including one predicted at 7581 A which he claims to have detected, to a series of H- autoionization resonances (1984 A&A 135, p77).

INTERSTELLAR GRAINS

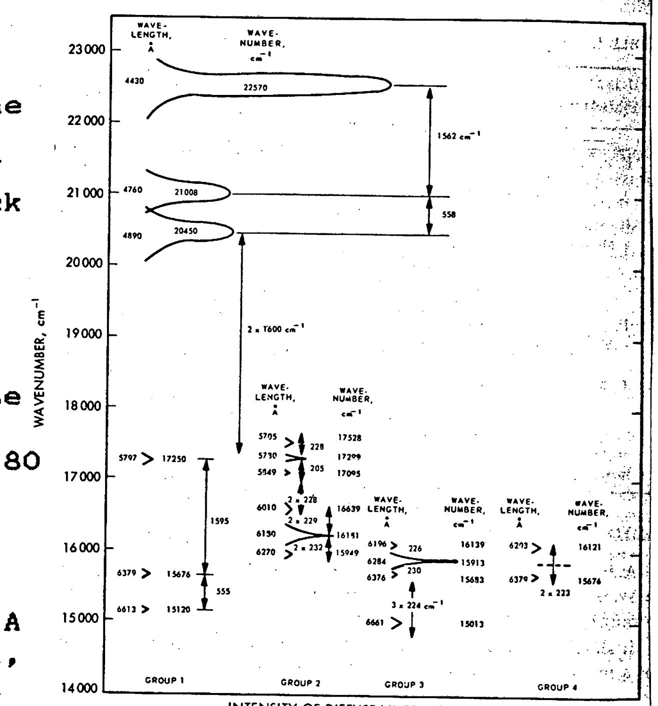

FIGURE 1.—Relative intensities and wavelengths of diffuse lines.

Make a name for yourself, figure out precisely what these are due to!

Optical extinction around B361 has been analyzed by Schmidt (1975 MNRAS 172, p401), who concludes that the dust follows a density law of r-3.4. The gas in this object follows a law of approximately r-2. This implies that the grains can behave differently from the gas, with interesting consequences.