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The Interstellar Medium of our Galaxy

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Abstract. I review the current knowledge and understanding of the interstellar medium of our Galaxy, based on a broad range of observational studies and theoretical models. Amongst the three basic constituents (ordinary matter, cosmic rays, and magnetic fields) of the interstellar medium, I focus on the ordinary matter. I describe its general physical and chemical properties as well as the specific attributes of its five different components. I then discuss the role played by stars, and more particularly by supernova explosions, in the Galactic ecosystem.

Contents

1. Introduction

The stars of our Galaxy are embedded in an extremely tenuous medium, the so-called "interstellar medium" (ISM), which contains ordinary matter, relativistic charged particles known as cosmic rays, and magnetic fields. These three basic constituents have comparable pressures and are intimately coupled together by electromagnetic forces. Through this coupling, cosmic rays and magnetic fields influence both the dynamics of the ordinary matter and its spatial distribution at all scales, providing, in particular, an efficient support against the gravitational force. Conversely, the weight of the ordinary matter confines magnetic fields and, hence, cosmic rays to the Galaxy, while its turbulent motions can be held responsible for the amplification of magnetic fields and for the acceleration of cosmic rays.

The ISM encloses but a small fraction of the total mass of the Galaxy. Moreover, it does not shine in the sky as visibly and brightly as stars do. Yet, it plays a vital role in many of the physical and chemical processes taking place in the Galactic ecosystem.

The most important aspect of Galactic ecology is probably the cycle of matter from the ISM to stars and back to the ISM. In the first step of this cycle, new stars form out of a reservoir of interstellar material. This material, far from being uniformly spread throughout interstellar space, displays dramatic density and temperature contrasts, such that only the densest, coldest molecular regions can offer an environment favorable to star formation. In these privileged sites, pockets of interstellar gas, losing part of their magnetic support, tend to become gravitationally unstable and collapse into new stars.

Once locked in the interior of stars, the Galactic matter goes through a succession of thermonuclear reactions, which enrich it in heavy elements. A fraction of this matter eventually returns to the ISM, be it in a continuous manner via powerful stellar winds, or in an instantaneous manner upon supernova explosions. In both cases, the injection of stellar mass into the ISM is accompanied by a strong release of energy, which, in addition to generating turbulent motions in the ISM, contributes to maintaining its highly heterogeneous structure and may, under certain circumstances, give birth to new molecular regions prone to star formation. This last step closes the loop of the partly self-induced ISM-star cycle.

Thus, the ISM is not merely a passive substrate within which stars evolve. It constitutes their direct partner in the Galactic ecosystem, continually exchanging matter and energy with them, and controlling many of their properties.

The purpose of the present article is to provide an overview of the ISM within the context of the whole Galactic ecosystem, so as to set the stage for the study of Galactic cosmic rays. In the following, I will use $R_\odot = 8.5$ kpc for the Galactocentric radius of the Sun.

2. Interstellar Matter

2.1 General Properties

The interstellar matter accounts for $\sim 10 - 15$ % of the total mass of the Galactic disk. It tends to concentrate near the Galactic plane and along the spiral arms, while being very inhomogeneously distributed at small scales. Roughly half the interstellar mass is confined to discrete clouds occupying only $\sim 1 - 2$ % of the interstellar volume. These interstellar clouds basically come into two types: the dark clouds, which are essentially made of very cold ($T \sim 10 - 20$ K) molecular gas and block off the light from background stars, and the diffuse clouds, which consist of cold ($T \sim 100$ K) atomic gas and are almost transparent to the background starlight, except at a number of specific wavelengths where they give rise to absorption lines. The rest of the interstellar matter, spread out between the clouds, exist in three different forms: warm (mostly neutral) atomic, warm ionized, and hot ionized, where warm refers to a temperature $\sim 10^4$ K and hot to a temperature $\sim 10^6$ K (see Table 1).

Table 1.: *Temperature and hydrogen number density for the five different components of the interstellar gas in the vicinity of the Sun.*

Component	T (K)	n (cm^{-3})
Molecular	$10 - 20$	$10^2 - 10^6$
Cold atomic	$50 - 100$	$20 - 50$
Warm atomic	$6000 - 10000$	$0.2 - 0.5$
Warm ionized	~ 8000	$0.2 - 0.5$
Hot ionized	$\sim 10^6$	a few 10^{-3}

By terrestrial standards, the interstellar matter is exceedingly tenuous: in the vicinity of the Sun, its density varies from $\sim 1.5\times10^{-26}$ g cm^{-3} in the hot medium to $\sim 2\times10^{-20} - 2\times10^{-18}$ g cm^{-3} in the densest molecular regions, with an average of about 2.7×10^{-24} g cm^{-3}. This mass density, which corresponds to approximately one hydrogen atom per cubic centimeter, is over twenty orders of magnitude smaller than in the Earth's lower atmosphere.

The chemical composition of interstellar matter is close to the "cosmic composition" inferred from abundance measurements in the Sun, in other disk stars, and in meteorites, namely, 90.8 % by number [70.4 % by mass] of hydrogen, 9.1 % [28.1 %] of helium, and 0.12 % [1.5 %] of heavier elements, customarily termed "metals" in the astrophysical community. However, observations of interstellar absorption lines in the spectra of hot stars indicate that a significant fraction of these heavier elements is often missing or "depleted" from the gaseous phase of the ISM, being, in all likelihood, locked up in solid dust grains. On average, the most common "metals", C, N, and O, are only depleted by factors $\sim 1.2 - 3$, whereas refractory elements like Mg, Si, and Fe are depleted by factors $\sim 10 - 100$. Altogether, about $0.5 - 1$ % of the interstellar matter by mass is in the form of dust rather than gas.

In the following subsections, I focus on the interstellar gas and successively describe the five different forms under which it can be found: molecular, cold atomic, warm atomic, warm ionized, and hot ionized.

2.2 Molecular Gas

The structure and large-scale distribution of the molecular gas is explored mainly through radio spectroscopy, taking advantage of the fact that radio waves are not subject to interstellar extinction. The most abundant interstellar molecule, H_2, has no permitted line in the radio domain – basically because of its symmetric structure. However, the next most abundant molecule, CO, has a $J = 1 \rightarrow 0$ rotational transition at a radio wavelength of 2.6 mm. The corresponding emission line has been, for over three decades, the primary tracer of molecular interstellar gas.

Large-scale surveys of CO 2.6-mm emission (e.g., Clemens *et al.* 1988; Bronfman *et al.* 1988; Heyer 1999) show that most of the molecular gas resides in a well-defined ring extending radially between 3.5 kpc and 7 kpc from the Galactic center (see Figure 1). A more localized (and stronger) peak also appears in the central region interior to 0.4 kpc. In addition, the molecular gas concentrates toward the spiral arms, especially in the outer Galaxy ($R > R_\odot$), where interarm regions appear almost devoid of molecular gas. In the vertical direction, the molecular gas is strongly confined to the Galactic plane; for reference, the Z-dependence of its space-averaged density can be approximated by a Gaussian, with a midplane value $\simeq 0.55$ cm^{-3} and a scale height $\simeq 75$ pc at the solar circle (see Figure 2).

High-resolution observations indicate that the molecular gas is contained in discrete clouds organized hierarchically from giant complexes (with a size of a few tens of parsecs, a mass of up to $10^6\ M_\odot$, and a mean hydrogen number density $\sim 100 - 1000$ cm^{-3}) down to small dense cores (with a size of a few tenths of a parsec, a mass $\sim 0.3 - 10^3\ M_\odot$, and

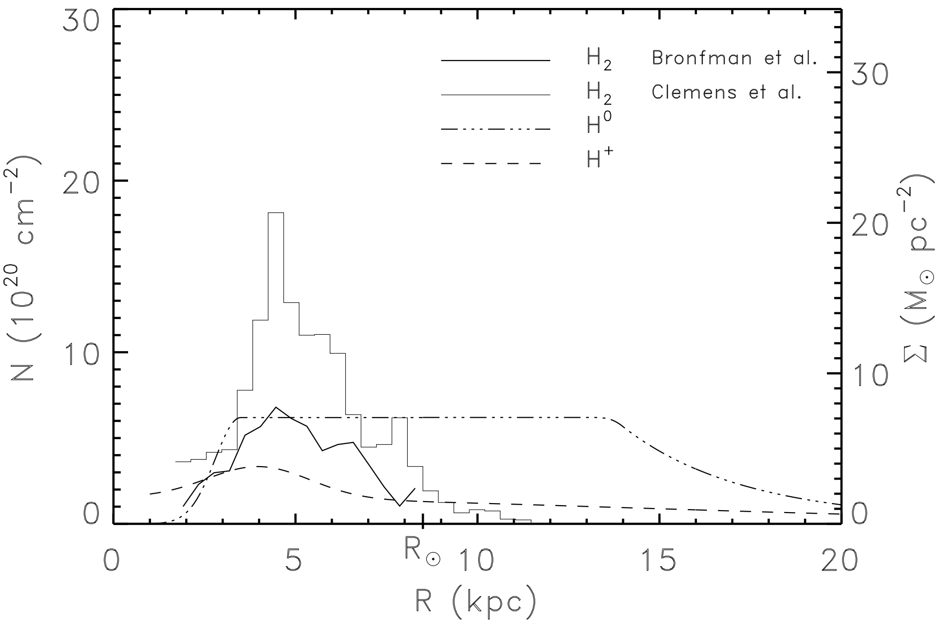

Figure 1.: *Column density of interstellar hydrogen, defined as the number of hydrogen nuclei contained in a vertical cylinder of unit cross section through the Galactic disk, N, and mass density per unit area of interstellar matter, $\Sigma = 1.42\, m_{\rm P}\, N$, averaged over Galactocentric azimuthal angle, as a function of Galactic radius, R, for the different gas components. The solid lines give the contribution from the molecular gas, the triple-dot–dashed line that from the cold + warm atomic gas, and the dashed line that from the ionized gas outside the traditional* H II *regions.*

a mean hydrogen number density $\sim 10^4 - 10^6$ cm^{-3}) (Goldsmith 1987). The majority of molecular clouds are sufficiently massive to be bound by self-gravity, and it can be verified that they approximately satisfy the virial balance equation, $G\,M/R \sim \sigma^2$, where M, R, and σ are the cloud mass, radius, and internal velocity dispersion, and G is the gravitational constant (Myers 1987).

From measurements of the peak specific intensity of CO emission lines, it emerges that molecular clouds are, in general, extremely cold, with typical temperatures in the range $10 - 20$ K (Goldsmith 1987). Thermal speeds at these low temperatures are small compared to the measured internal velocity dispersions. This means that the total gas

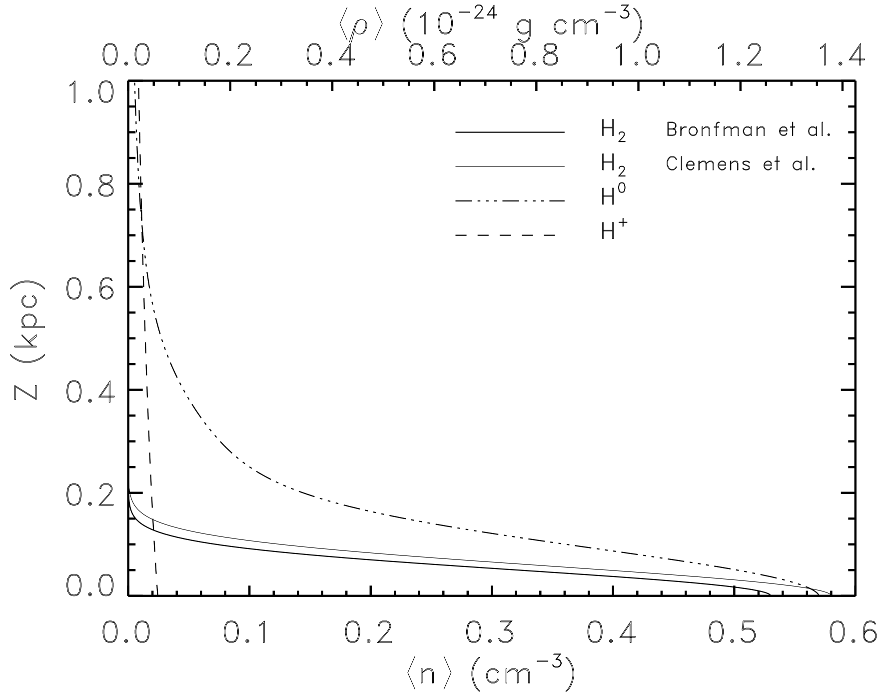

Figure 2.: *Space-averaged number density of interstellar hydrogen nuclei,* $\langle n \rangle$*, and space-averaged mass density of interstellar matter,* $\langle \rho \rangle = 1.42\, m_{\rm P}\, \langle n \rangle$*, as a function of Galactic height,* Z*, at the solar circle (*$R = R_\odot$*), for the different gas components. The solid lines give the contribution from the molecular gas, the triple-dot–dashed line that from the cold + warm atomic gas, and the dashed line that from the ionized gas outside the traditional* H II *regions.*

pressure inside molecular clouds has but a small contribution from its purely thermal component, the dominant contribution arising from internal turbulent motions. Moreover, in accordance with the notion that molecular clouds are gravitationally bound, the total gas pressure in their interior is much higher than in the intercloud medium.

H_2 molecules are believed to form by recombination of hydrogen atoms on the surface of interstellar dust grains. The only regions where they can actually survive in vast numbers are the interiors of dark interstellar clouds (and possibly the deep interiors of diffuse clouds), which are simultaneously shielded from radiative dissociation by external UV photons and cold enough to avoid collisional dissociation (Shull & Beckwith 1982). The observed temperatures of molecular regions are easily explained as the result of thermal balance between heating by cosmic rays (and, at the cloud edges, collisions with photoelectrons from dust grains and with radiatively excited H_2 molecules) and cooling by molecular line emission (primarily CO), the rate of which increases steeply with increasing temperature. Collisions with dust grains also enter the thermal balance, either as a coolant or as a heat source, depending on the dust temperature with respect to that of the gas (Hollenbach & Tielens 1999).

2.3 Neutral Atomic Gas

The primary probe of neutral atomic gas is the 21-cm hyperfine line of atomic hydrogen (usually denoted by H I, as opposed to H II for ionized hydrogen), observed both in emission and in absorption.

In emission, the 21-cm line yields the total H I column density in the observed direction. Moreover, the contribution from each segment along the line of sight can be extracted from the shape of the line profile combined with the Galactic rotation curve. This is how 21-cm emission line measurements covering the whole sky have been able to yield the H I space-averaged density as a function of position in the Galaxy (e.g., Lockman 1984; Burton & te Lintel Hekkert 1986; Diplas & Savage 1991).

H I maps projected onto the Galactic plane exhibit long arc-like features organized into a spiral pattern. Radially, the H I gas extends out to at least 30 kpc from the Galactic center, and its azimuthally-averaged column density through the disk is characterized by a deep depression inside 3.5 kpc, a relatively flat plateau out to almost 14 kpc, and an exponential fall-off beyond 14 kpc (see Figure 1). The vertical structure of the H I space-averaged distribution is roughly uniform in the radial range 3.5 kpc $< R < R_\odot$, with a midplane density $\simeq 0.57$ cm^{-3} and an equivalent half-thickness $\simeq 175$ pc (Dickey & Lockman 1990; see also Figure 2). The half-thickness of the H I layer drops to $\lesssim 50$ pc inside 3.5 kpc and grows more than linearly with R outside $R_\odot$, reaching ~ 1.5 kpc at the outer Galactic boundary.

21-cm absorption spectra generally look quite different from emission spectra taken in a nearby direction: while the emission spectra contain both distinct narrow peaks and much broader features, only the narrow peaks are present in the absorption spectra. The conventional interpretation of this difference is that the narrow peaks seen in emission and in absorption are produced by discrete cold ($T \simeq 50 - 100$ K) H I clouds, whereas the broader features seen in emission only are due to a widespread H I gas that is too warm to give rise to detectable 21-cm absorption. The estimated temperature of the warm H I component is $\simeq 6000 - 10000$ K (Kulkarni & Heiles 1987).

Comparisons between 21-cm emission and absorption measurements indicate that, in the vicinity of the Sun, the warm H I has roughly the same column density as the cold H I and about 1.5 times its scale height (Falgarone & Lequeux 1973). The average fraction of cold H I appears to remain approximately constant from $R_\odot$ in to ~ 5 kpc and to drop by a factor ~ 2 inside 5 kpc. Outside the solar circle, H I is probably mainly in the warm phase.

High-resolution maps of the 21-cm emission sky strikingly show that the cold H I clouds are sheet-like or filamentary. A sizeable fraction of them appear to be parts of expanding shells and supershells, with diameters ranging from a few tens of parsecs to ~ 2 kpc and with expansion velocities reaching a few tens of km s^{-1} (Heiles 1984). The true hydrogen density in cold H I clouds is $\simeq 20 - 50$ cm^{-3}, i.e., some two orders of magnitude larger than in the warm intercloud H I (Kulkarni & Heiles 1987). The fact that this density ratio is approximately the inverse of the temperature ratio supports the view that the cold and warm atomic phases of the ISM are in rough thermal pressure equilibrium.

The existence of two H I phases with comparable thermal pressures but with radically different temperatures and densities is a direct consequence of the shape of the cooling curve: fairly flat between a steep rise due to the [C II] 158 μm transition at $T \sim 100$ K and another steep rise due to the hydrogen Lα transition at $T \sim 8000$ K. Heating of the H I gas results from a combination of different factors, including low-energy cosmic rays, photoelectric ejection off dust grains, and magnetohydrodynamic wave dissipation (e.g., Wolfire *et al.* 1995).

2.4 Warm Ionized Gas

The existence of an ionized interstellar gas component has long been known from the observed dispersion of pulsar signals. The underlying physical idea is easily understood: the periodic pulses emitted by a pulsar can each be decomposed into a spectrum of electromagnetic waves spanning a whole range of radio wavelengths. When these waves travel through an ionized region, they are slowed down by the free electrons of the medium in a wavelength-dependent manner. The resulting spread in arrival times (which can be measured) is directly proportional to the column density of free electrons between the pulsar and the observer, a quantity known as the dispersion measure. Pulsar signals are, in addition, scattered by fluctuations in the free-electron density. Scattering measures (which are also directly related to measurable quantities) provide further information, especially valuable in the direction of the Galactic center and for pulsars without an independent distance estimate. The discovery of pulsars out to large distances from the Sun and the continuous improvement in the determination of pulsar distances, dispersion measures, and scattering measures have made it possible to model the large-scale distribution of interstellar free electrons.

The best-fit axisymmetric models consist of the superposition of an annular component centered on $R \simeq 4$ kpc and a radially extended component with Gaussian scale length $\gtrsim 20$ kpc. The annular component, which is presumably linked to the molecular ring, is thin (exponential scale height $\simeq 0.15$ kpc) and makes a negligible contribution at the solar circle, whereas the extended component is much thicker (exponential scale height $\simeq 1$ kpc) and has a midplane space-averaged density $\simeq 0.025$ cm^{-3} at the solar circle (Cordes *et al.* 1991). More refined, non-axisymmetric models suggest that the free-electron density is ~ 3 times higher in spiral arms than in interarm regions (Taylor & Cordes 1993).

The presence of ionized interstellar gas outside well-defined H II regions is also revealed by the detection of optical emission lines produced by radiative recombination of hydrogen and helium ions with free electrons and by radiative de-excitation of collisionally excited ionized metals. The most important of these lines is the hydrogen Hα recombination line at a wavelength of 6563 Å.

High-resolution Hα maps display a complex structure made of patches, filaments, and loops of enhanced Hα emission, superimposed onto a fainter background (Reynolds *et al.* 1999). The temperature of the diffuse emitting gas, inferred from the width of the Hα, [S II] and [N II] emission lines, is ~ 8000 K near the midplane, with a likely rise at high $|Z|$ (Haffner *et al.* 1999). Furthermore, the non-detection of [O I] and [N I] emission indicates that hydrogen is almost fully ionized in this warm medium – hence the designation of warm ionized medium.

At 8000 K, the observed Hα intensity along the Galactic equator together with an estimated mean free-path for absorption of Hα photons $\simeq 2$ kpc translates into a space-averaged electron density squared $\simeq 4.5 \times 10^{-3} - 11.5 \times 10^{-3}$ cm^{-6} at low $|Z|$. If we combine this space-averaged electron density squared with the space-averaged electron density deduced from pulsar dispersion measures, we find that the warm ionized medium has a true density $\simeq 0.18 - 0.46$ cm^{-3} and a filling factor $\simeq 5 - 14$ % at low $|Z|$.

The weakness of the measured He I recombination line emission suggests that helium remains largely neutral in the warm ionized medium. In the hot medium (see Section 2.5), helium is doubly ionized, but its contribution to free electrons can be shown as negligible. In consequence, the space-averaged density of ionized hydrogen may be identified with the free-electron space-averaged density inferred from pulsar data. The axisymmetric model of Cordes *et al.* (1991) then leads to the radial and vertical profiles plotted in Figures 1 and 2, respectively.

By comparing the interstellar hydrogen recombination rate implied by the measured Hα emission to the ionizing power of known sources of ionizing radiation in the solar neighborhood, one may conclude that only O stars are potentially able to do, by themselves, the desired job of maintaining the warm ionized medium in an almost fully ionized state – and, at the same time, at a temperature $\sim$ 8000 K (Reynolds 1984). There exist, however, two inherent problems with O stars being the primary source of ionization. First, O stars are preferentially born in dense molecular clouds close to the Galactic plane, which makes it difficult for a sufficient fraction of their ionizing photons to escape their immediate vicinity and pervade the general ISM up to the high altitudes where warm ionized gas is found. Second, the observed emission-line spectrum of the warm ionized medium differs markedly from that characteristic of the compact H II regions surrounding O stars. The first problem can be overcome by taking into account the multi-component nature and the vertical structure of the ISM. In contrast, the second problem suggests that supplemental ionization/heating mechanisms are at play, such as photoelectric ejection off dust grains, dissipation of interstellar plasma turbulence, Coulomb encounters with Galactic cosmic rays, or magnetic reconnection.

2.5 Hot Ionized Gas

The presence of hot interstellar gas manifests itself in two different ways: (1) through the broad UV absorption lines of high-stage ions found in the spectra of O and B stars and (2) through the soft X-ray thermal radiation emitted by the hot gas.

Amongst the high-stage ions accessible to UV observations, O VI and N V are the best tracers of hot collisionally ionized gas, insofar as their high ionization potential makes them difficult to produce by photoionization. Their degree of ionization together with the measured line widths imply temperatures of a few 10^5 K (York 1977). In addition, the integrated line intensities, which directly yield the ion column densities between the Earth and the target stars, shed some light on their spatial distribution in the vicinity of the Sun. In particular, a rough estimation of their local exponential scale height leads to values $\sim$ 2.7 kpc for O VI (Savage *et al.* 2000) and $\sim$ 3.9 kpc for N V (Savage *et al.* 1997).

The soft X-ray background radiation around 0.25 keV appears to arise predominantly from the Local Bubble, i.e., the H I cavity within which the solar system is embedded (Cox & Reynolds 1987). The temperature of the emitting gas, deduced from the relative intensities of three adjacent energy bands, is $\simeq 10^6$ K (McCammon & Sanders 1990). Its average density can be inferred from the observed intensity of the soft X-ray flux, provided that the emission path lengths are known. By calibrating the latter with the help of the estimated distance to a shadowing molecular cloud, Snowden *et al.* (1998) obtained an average hydrogen density $\simeq 0.0065$ cm^{-3}.

It is very likely that 0.25-keV X-ray–emitting regions exist throughout the Milky Way, but because their radiation is efficiently absorbed by the intervening cool interstellar gas, the majority of them must escape detection. On the other hand, a number of bright features have been observed in the intermediate energy band $0.5 - 1.0$ keV, which is less affected by photoelectric absorption. Most of these features were shown to be associated either with individual supernova remnants or with superbubbles, and their X-ray radiation was attributed to thermal emission from a hot plasma at a temperature of a few 10^6 K (Aschenbach 1988; McCammon & Sanders 1990).

It is now widely accepted that the hot interstellar gas is generated by supernova explosions and, to a lesser extent, by the generally powerful winds from the progenitor stars (Spitzer 1990). Supernova explosions drive rapidly propagating shock waves in the ISM, which sweep out cavities filled with hot rarefied gas and surrounded by a cold dense shell of collapsed interstellar matter. Because the hot gas inside the cavities has a sufficiently long radiative cooling time to persist for millions of years, the hot cavities occupy on average a significant (albeit very uncertain) fraction of interstellar space.

3. Interstellar Cosmic Rays and Magnetic Fields

The high-energy and magnetic constituents of the ISM are covered in other chapters of these proceedings, where both our observational knowlegde and our theoretical understanding of their properties are discussed in detail. Here I will be content to illustrate their relative importance with respect to the ordinary matter, by showing a plot of the space-averaged pressure associated with each of the three ISM constituents as a function of Galactic height at the solar circle (Figure 3).

It clearly emerges from Figure 3 that cosmic-ray and magnetic pressures are comparable across the disk, and that they dominate over the ordinary-gas pressure outside the thin gas layer ($|Z| \gtrsim 200$ pc).

4. Stars and Supernovae

4.1 Role Played by Stars

Stars affect the interstellar matter essentially through their radiation field, their wind, and, in some cases, their terminal supernova explosion. Globally, the massive, luminous O and B stars are by far the dominant

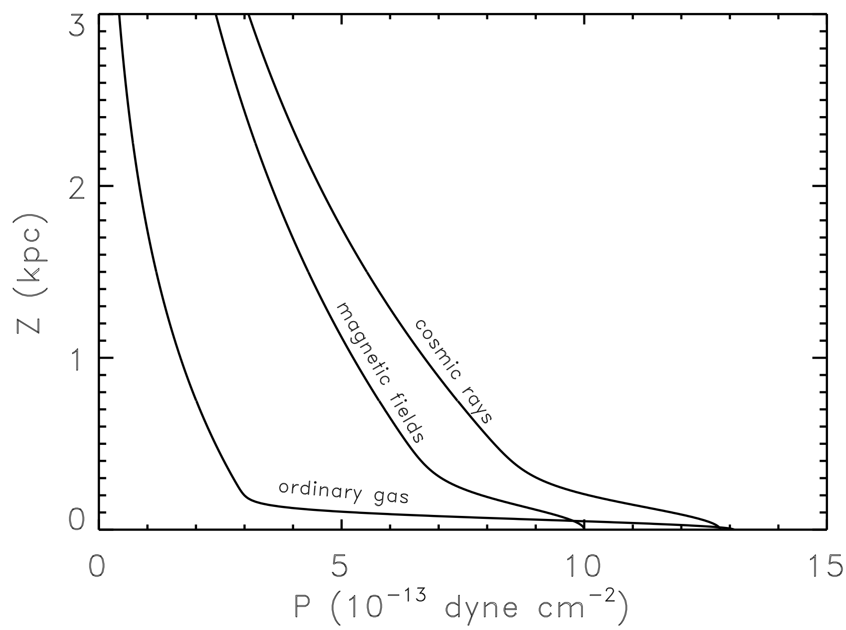

Figure 3.: *Space-averaged interstellar pressure associated with the three ISM constituents as a function of Galactic height at the solar circle ($R = R_\odot$).*

players, even though they represent but a minor fraction of the stellar population. Low-mass stars appear on the scene only for short periods of time, during which they have important outflows or winds.

Stellar radiation photons, above all the energetic UV photons from O and B stars, have a threefold direct impact on the interstellar matter. (1) They dissociate H_2 molecules (provided $\lambda < 1120$ Å) at the surface of molecular clouds. More generally, they dissociate molecules such as H_2, CO, OH, O_2, H_2O ... in photodissociation regions. (2) They ionize the immediate vicinity of O and B stars, thereby creating compact H II regions, and they ionize more remote diffuse areas, which together constitute the warm ionized medium. In neutral regions, they ionize elements such as C, Mg, Si, and S, whose ionization potential lies below the 13.6 eV threshold of hydrogen. (3) They heat up the interstellar regions that they ionize to a temperature ~ 8000 K, by imparting an excess energy to the liberated photoelectrons. They also contribute to the heating of neutral regions, mainly through the ejection of photoelectrons from dust grains and through the radiative excitation of H_2 molecules followed by collisional de-excitation. As a side effect of ionization and heating by stellar photons, the traditional H II regions reach high thermal pressures, which cause them to expand into the ambient ISM.

Stellar winds pertain to stars of all masses. Low-mass stars are concerned only for limited periods in their lifetime. Early on, just before joining the main sequence, they experience energetic, more-or-less collimated outflows. Toward the end of their life, after they have moved off the main sequence, they successively pass through the red-giant, asymptotic-giant-branch (AGB), and planetary-nebula stages, during which they lose mass again at a very fast rate. High-mass stars suffer rapid mass loss throughout their lifetime. Their wind becomes increasingly powerful over the course of the main-sequence phase and, if their initial mass exceeds $\simeq 32\ M_\odot$, the wind reaches a climax during a brief post–main-sequence Wolf-Rayet phase.

Supernovae are customarily divided into two categories according to the nature of their progenitor star. Type Ia supernovae arise from old, degenerate low-mass stars, which supposedly are accreting from a companion and undergo a thermonuclear instability upon accumulation of a critical mass. Type Ib, Type Ic, and Type II supernovae arise from young stars with initial mass $\gtrsim 8\ M_\odot$, whose core collapses gravitationally once it has exhausted all its fuel. Both categories of supernovae release an amount of energy $\simeq 10^{51}$ ergs.

To a large extent, stellar winds and supernova explosions act in qualitatively similar ways, although supernova explosions are more sudden and usually far more spectacular. First of all, both constitute an important source of matter for the ISM. Since this matter has been enriched in heavy elements by the thermonuclear reactions taking place inside the stars, the metallicity of the ISM is gradually enhanced. The main contributors to the injection of mass into the ISM are the old red-giant, AGB, and planetary-nebula stars.

Second, stellar winds and supernova explosions forge the structure of the ISM and are largely responsible for both its multi-phase nature and its turbulent state. Here, the main contributors are the young, massive O and B stars. To start with, the wind from a massive star blows a cavity of hot gas in the surrounding ISM and compresses the swept-up interstellar gas into a rapidly expanding circumstellar shell. If it is initially more massive than $\simeq 8\ M_\odot$, the star explodes at the end of its lifetime, and the shock wave driven by the explosion pursues, in an amplified fashion, the action of the wind, sweeping up a lot more interstellar matter into the expanding shell, and greatly enlarging the hot cavity enclosed by the shell. The compressed swept-up gas, at the elevated postshock pressure, radiates efficiently, cools down, and collapses, so that the shell soon becomes cold and dense. Part of it may even turn molecular.

If the shell collides with a comparatively massive interstellar cloud or, at the latest, when the shock expansion velocity slows to roughly the external "signal speed" (generalized sound speed, based on the total pressure, i.e., the ordinary-gas + magnetic + cosmic-ray pressure, rather than the purely thermal pressure), the shell begins to break up and lose its identity. The resulting shell fragments keep moving independently of each other and start mixing with the interstellar clouds; at this point, the shell is said to merge with the ambient ISM. Meanwhile, the hot rarefied gas from the interior cavity comes into contact with the ambient interstellar gas, mixes with it, and cools down – through thermal conduction followed by radiation – to a temperature $\sim 10^4$ K.

Ultimately, what an isolated massive star leaves behind is a cavity of hot rarefied gas, surrounded by an increasingly thick layer of warm gas, plus several fragments of cold dense matter moving at velocities ~ 10 km s^{-1}. These fragments, be they atomic or molecular, appear to us as interstellar clouds.

The majority of O and B stars are not isolated, but grouped in clusters and associations, so that their winds and supernova explosions act collectively to engender superbubbles. A superbubble behaves qualitatively like an individual supernova remnant, with this difference that it has a continuous supply of energy. For the first 3 Myr at least, this energy supply is exclusively due to stellar winds, whose cumulative power rises rapidly with time. Supernovae start exploding after $\gtrsim 3$ Myr, and within ~ 2 Myr they overpower the winds. From then on, the successive supernova explosions continue to inject energy into the superbubble, at a slowly decreasing rate, depending on the initial mass function of the progenitor stars, until ~ 40 Myr. Altogether, stellar winds account for a fraction ~ 15 % of the total energy input.

Type Ia supernovae are less frequent than core-collapse supernovae. (see Section 4.2). All of them are uncorrelated in space, and they have basically the same repercussions on the ISM as isolated Type II/Ibc supernovae.

To fix ideas, in the local ISM, the remnant of a typical isolated supernova grows for ~ 1.5 Myr and reaches a maximum radius ~ 50 pc. An "average superbubble", produced by 30 clustered Type II/Ibc supernovae, grows for ~ 15 Myr to a radius varying from ~ 200 pc in the Galactic plane to ~ 300 pc in the vertical direction. This vertical elongation is a direct consequence of the ISM stratification: because the interstellar density and pressure fall off away from the midplane, superbubbles encounter less resistance and, therefore, manage to expand farther along the vertical than horizontally.

Let us now inquire into the long-term evolution of the cold shell fragments produced by supernova explosions. Some of them remain mostly atomic and are observed as diffuse atomic clouds, moving randomly at velocities ~ 10 km s^{-1}. Others, typically those arising from old superbubbles, become largely molecular, at least away from their surface. These molecular fragments are responsive to self-gravity, which, past a critical threshold, drives them unstable to gravitational collapse. The collapse of individual fragments or pieces thereof eventually leads to the formation of new stars, which, if sufficiently massive, may in turn initiate a new cycle of matter and energy through the ISM.

Beside their obvious impact on the interstellar matter, stars are equally vital for Galactic cosmic rays and magnetic fields. They are the likely birthplaces of most Galactic cosmic rays, and the shock waves sent by supernova explosions constitute important sites of further cosmic-ray acceleration. Likewise, interstellar magnetic fields could have their very first roots in stellar interiors; while this possibility remains to be proven, there is now little doubt that, once a tiny magnetic field has been created, the turbulent motions generated by supernova explosions amplify it at a fast rate.

4.2 Supernova Parameters

The Galactic frequency of both categories of supernovae can be estimated by monitoring their rate of occurrence in a large number of external galaxies similar to the Milky Way. By combining five independent supernova searches, involving a total of 7773 galaxies, Cappellaro *et al.* (1997) derived average frequencies of 0.41 h^2 SNu for Type Ia supernovae and 1.69 h^2 SNu for Type II/Ibc supernovae in Sbc-Sd galaxies, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} and 1 supernova unit (SNu) represents 1 supernova per $10^{10}\ (L_B)_\odot$ per 100 yr.

The value of the Hubble constant, which gives the present expansion rate of the Universe, was under heavy debate for over half a century, until various kinds of observations made in the last few years finally converged to a narrow range $\simeq 60-70$ km s^{-1} Mpc^{-1} (Freedman *et al.* 2001). If we choose the median value of this range, corresponding to $h = 0.65$, and assume that the Milky Way is an average Sbc galaxy with a blue luminosity of $2.3 \times 10^{10}\ (L_B)_\odot$ (van den Bergh 1988), we find that Cappellaro *et al.*'s (1997) results translate into a Type Ia supernova frequency $\simeq 1/(250$ yr) and a core-collapse supernova frequency $\simeq 1/(60$ yr) in our Galaxy.

The corresponding total supernova frequency in our Galaxy is $\simeq 1/(48$ yr), in reasonably good agreement with the evidence from historical supernovae. Only five Galactic supernovae brighter than zeroth magnitude were recorded in the last millenium, but it is clear that many more supernovae occurred without being detected from Earth, mainly

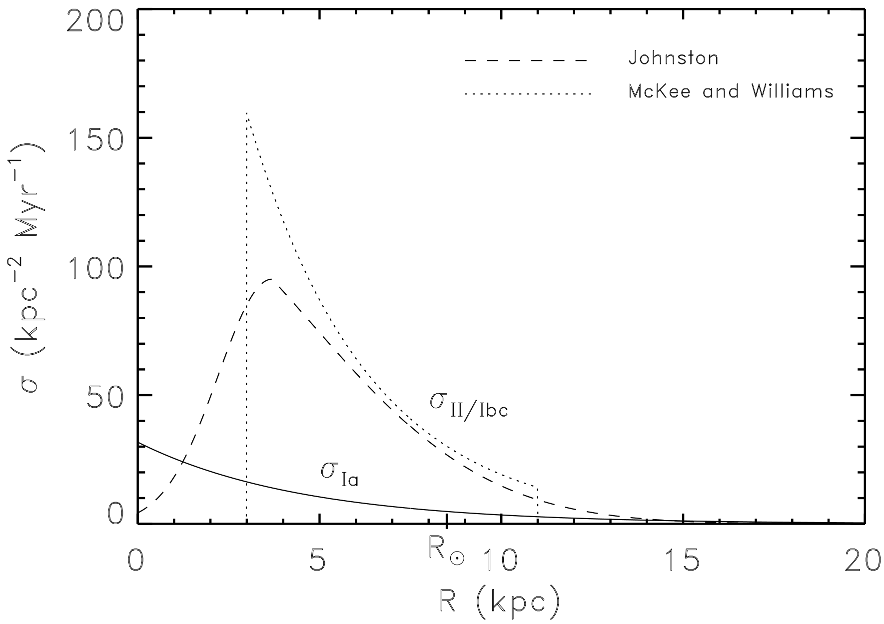

Figure 4.: *Galactic supernova rate per unit area, σ, as a function of Galactic radius, R, both for Type Ia supernovae (solid line) and for Type II/Ibc supernovae (pulsar model: dashed line;* H II*-region model: dotted line).*

because they remained obscured by the interstellar dust. Tammann *et al.* (1994) extrapolated from the five recorded events, with the help of a detailed model of the Galaxy accounting for obscuration by dust, and they concluded that a Galactic supernova frequency $\sim 1/(26 \text{ yr})$ – with a large uncertainty due to small-number statistics – could reproduce the historical observations.

The spatial distribution of supernovae in our Galaxy can be inferred from that of related objects. For instance, one may reasonably suppose that Type Ia supernovae follow the distribution of old disk stars, with an exponential scale length $\simeq 4.5$ kpc along R and an exponential scale height $\simeq 325$ pc along Z (Freeman 1987). If we normalize this distribution with the Type Ia supernova frequency cited above, we obtain for the Type Ia supernova rate per unit area and for their rate per unit volume at the solar circle the solid curves drawn in Figures 4 and 5, respectively.

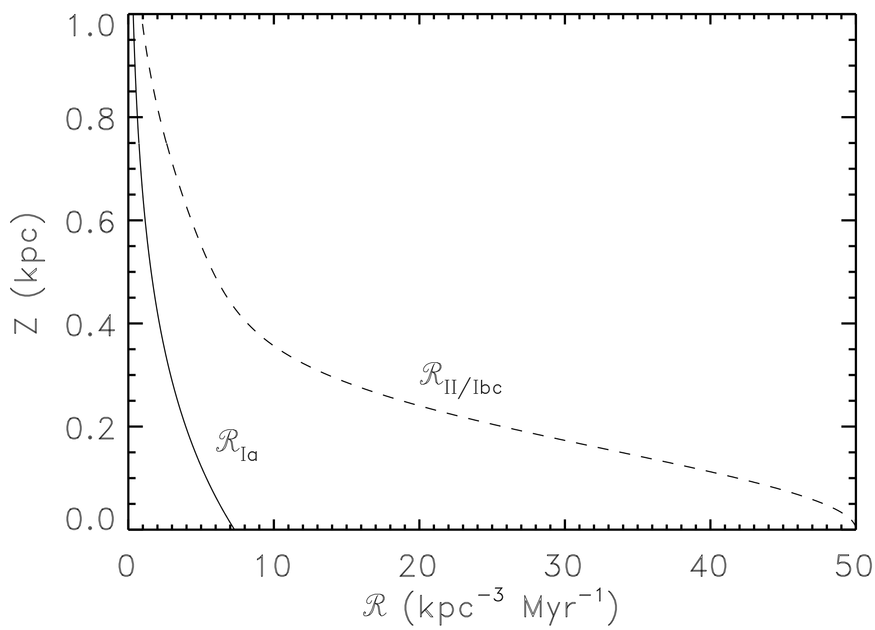

Figure 5.: *Galactic supernova rate per unit volume, $\mathcal{R}$, as a function of Galactic height, Z, at the solar circle ($R = R_\odot$), both for Type Ia supernovae (solid line) and for Type II/Ibc supernovae (dashed line).*

For core-collapse supernovae, one may use either H II regions, which are produced by their luminous progenitor stars, or pulsars, which are the likely leftovers of core-collapse explosions. McKee & Williams (1997) found that Galactic giant H II regions are approximately distributed in a truncated exponential disk with a radial scale length $\simeq 3.3$ kpc over the radial range $R \simeq 3 - 11$ kpc. Galactic pulsars, for their part, were shown to be radially distributed according to a rising Gaussian with a scale length $\simeq 2.1$ kpc for $R < 3.7$ kpc and a standard Gaussian with a scale length $\simeq 6.8$ kpc for $R > 3.7$ kpc (Narayan 1987; Johnston 1994). Their vertical distribution at birth can be approximated by the superposition of a thin Gaussian disk with a scale height $\simeq 212$ pc and a thick Gaussian disk with a three times greater scale height, containing, respectively, 55 % and 45 % of the pulsar population (Narayan & Ostriker 1990). The pulsar model together with the Type II/Ibc supernova frequency cited above leads to the dashed curves in Figures 4 and 5.

Let us now estimate the fraction of core-collapse supernovae that are clustered and the way they are distributed amongst different clusters. In the catalog of 195 Galactic O stars compiled by Gies (1987), 71 % lie in groups and 29 % lie in the field. For the O stars in groups, we may use the radial peculiar velocities tabulated by Gies together with the assumption of isotropy in peculiar-velocity space to reconstruct the distribution in total peculiar velocity. This distribution clearly possesses an excess of high-velocity stars, amounting to $\simeq 15$ % of the group stars, i.e., $\simeq 11$ % of all O stars. According to Gies' interpretation, these high-velocity stars were recently ejected from their native cluster and will end up in the field. From this, we conclude that ~ 60 % of the O stars were born and will remain in groupings, while ~ 40 % of them will die in the field.

Can these figures be extended to all Type II/Ibc supernova progenitors? Humphreys & McElroy (1984) compiled a list of all known-to-date Galactic luminous stars and found that 47 % of them are grouped. Since their list contains on average older stars than Gies' (1987), it is not surprising that a larger fraction of their stars appear in the field. Indeed, stars born in a group may after some time be observed in the field, either because they have been ejected from the group or because the group has dispersed. If we accept that $\simeq 11$ % of the O stars are observed as group members but will end up in the field as a result of ejection, and if we assume that OB associations disperse into the field after ~ 15 Myr, we find that Humphreys & McElroy's (1984) compilation is consistent with 60 % of all Type II/Ibc supernovae being clustered.

Clustered core-collapse supernovae are very unevenly divided between superbubbles. In other words, the number of clustered supernovae contributing to one superbubble, N, is extremely variable. The distribution of N can be deduced from the observed luminosity distribution of H II regions, which suggest a power-law distribution in N^{-2} (McKee & Williams 1997). Moreover, relying on local observations of OB stars and stellar clusters, Ferrière (1995) estimated that N averages to $\simeq 30$ and varies roughly between 4 and ~ 7000.

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