

2 The Interstellar Medium

In the previous chapter we reviewed the gravitational structure of bright (S and E) galaxies. But the stars and dark matter are not all of the story. Each type of galaxy contains gas as well as stars: this is the interstellar medium (ISM). To set the stage, paraphrase from Elmgreen, who's talking specifically about our galaxy¹: “the ISM is like the ocean of a galaxy, a fluid confined by gravity to a thin layer, and serving as a reservoir for all of the material in stars and planets that will ever form, evolve, and disperse.” The physics of this ISM, and its connection to stellar birth and stellar death, will be one of our main applications in this course.

2.1 The diffuse ISM in our galaxy

What I call the *diffuse ISM* is the ISM that is truly “interstellar” – sitting in the potential well of the overall galactic disk, and not immediately involved with stars or star formation regions.

2.1.1 How we observe the ISM

Our understanding of the physical state of the ISM has been driven by the data: recent work in radio astronomy and high-energy astronomy has dramatically changed the field. What are our current ways of looking at the ISM?

• **Optical:** Gas with temperatures in the range roughly 10^3 to 10^4 K emits both continuum and spectral line optical radiation, and cooler gas can be detected by the absorption lines it produces when there is a continuum optical source behind. We see interstellar absorption lines, stellar reddening, diffuse $H\alpha$ and other emission lines, and dark dust clouds. In addition “stellar ISM” regions such as HII regions, supernova remnants (SNR), and planetary nebulae emit optically. Galactic dust tends to prevent us seeing through the plane of the disk beyond a kpc or so, aside from special lines of sight.

• **Radio:** the major discovery here was the HI 21 cm line, which we see in absorption and emission. This tracks atomic hydrogen, which is (of necessity) fairly cool ($T < 8000$ K). In addition, the diffuse ISM is a source of synchrotron radiation, which we see in the radio. This latter comes from relativistic electrons (the

cosmic ray population) interacting with the galactic magnetic field.

• **Infrared:** another strong radiation source – one of the strongest cooling mechanisms – is IR radiation from dust grains. They absorb starlight and reradiate it at temperatures $\sim 10 - 100$ K. Dust exists in many places throughout the ISM, at several temperatures (“near IR”, “far IR”, *etc.*)

• **Millimeter:** most of the common molecules have rotational transitions in the mm region (with the notable exception of H_2); mm-wave astronomy is now a powerful tool for studying star formation regions and molecular clouds.

• **Ultraviolet:** this again typically samples only the local region, $\lesssim 1/2$ kpc, due to obscuration. At this band we see hot gas, $10^5 - 10^6$ K, from the so-called “local bubble”; in absorption, there are important transitions of atomic and molecular hydrogen. With the advent of UIT, the UV is also becoming a nice tool for studying the ISM in external galaxies.

• **X- and γ -rays:** the local bubble also emits soft X-rays. In addition, the galactic plane is a source of harder X-rays and γ -rays; some of these come from hot gas (such as in SNR), and the hardest component comes from nuclear reactions between the cosmic rays and the ISM.

• **Plasma propagation:** radio signals are affected by propagation through an ionized plasma. In addition, the ionized plasma can emit thermal bremsstrahlung. We can use the following three means to measure electron densities, path lengths and magnetic field:

$$\begin{aligned} \text{dispersion measure :} & \quad \text{DM} \propto \int n_e dl \\ \text{emission measure :} & \quad \text{EM} \propto \int n_e^2 dl \\ \text{rotation measure :} & \quad \text{RM} \propto \int n_e \mathbf{B} \cdot d\mathbf{l} \end{aligned} \quad (2.1)$$

The first refers to *plasma dispersion*, the fact that the phase speed of an EM wave depends on its frequency. The second measures the emissivity due to bremsstrahlung radiation. The third refers to *Faraday rotation*, the rotation of the plane of polarization due to passage through an ionized, magnetized plasma.

2.1.2 A multi-phase equilibrium?

From such observations, we find that the diffuse ISM is very complex. It comes in several phases, with com-

¹in Burton, Elmegreen, & Genzel, eds., *The Galactic Interstellar Medium*, SAAS-FEE Advanced Course 21, 1991.

plex spatial structure. Different authors classify the phases differently, and papers on this topic can contain a flurry of acronyms (CNM, WNM, WIM, MOWIM, RWIM, HIM, etc, etc, etc). I summarize as follows.

- **Neutral gas** refers to atomic hydrogen, HI. (Molecular H_2 and other species are found in self-gravitating clouds, thus are discussed in the next section; they are not really part of the diffuse ISM). We now know that the spatial structure of neutral HI is quite complicated. First, there is “cold” HI (seen in absorption) and “warm” HI, still neutral, seen in emission. Heiles estimates the warm HI has $T \gtrsim 1000$ K, $n \sim 0.3 \text{ cm}^{-3}$

The cold phase comes in sheets, filaments, and bubbles. Early observations – which had only spectral resolution (and so picked up gas at different velocities), not spatial, talked about “interstellar clouds”. This terminology is still around, but our cartoon is no longer a raisins-in-a-pudding picture. Typical temperatures are $\sim 10 - 75$ K and typical densities are $\sim 20 - 2500 \text{ cm}^{-3}$. There seems to be a wide range of “cloud” sizes (*i.e.*, path lengths through clumps or sheets), up to big “clouds” $\gtrsim 100 M_\odot$.

- **Warm ionized gas** refers to partly to mostly ionized hydrogen. This used to be the “intercloud medium”; then for awhile it was thought to be located on interfaces between the cold HI clouds and the really hot, coronal gas. Now, observations of external galaxies show that there is also a diffuse, extended warm component, occupying filaments, clouds, bubbles and chimneys. We see it mainly in diffuse $H\alpha$ and other optical lines; earlier work also found it locally in absorption lines.

Heiles argues that these are two separate types of warm, ionized gas. One is the diffuse component, throughout the galactic plane, maintained by photoionization by starlight. Heiles estimates $T \sim 8000$ K and $n \lesssim 0.1 \text{ cm}^{-3}$ for this gas (sometimes called the *Reynolds layer*, after the person who first studied it in depth). The second type is, indeed, the warm interfaces between cold and hot gas. Heiles gives $T \sim 8000$ K and $n \sim 0.1 - 0.4 \text{ cm}^{-3}$.

- **Hot “coronal” gas** refers to the phase at $T \sim 10^5 - 10^6$ K, $n \sim 10^{-3} - 10^{-2} \text{ cm}^{-3}$. We detect this gas by its X-ray emission, and also some UV lines. It is associated with, but not confined to, the interiors of supernova remnants and “superbubbles” (large, multi-SN complexes).

If we look at all phases, we see that each has the prod-

uct nT on the order of a few thousand (cm^{-3}K). Thus, within the accuracy of the diverse data, each has the same typical pressure: this product converts to an energy density $\sim 1 \text{ eV/cm}^{-3}$. We are seeing three phases in approximate pressure balance with each other.

2.1.3 Other components of the ISM

There are three other significant components of the diffuse ISM.

- **Dust grains** tie up about 1% of the mass of the ISM, including most of the heavy elements. They are often found with, or comprised of, complex organic molecules. Polycyclic aromatic hydrocarbons (PAH’s, the stuff of soot) are thought to be one major group. Dust absorbs and scatters optical starlight very effectively (this is why we can’t see very far optically) and reradiates it in the infrared, providing a major part of the bolometric luminosity of the galaxy.

- **Cosmic rays** are relativistic particles, electrons and ions, tied to the galaxy by its magnetic field. We detect them directly at the earth though their distribution is modified by passage through the solar wind and the earth’s atmosphere. Their detected energies range from $\sim 10^{10}$ eV to $\sim 10^{21}$ eV. We also detect them indirectly by their diffuse synchrotron emission (in the galactic magnetic field) and by their high-energy photon emission (arising from nuclear reactions with the thermal ISM). Their energy density locally is comparable to that of the ISM gas, $\sim 1 \text{ eV/cm}^{-3}$, and may increase by a factor of a few going inwards towards the center of the galaxy.

- **the Magnetic field** of the galaxy is detected through Faraday rotation, synchrotron emission, optical polarization of starlight (due to alignment of IS grains across \mathbf{B}) and Zeeman splitting. It is fairly ordered, with field lines tending to lie in the galactic plane, and somewhat along the spiral arms. Typical field strength is usually quoted as $\sim 3\mu\text{G}$, with strong spatial variation, and higher fields locally in some regions. Its energy density locally is also – you guessed it – $\gtrsim 1 \text{ eV/cm}^{-3}$. As with cosmic rays, there is some suggestion that the energy density in the field rises going towards the galactic center.

2.2 “Star stuff” in our galaxy

In addition to the diffuse medium, many well-known examples of so-called interstellar matter come from ISM closely related to stars. In particular, any of the

prettiest pictures come from nebulae associated with young stars or old, dying stars. They include:

- **HII regions** are regions of ionized hydrogen surrounding, and ionized by, hot young stars. They are strong optical and radio sources.
- **Planetary nebulae** are the outer layers of older stars, ejected by instabilities in the star's structure.
- **Stellar winds** are produced by nearly all stars at some level; hot, young stars have by far the strongest winds. While not as spectacular as the first two, winds are strong sources of mass and energy supply for the ISM.
- **Stellar jets** are produced both by young stars, in the formation process, and by compact stellar remnants (*e.g.*, neutron stars and their surrounding accretion disks). They are striking radio and optical sources when we can catch them; a few have apparent superluminal expansion velocities.
- **Supernovae remnants** result when massive stars eject something like half their mass, or more, in a violent explosion. We see SNR as strong radio, optical and X-ray sources; in addition they are thought to be strong sources of cosmic rays. They are also important contributors to the energy and mass budget of the ISM. These nebulae all share the property that they are over-pressured relative to the diffuse ISM: they arise from and are tied to stars. In addition, molecular gas is found in overpressured, self gravitating clumps called
- **Molecular Clouds.** These are detected in "trace" heavy-element molecules such as CO, which have strong millimeter line transitions; we infer that H_2 is also present, in larger quantities. These clouds can be very cold, $T \sim 30 - 100\text{K}$, and very big, up to $\sim 10^5 - 10^6 M_\odot$. They have line widths much greater than the Doppler width one would expect from their temperatures: thus they are either collapsing (under their own self-gravity) or supported by turbulent, disordered internal motions. They are the stellar nurseries of the galaxy, the sites of ongoing star formation.

2.3 Galactic ecology

Taking the galaxy as a whole, we must keep in mind that the ISM is not static. It is continually being consumed in new star formation (at a rate $\sim 3 - 10 M_\odot/\text{yr}$ over the galaxy) and continually being replenished by stellar ejecta (everything from winds to supernovae). It loses energy by radiation, over all wavelengths, and

gains energy as it is replenished by the stellar ejecta. Thus, we can think of stars as simply long-lived phases of the ISM; they are formed from it and they return to it.

However, there is a trend: not all stellar material is returned to the ISM. Low-mass stars become white dwarfs, and quietly cool forever; high-mass stars recycle much of their mass, but most are believed to leave compact cores, neutron stars or black holes. Thus, the overall trend of the system is towards cold, dense ex-stars. This will take awhile, however; at present we find quite a mixture of stellar and diffuse matter in the galaxy.

2.4 The ISM in Ellipticals

Our understanding of ellipticals (the stars as well as the ISM) has changed dramatically over the past couple of decades. Originally it was thought that these galaxies have no ISM. The older stellar population characteristic of E's, and the lack of strong star formation, also seemed to argue against any interstellar matter. Then people started looking...and it now appears that these galaxies also have a complex, multi-phase ISM, with total mass comparable to that in spirals. Unlike spirals, however, the ISM in E's tends to be hotter, that is with smaller amounts in cool, neutral or "warm" phases, and most of the gas being in the hot phase. This is still a new and evolving field, being limited both by detector sensitivity and by amount of effort (not as many people look at these faint, distant things). In these notes I summarize the current state of things.

2.4.1 Everything that isn't the hot phase

Some – not all – E's have now been shown to have neutral hydrogen, molecular gas, dust grains, and a "warm" ISM (the latter detected in optical emission lines, placing it at $\sim 10^4\text{K}$). Some have been shown to have ongoing star formation in their cores. Because a smaller fraction of the total ISM is "cool", its signal is faint; a non-detection does not necessarily mean there is no cool gas in a particular galaxy. On the other hand, there seems to be an ongoing argument as to whether galaxies detected strongly in, say, HI or CO are "typical" ("real ellipticals don't eat quiche," to quote Rupen²). Some authors argue that only unusual, or disturbed, E's contain detectable amounts of cool gas...thereby defining a "pure E" as one without such

²M. Rupen, private communication, a few years back.

gas. Given sensitivity limitations, I tend to think this view may eventually be proved wrong. But I agree that we do not, yet, understand the multi-phase cool gas in the ISM of an elliptical.

2.4.2 The hot phase – the x-ray loud gas

Our understanding of the ISM in E's started to change in 1985, when the Einstein X-ray observatory discovered that normal E's are strong X-ray sources. (This has since been explored in detail by ROSAT, and now CHANDRA is adding to the picture). "Hot" means at temperatures to emit X-ray bremsstrahlung: $T \sim 10^7\text{K}$. (We can estimate the temperature roughly from the fact that the gas is an X-ray source, and more specifically from X-ray emission lines). The spatial distribution of the gas is consistent with it sitting in hydrostatic equilibrium in the potential well of the galaxy. The amounts are large: Sarazin gives $10^9 - 10^{11} M_\odot$ in gas, or comparing to the optical (blue) light of the galaxy, $M_{gas}/M_\odot \simeq 0.2(L_B/L_{sun})$. This is most of the ISM; the fractions estimated in all of the cool components are much smaller.

Why is so much of the ISM hot in an elliptical? Think about the ecology of this ISM. As in a spiral, the gas is ejected from stars, by the usual mass-loss processes (stellar winds and SNe). Unlike a spiral, however, the stars have quite high random motions (200-300 km/s is typical for gravitational support). It follows that collisions between the ejected gas, and either gas ejected by nearby stars or the local ambient ISM will thermalize the kinetic energy of the injected gas. (This is a direct application of shock physics — which we'll see later in the course). This means the gas is effectively injected with at least $T \sim m\sigma^2/k \sim 7 \times 10^7 K (\sigma/300 \text{ km s}^{-1})^2$ (any larger injection velocities, due to winds or SN flows, will only raise this number). We can also note that the radiative cooling from this hot gas will be less effective than from the cooler, denser gas of a spiral galaxy. The details of why this is so must wait until later in the course; it has to do with lower density (the same amount of gas spread over a larger volume) and strongly ionized gas at these hot temperatures (so emission lines, which are strong coolants, aren't as important).

Much of the general discussion is just "off the top of my head". Useful recent references come from meeting proceedings:

- Arnaboldi, Da Costa, & Saha, eds, 1996, *The Second Stromlo Symposium: the Nature of Elliptical Galaxies*. Several articles; especially that by Sarazin on the X-ray loud gas in E's.
- Duric, 1999, in *New Perspectives on the ISM*, eds. Taylor, Landecker & Jones; p. 161 – on cosmic rays and galactic B field.
- Sadler, 2002, in Da Costa & Jerjen, eds., *The Dynamics, Structure & History of Galaxies*, p. 215.
- Woodward, Bica & Shull, eds, 2001, *Tetons 4: Galactic Structure, Stars, & the ISM*; especially the articles by Heiles & Dickey.