Chapter 1

Introduction

In around 1784, William Herschel, noted some apparent voids in the distribution of stars in the sky and called them the “holes in the sky”. Whether these holes are true absence of stars, as Herschel proposed or ‘something’ was obscuring the radiation from distant star field was not clear at that time. However, that was perhaps the first indication that there are materials in the space between stars, which we now call the Interstellar Medium (ISM). It primarily consists of a tenuous gas, small sub-micron particles called grains, cosmic rays and magnetic field. ISM is a very important constituent in the galactic eco-system. Due to its intermediate role between the stellar and the galactic scales it plays a vital role in many of the physical and chemical processes taking place. One such example is the process of star formation. Stars are born in the densest regions of the ISM. Therefore, the initial composition of the stars are essentially the same as the ingredients provided by the ISM.

The primordial interstellar medium is formed in the big bang. The chemical history of the universe as a result of big bang is not very diverse, being made up of mostly hydrogen, small amount of helium and with a sprinkling of lithium, beryllium and boron. The first generation stars are made up of this simple elements only. These elements are continuously fused in the stellar interior to yield heavier elements like, carbon, nitrogen and elements up to iron. Then, some of these stars which are massive die with a gigantic explosion called supernovae which provided the favorable condition for the synthesis of elements heavier than iron. Supernovae explosions also throw much of the material from their parent stars back into the interstellar medium, changing its chemical composition. In this way, the abundance
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of heavy elements in the ISM gradually increases which in turn provide essential ingredients for the next generation stars.

But this is only a part of the whole story. Another part of this fiery tale is that the residing matter in the ISM undergoes a rich chemistry which leads to the formation of numerous exotic molecules. So far, 134 molecules have been discovered (http://www.cv.nrao.edu/~awootten/allmols.html) through their electronic (these transitions are in the ultraviolet or in the visible range), vibrational (arises in the infrared wavelengths), and rotational spectra (lie in the radio wavelengths). Many of these molecules deplete during various evolutionary phases of star formation onto cold grains and are eventually incorporated into the planetesimals of new stellar systems. Recent observations of comets such as Hyakutake and Hale-Bopp show remarkable similarity between the composition of interstellar and cometary ices. Analysis of carbonaceous meteorites shows a high deuterium level which is also an indicator of their interstellar origin.

Thus interstellar medium is the stage and the star formation and chemical evolution are the major players which are involved in our discussion. In this Chapter, we will discuss all the relevant components that are needed for this work.

1.1 Brief Historical Overview

It took quite some time for the scientists to realize that there is a medium in between the stars and plenty of activities are going on inside it.

In the year 1904, Hartmann, while observing the spectrum of a spectroscopic double star found that Ca\(^++\) absorption line does not share with the periodic displacement of lines caused by the orbital motion of the stars. He suggested that their origin must be outside the star.

In the 1930's, the interstellar extinction was discovered by Trumpler (1930) and van de Kamp (1932). Trumpler noticed that the linear diameters of open clusters increase with distance from the Sun. He concluded that this apparent increase is caused by the unaccounted interstellar extinction that makes photometric distances to the open clusters greater than they are in reality. It was also the first indication for the existence of dust particles. van de Kamp found that the galaxy count decreases
towards the galactic plane. He calculated the total absorption by which the intensity of light passing perpendicularly through the intervening layers is diminished.

Karl Guthe Jansky first built an antenna to receive radio waves at a frequency of 20.5 MHz (wavelength about 14.5 meters). After recording signals from all directions for several months, he found a faint steady hiss of unknown origin. He figured out that the radiation was coming from the Milky Way and was strongest in the direction of the center of our galaxy, in the constellation of Sagittarius. This marks the beginning of radio astronomy.

First signature of molecular species were found by Merill (1936). He detected four new bands whose the wavelengths are 5780, 5796, 6284 and 6614 Å. The carriers of which were unknown at that time. In the subsequent years, the possible signature of CH, CH+ and CN are found in the interstellar absorption lines (Dunham 1937, Swings and Rosenfeld 1937, Mckellar 1940). These lines are detected in the optical wavelengths.

Then came possibly the most important prediction and subsequent discovery made in the ISM research, namely, the prediction and detection of 21 cm hydrogen line. H. C. Van de Hulst, a student of the great astronomer Jan Oort, was assigned to find the possible spectral line in radio wavelengths. Since hydrogen is the most abundant element in the universe, he started his studies with hydrogen. He found that a “hyperfine” transition in the ground state of neutral hydrogen would produce radiation in the radio range, at a frequency of 1420 MHz, or about 21 cm wavelength. In the ground state of hydrogen, an electron can have its magnetic moment either parallel or anti-parallel to that of the proton. The parallel state has a little more energy, so a transition to the anti-parallel state results in an emission of 21 cm radiation. Using this in the 1951, Ewen and Purcell conclusively proved the existence of neutral hydrogen in the ISM. Subsequently, Muller and Oort (1951) also detected this line.

In the Year 1949, Hall (1949) and Hiltner (1949), inspired by a prediction of Chandrasekhar on intrinsic stellar polarization, independently discovered linear polarization in interstellar medium. It was also found that the polarization correlates with the reddening and hence with the extinction. The implication for the linear polarization is that the extinction is caused by the non-spherical dust grains aligned
in the interstellar magnetic field.

The first detection of the 18-cm lines of the OH radical was reported by Weinreb et al. (1963). They observed the lines in the absorption in the spectrum of Cassiopeia A at frequencies which closely agrees with laboratory values. In the subsequent years, interstellar ammonia (Cheung, 1968), water (Cheung, 1969), formaldehyde (Snyder, 1969) have been detected through radio detection. Wilson et al. (1970) detected interstellar carbon monoxide in the direction of Orion nebula. Then the discovery of Lyman resonance-absorption bands of interstellar molecular hydrogen was made (Carruthers, 1970). This period marks the beginning for the search of interstellar molecules and, in the next few decades, it becomes one of the most important aspect of the subject.

Discovery of several molecules in the interstellar medium led scientists inevitably towards its theoretical study. They started with the most abundant molecule, i.e., $\text{H}_2$. It was readily realized that the molecular hydrogen could not form efficiently in the gas phase, and, grain surfaces are needed (Gould & Salpeter, 1963). Interstellar grains act as catalysts. Hollenbach & Salpeter (1970, 1971) developed a semi-classical model in which mobility of the atoms on a grain surface is treated quantum mechanically. We will discuss molecular hydrogen formation in great details in Chapter 3. Subsequently, Watson and Salpeter (1972a, b) considered the hydrogenation reactions between mobile H atoms and more stationary heavy atoms. Herbst & Klemperer (1973) constructed a homogeneous gas phase model with around 100 reactions and calculated the production of $\text{H}_2\text{O}$, HCN, $\text{NH}_3$ etc. and compared their results with observations. Allen & Robinson (1975, 1976, 1977) considered a wider range of surface reactions to produce even more complex molecules.

Tielens & Hagen (1982) studied the chemical evolution of grain mantles using the steady state gas phase abundances and introduced a Monte Carlo method to handle the grain chemistry. They traced the migration of simple molecules which tend to migrate more rapidly than heavier molecules, hence dominates the chemistry. D'Hendecourt, Allamandola & Greenberg (1985) modeled the gas-grain chemistry and showed that a steady state between the grain surface and gaseous molecular abundance is maintained via grain explosions and photo-desorption. Several other groups have addressed the issue.
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Figure 1.1: Astronomer’s periodic table. Area of the each element is proportional to its cosmic abundance.

The theoretical investigations mentioned so far produced mixed results. In some cases, they are remarkably successful in explaining many observed features of the interstellar chemistry. First and the foremost is the explanation of huge abundance of molecular hydrogen. Then, the abundance of simple species in diffuse and translucent clouds; the presence of $H_3^+$ and related high abundances of protonated species such as HCO$^+$ and N$_2$H$^+$ in dark clouds; the high abundances of unsaturated and metastable molecules in dark clouds such as l- and c-C$_3$H or HNC; the large isotopic fractionation, to name only a few. There are several drawbacks too, this includes the failure to explain the abundance of $O_2$, $H_2O$, CH$_3$OH. One major problem is the uncertainty in the reaction rates which has serious consequences in these models. We will discuss in detail about various aspects of these models and present our results in Chapter 4.
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1.2 Interstellar Matter

1.2.1 General Properties

The interstellar medium, by volume, is the largest object of our galaxy which accounts for \( \sim 10 -15 \% \) of the total mass of our galaxy. Nearly half of the interstellar matter is confined to discrete clouds occupying only \( \sim 1 - 2 \% \) of the interstellar volume and densest region of these clouds are the site of star formation. Early models (e.g., McKee & Ostriker 1977) classified ISM into three phases: the Cold Neutral Medium (CNM), often referred to as clouds; the Warm Ionized Medium or Warm Neutral Medium (WIM, WNM), which is sometimes considered as the boundary layers of CNM; and the Hot Ionized Medium (HIM), which is often referred to as the intercloud medium or coronal gas, where warm refers to a temperature around \( 10^4 \) K and hot refers to a temperature around \( 10^6 \) K. The CNM is comprised of variety of interstellar clouds of different physical and chemical environment.

The main chemical composition of the interstellar medium is: the hydrogen which is about 90.8 \% by number (70.4 \% by mass) and the helium which is about...
9.1% by number (28.1% by mass), and 0.12% (1.5% by mass) of heavier elements (Ferrière, 2001). In the Fig. 1.1, a periodic table from the astronomers point of view is shown. The observations of the interstellar line emission of hot stars show that a good portion of these heavier elements are missing or 'depleted' from the gas phase and are most likely locked up with the dust grains. The depletion factors vary from cloud to cloud due to change in the physical conditions, especially with the density and the ionization potential. Higher is the density, more severe is the depletion and the fact that the depletion is less in warm ionized medium than warm neutral medium confirms its dependence on ionization potential. On the average, the common elements like C, N, and O, are only depleted by a factor of \( \sim 1.2 - 3 \), whereas refractory elements like Mg, Si, and Fe are depleted by a factor of 10 - 100. Altogether, about 0.5 - 1% of matter by mass is found in grains rather than in gas.

Although the average density of ISM is about one hydrogen atom per cubic cm, the density distribution is far from uniform. The density varies from \( \sim 0.01 \text{ cm}^{-3} \) in the hot medium to \( \sim 10^4 - 10^7 \text{ cm}^{-3} \) in the dense molecular clouds. Similarly, temperature can also vary from 10 K in dense clouds to \( \sim 10^6 \text{ K} \) in hot ionized gas.

In the next subsections, we will discuss various molecular clouds and other significant components of an interstellar medium.

1.2.2 Interstellar Clouds

The interstellar clouds are the local concentrations of matter in ISM separated by the low density intercloud medium. These clouds constitute an extremely important component of ISM because these are the sites for star formation and contain the bulk of the total mass of ISM.

We already mentioned that the interstellar clouds differ significantly in their physical and chemical structure. Depending on various physical quantities like visual extinction, number density of hydrogen, the clouds can be divided into four major classes (Table 1.1): i) Diffuse atomic cloud and ii) Diffuse molecular cloud – these are the most tenuous clouds which are completely exposed to the star light. iii) Dense clouds – these are the densest regions of interstellar medium, and finally, iv) the translucent clouds are of intermediate density (Snow & McCall, 2006).
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Table 1.1: Classification of interstellar cloud types

<table>
<thead>
<tr>
<th></th>
<th>Diffuse Atomic</th>
<th>Diffuse Molecular</th>
<th>Translucent</th>
<th>Dense Molecular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Defining characteristics</td>
<td>$f_{H_2} &lt; 0.1$</td>
<td>$f_{H_2} &gt; 0.1$, $f_{C+} &gt; 0.5$</td>
<td>$f_{C+} &lt; 0.5$, $f_{CO} &lt; 0.9$</td>
<td>$f_{CO} &gt; 0.9$</td>
</tr>
<tr>
<td>$A_V$</td>
<td>0</td>
<td>$\sim 0.2$</td>
<td>$\sim 1 - 2$</td>
<td>$\sim 5 - 10$</td>
</tr>
<tr>
<td>Typ. $n_H$</td>
<td>10 - 100</td>
<td>100 - 500</td>
<td>500 - 5000</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Typ. T(K)</td>
<td>30 - 100</td>
<td>30 - 100</td>
<td>15 - 50</td>
<td>10 - 50</td>
</tr>
<tr>
<td>Operational</td>
<td>UV/ Vis</td>
<td>UV/ Vis, IR</td>
<td>Vis (UV ?) IR</td>
<td>IR</td>
</tr>
</tbody>
</table>

Diffuse Atomic Clouds

The diffuse atomic clouds are the region of ISM which are completely exposed to the Interstellar Radiation Field (ISRF). The visual extinction is less than 0.1, typical temperature is in between 30 K and 100 K and density is around $10^{-1} - 10^2$ cm$^{-3}$. The fraction of hydrogen in its molecular form ($f_{H_2}$) is less than 0.1. These regions are sufficiently optically thin and can be observed by means of visible and ultraviolet (UV) absorption lines. Hydrogen is mostly in neutral form, and atoms with lesser ionization potential than hydrogen are in ionized form. Scarcity of molecular species implies that very little chemical processes occur in these clouds (Snow & McCall, 2006).

Diffuse Molecular Clouds

This is the region of the diffused cloud where molecules begin to form due to some attenuation of the interstellar radiation field provided by the diffuse atomic gas that surrounds these regions. Typical visual extinction is less than that of 1. Molecular hydrogen begins to form in substantial amount ($f_{H_2} > 0.1$). Although few molecules e.g., CO, CH, CN, C$_2$, C$_3$, H$_3^+$, HCO$^+$, OH, C$_2$H etc. are observed in this region for $A_V > 0.3$, the ISRF is still sufficiently strong to keep most of the carbon in C$^+$ form ($f_{C^+}$, the fraction of carbon in the form of C$^+$) through photo-ionization (atomic carbon) and photo-dissociation (CO). This also implies that the chemical reactions have only just started. These clouds have temperatures typically between 30 K and 100 K (since ISRF causes the heating of gas, the temperature of these clouds decrease with increasing column density) and densities between $10^2$ cm$^{-3}$.
Figure 1.3: The well known Horsehead nebulae is a dark cloud which is a site for active star formation.

and 500 cm$^{-3}$.

Diffuse molecular clouds can be observed for a wide variety of visual extinction, or total column density. In the Fig. 1.2, one such diffuse cloud is shown. The lower limit of hydrogen column density for which it can shield itself from the interstellar radiation field is a few times $10^{20}$ cm$^{-2}$, or $A_V \sim 0.2$.

**Translucent Clouds**

These are the regions of ISM where ISRF is so attenuated that conversion of ionized carbon to neutral carbon or carbon monoxide is possible at a substantial rate. These types of clouds are introduced (van Dishoeck & Black, 1989) to emphasize on this change. These clouds, in steady states, must be surrounded by diffuse molecular clouds and therefore, the visual extinction for these clouds should be more than unity. The translucent cloud regime is the least understood of all the clouds due to the lack of the observational data. The existing theoretical models also do not always agree. Recently, a working definition for these clouds has been proposed as the gas which has $f^a_{C^+} < 0.5$ and $f^a_{CO} < 0.9$ (where, $f^a_{C^+}$ and $f^a_{CO}$ are the fractions of carbon in ionized form and in the form of carbon monoxide respectively). Thus, the ionized carbon is no longer the dominant form of carbon. The presence of the molecular hydrogen and the absence of $C^+$ make the chemistry different from that...
Dense Molecular Clouds

These are the clouds with significant visual extinction of 2 to 10 magnitudes or more. The gas in these clouds is mostly molecular. A rich chemistry is one of the main characteristics of these regions and most of the recently known interstellar molecules are discovered in these regions through observations of microwave rotational transitions. Hydrogen is mainly in the molecular form and carbon is in the form of CO. These clouds are mainly self-gravitating and the temperature can be as low as 10 K. The typical density is in between $10^4$ cm$^{-3}$ and $10^7$ cm$^{-3}$. These regions are very well studied both from the observational and the theoretical point of view. The Fig. 1.3 shows, the Horsehead nebula a well known dark cloud.

1.3 Components of the Interstellar Medium

1.3.1 Neutral Atomic Gas

This component contains most of the mass of the interstellar medium. This medium is best studied through the well known 21-cm line of the atomic hydrogen. In brief, this line arises due to the interaction between magnetic moment of the electron and
that of the proton which cause a splitting of the electronic ground level into two very closely spaced energy levels, in which electron spin is either parallel or anti-parallel to the proton spin. The transition between these two energy levels gives rise to the well known 21-cm line. The existence of this line was predicted by Hendrik van de Hulst and observed by Ewen and Purcell in 1951. The major advantage of this 21-cm photon is that it can penetrate deep into the ISM, thereby offering a unique opportunity to probe the interstellar HI gas in the milky way. On the other hand, this transition is so rare that very long paths are needed for the detection of 21-cm line. This neutral gas can also be observed in optical and UV absorption lines of various elements present towards the bright background star. A neutral hydrogen map of our galaxy is shown in the Fig. 1.4.

The medium containing neutral atomic gas is mainly found in two phases: a cold dense phase (diffuse HI clouds), temperature $\sim 100$ K, and in the warm intercloud gas (warm neutral medium, WNM) with a temperature $\sim 8000K$. Typical HI cloud has a density $\sim 20-50$ cm$^{-3}$ and size about 10 pc. The density of WNM is much less $\sim 0.5$ cm$^{-3}$. The fact that this density ratio is approximately the inverse of the temperature ratio supports the view that the cold and the warm atomic phases of the interstellar medium are in rough pressure equilibrium. The observed atomic clouds have random motion characterized by a one-dimensional velocity dispersion $\sim 6.9$ km s$^{-1}$, and a sizable fraction of them appears to be parts of expanding shells and supershells.

1.3.2 Warm Ionized Gas

This type of gas resides near the most massive and the hottest O and B stars and is the most spectacular object in the ISM (Fig. 1.5). It emits a strong UV radiation, with energies exceeding 13.6 eV, the ionization energy of hydrogen. The stars are surrounded by so called ‘HII’ region within which hydrogen is almost fully ionized. Inside a HII region, ions and free electrons keep recombining and this region grows until the rate of recombination within it becomes strong enough to balance the rate of photo-ionization. In a uniform medium, the balance occurs at the so-called Strömgren radius.

The equilibrium temperature, set by a balance between the photo-electric heating
and the radiative cooling, has a typical value of 8000 K, depending on the density and the metallicity (Ferrière, 2001). It has a density of 0.1 cm$^{-3}$. Early observations have used mainly the H$\alpha$ line as the probe of these regions. But due to the obscuration effect of the interstellar dust, H$\alpha$ and other optical and UV probes are limited to a cylindrical volume of radius $\sim 2-3$ kpc around the sun. Therefore, these regions are best studied through the dispersion of pulsar (rapidly spinning, magnetized neutron star) signals, since this dispersion is directly proportional to the column density of the free electrons between the pulsar and the observer. The chemical compositions of these regions are close to that of the cosmic value.

1.3.3 Hot Ionized Gas

The existence of these clouds made up of hot rarefied gas has long been suggested and it provides the necessary pressure balance to confine the observed high altitude galactic clouds (Spitzer, 1956). Two decades later, the presence of such a medium was felt through the detection of UV absorption lines (Jenkins & Meloy, 1974; York, 1974) of high stage ions that are formed only at elevated temperature and through
the observation of soft X-ray background radiation (Williamson et al. 1974). This has a typical temperature of around $10^5 - 10^6$ K and a typical density of around $10^{-3}$ cm$^{-3}$.

This gas can be traced through UV absorption lines emitted from highly ionized species (e.g., CIV, SVI, NV, OVI) seen against the background stars. It also emits continuum and line radiation in the extreme ultraviolet and X-ray wavelengths and fills most of the volume of the halo. This medium is mainly generated by supernovae explosions and, to a lesser extent by the stellar winds of early type stars.

1.3.4 Interstellar Grains

Interstellar dust grains, with sizes ranging from nanometers to micrometers, irregularly shaped, composed of carbon and/or silicates, are intimately mixed with the interstellar gas. They are formed in the atmospheres of evolved stars as well as in novae and supernovae. They are only 1% of the mass of the interstellar medium. In spite of that, they play a vital role in the physics and chemistry of this medium, in the energy balance of the galaxy, in the star and the planet formation and in many other activities.

Dusts manifest their presence in two major ways on light passing through it: the light is dimmed due to absorption of star light (Fig. 1.6), this is called the interstellar extinction, and through reddening of star light due to scattering which is known as
the interstellar reddening. They also feel their presence through the polarization of starlight, giving rise to reflection nebula through scattering. Finally, the ISM is bright in infrared due to the continuum emission by cold dust grains.

Interstellar grains also take part in the chemical evolution of the interstellar matter. There are two ways in which interstellar grains control the chemistry. In one, it provides the surface for chemical reactions, say, for example the huge abundance of molecular hydrogen cannot be explained without grain surface reactions. This will be discussed extensively in the Chapters 3 and 4. In other, the grains control the gas phase chemistry through freeze out and desorption processes. In the cold clouds, the gas phase species sticks very efficiently onto the grains forming ice mantles. In the absence of suitable desorption mechanism this mantle grows until on the later stage of star formation when the grains are warmed to the temperature where the molecules can desorb again. These desorbed molecules then takes part in the chemical evolution and a rich chemistry is observed it this stage of star formation. The ground-based and ISO studies discovered a nearly complete inventory of these ice mantles for deeply embedded massive young stars such as NGC 7538 IRS9, W33 A and RAFGL 7009S (Whittet et al. 1996, d'Hendecourt et al. 1996, Ehrenfreund et al. 1997)(Fig. 1.7). Abundance down to ~ 0.5 of H$_2$O-ice (10$^{-7}$ with respect to H$_2$) can be probed. The observed grain mantle composition are very simple mainly consisting of hydrogenated species like H$_2$O, CH$_3$OH etc. and some oxidized species like CO, CO$_2$ etc.

1.3.5 Interstellar Molecules

The interstellar medium contains a large number of complex molecules (Table 1.2). Many of these molecules are organic, i.e., they include hydrogen, carbon and nitrogen. These molecules range in complexity from H$_2$ to a 13-atom linear nitrile, HC$_{11}$N and many of these molecules are quite unusual to find in ISM by terrestrial standards. H$_2$ is the most abundant molecule by far, with CO in the second position, four order of magnitude lower. More complex molecules are even less abundant – at least 4 to 10 orders of magnitude lower than H$_2$. These molecules are very important because they can be the pre-cursors of more complex bio-molecules including simple amino acids, such as glycine. If amino acids and other pre-biotic
Table 1.2: Molecules below are found in interstellar clouds of various sorts.

<table>
<thead>
<tr>
<th>8 atoms</th>
<th>9 atoms</th>
<th>10 atoms</th>
<th>11 atoms</th>
<th>12 atoms</th>
<th>13 atoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH₃C₃N</td>
<td>CH₃C₄H</td>
<td>CH₃C₅N?</td>
<td>HCN</td>
<td>CH₃OC₂H₅</td>
<td>HC₃N</td>
</tr>
<tr>
<td>HCOOCH₃</td>
<td>CH₃CH₂CN</td>
<td>(CH₃)₂CO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₃COOH?</td>
<td>(CH₃)₂O</td>
<td>NH₂CH₂COOH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C₇H</td>
<td>CH₃CH₂OH</td>
<td>CH₃CH₂CHO</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H₂C₆</td>
<td>HC₇N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₃OHCHO</td>
<td>C₅H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CH₂CHCHO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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molecules are formed in the evolution of molecular cloud and accreted in the form of dust, meteorites and comets, they may have provided essential ingredients for pre-biotic synthesis on earth. Most interestingly, the possible molecular precursors of glycine such as, CH$_4$, H$_2$O, NH$_3$, HCOOH, CH$_3$COOH are all discovered in the various regions of ISM. However, the simplest amino acid, namely, glycine itself eluded confirmed detection. So far, numerous searches for interstellar glycine have been conducted but the intrinsic weakness of the glycine lines coupled with the contamination of the spectrum by other molecules make it very difficult for such confirmation (Kuan et al. 2003; Hollis et al. 2003). Fig. 1.8 shows the spectral line survey of various molecules which is done by Owens Valley Radio Observatory (OVRO).

Besides these, there are polycyclic aromatic carbons (PAHs), containing some 50 C atoms. These molecules are abundant, $\sim 10^{-7}$ relative to H, locking up about 10% of the elemental carbon. These molecules show broad emission mid-infrared features in the spectrum of most IR objects.
Figure 1.8: Owens Valley Radio Observatory (OVRO) spectral line survey of various molecules.
1.3.6 Supernova Remnants

Supernova remnants (SNR) are formed when the material ejected due to violent explosions which terminates the life of stars (Fig. 1.9). This explosion which is called the supernova explosion, is one of the most energetic events in the universe. SNR’s are bounded by an expanding shock waves and consist of ejected material which is rapidly expanding and slowly fading out. These are very important for distributing various elements through the interstellar medium. Eventually, these remnants cool down and collapse to form interstellar clouds from which new stars can be formed. Observationally, they are best detected at X-ray wavelengths because of the emission by hot the \(10^6\) K gas and at radio wavelengths due to the synchrotron emission.

1.3.7 Planetary Nebulae

A planetary nebula (Fig. 1.10) forms when a star can no longer support itself by fusion reactions in its center. The gravity from the material in the outer part of the star forces the inner parts to condense and heat up. The high temperature of the central region drives the outer half of the star to blow away in the form of the
stellar wind, which may last for several thousand of years. When the process is complete, the remaining core remnant is uncovered and heats up the now distant gases and causes them to glow. Planetary nebulae play a similar role like supernova explosions. They play a crucial role in the chemical evolution of the galaxy by returning the stellar material to the interstellar medium which has been enriched in heavy elements and other products of nucleosynthesis. In other galaxies, planetary nebulae may be the only objects observable enough to yield useful information about chemical abundances.

1.4 Energy Sources of Interstellar Medium

Interstellar medium has multiple energy sources: stellar radiation, high energy particles, and mechanical energy from supernovae, stellar winds and differential rotation of galaxy.
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1.4.1 Radiation Fields

There are two sources of radiation in the ISM which include: the galactic radiation field coming directly from the stars, photons produced from the secondary processes in the interstellar medium itself, and the extragalactic radiations emitted by other galaxies and by the universe as a whole.

The stellar radiation field contains the radiation from the late type stars predominantly in the far-ultraviolet (FUV) wavelengths, A-type stars which controls the visible region, and late type stars, which mainly contribute at far-red to near-infrared wavelengths. The strength of the FUV average interstellar radiation is often expressed in terms of Habing field, \(1.2 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}\). Interstellar grains absorb the stellar radiation and produce discrete emission bands in the mid-IR and in the continuum emission in the far-IR and sub-millimeter regions (Tielens, 2005).

The Cosmic Microwave Background (CMB) radiation of the universe corresponds to a temperature, \(\sim 2.726K\) and emits in the sub-millimeter and millimeter wavelengths. This can play a role in the population of the rotational levels of interstellar molecules because many of them have transitions in this wavelength range. The radiation originating from the other galaxies and in the intergalactic medium is considerably fainter and can be neglected in the galactic plane (Lequex, 2005).

1.4.2 Interstellar Magnetic Field

The magnetic field is an important energy and pressure source of ISM, which takes part in the overall hydrostatic balance and the stability of ISM. The presence of a magnetic field in our galaxy was first realized through the discovery of linear polarization of star light (Hall, 1949; Hiltner, 1949a, 1949b). The polarization arises due to partial alignment of dust grains with the interstellar magnetic field. They also produce far-infrared continuum emission of aligned dust grains, linear polarization of synchrotron radiation, Faraday rotation of background, polarized, radio sources, and Zeeman splitting of the 21-cm line of neutral hydrogen and lines of molecules with unpaired electrons such as OH.

The interstellar magnetic field has a typical strength of \(\sim 5\mu G\) in regions with the gas density between 0.1 - 100 cm\(^{-3}\). They might get to \(\sim 10 - 20\mu G\) in the
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higher density \( n = 10^2 - 10^4 \text{ cm}^{-3} \) (Troland & Heilis, 1986) region. Pulser rotation measurements within 3 kpc of sun reveals that the local interstellar magnetic field has two components: one uniform (or regular) component \( \sim 1.6 \mu \text{G} \) and a random (or irregular) component \( \sim 5 \mu \text{G} \) (Rand & Kulkarni, 1989).

The interstellar magnetic field plays a crucial role in supporting molecular clouds against their self-gravity and in the eventual gravitational collapse of the protostellar core. It also affects all kinds of turbulent motions in the ISM. The magnetic field also modifies the random motion of interstellar cloud through its magnetic tension force.

1.4.3 Cosmic Rays

The cosmic rays are high energy (> 100 MeV) charged particles, originating in outer space and traveling at nearly the speed of light. Cosmic rays include essentially all of the elements in the periodic table; about 89% of the nuclei are protons with energies between 1 and 100 GeV, 10% helium, and about 1% heavier elements with the same relative abundances as in the solar system. But there are important differences in elemental and isotopic composition that provide information on the origin and history of galactic cosmic rays. For example, there is a significant overabundance of the rare elements Li, Be, and B produced when heavier cosmic rays such as carbon, nitrogen, and oxygen fragment into lighter nuclei during collisions with the interstellar gas. The isotope \(^{22}\text{Ne}\) is also overabundant, showing that the nucleosynthesis of cosmic rays and of the solar system material have differed.

The interaction of cosmic rays with interstellar matter and photons gives rise to \( \gamma \) ray radiations through various mechanisms, such as, \( \pi^0 \) meson decay, Coulomb acceleration of cosmic ray electrons leads to \( \gamma \)-ray bremsstrahlung emission and inverse compton scattering. It is believed that the cosmic rays derive its energy from the supernova explosions with an efficiency of 10% of the kinetic energy of the ejecta. The pressure due to the cosmic rays provides a support against the gravity for the gas in ISM. Low energy \( \sim 100 \text{ MeV} \) cosmic rays are very important for the heating and ionization of interstellar matter. Indirect measurements provide a primary cosmic ray ionization rate in the ISM of \( \sim 2 \times 10^{-6} \text{ (H atom)}^{-1} \text{s}^{-1} \). In regions associated with massive stars, this rate can be significantly higher.
1.5 The Broader Perception

All these apparently different objects fit together in a grand picture whose backbone is the interstellar medium. The low density interstellar matter, perturbed by the supernova shocks or by local turbulence is packed up to form a relatively dense region or the clouds. These clouds are the starting point of chemical evolution. As we go from the diffuse atomic gas to dense molecular cloud the chemistry gets richer. The chemistry in the diffuse clouds is mainly dominated by the low temperature gas-phase reactions leading to the enhanced formation of small radicals and unsaturated molecules. In case the initial gas composition is carbon rich, long carbon chains can be formed.

These relatively denser clouds due to the self-gravity start collapsing. During this period many gaseous species accrete onto the grains. A rich chemistry occurs in the grains. The chemistry in grains is mainly dominated by the hydrogenation reaction and the saturated species like NH$_3$, H$_2$O, CH$_3$OH (methanol) are formed. These ices are also processed by the ultraviolet photons, X-ray and cosmic rays i.e., energetic particles of the ISM. As these cloud cores approach towards their starhood, they begin to warm up and form disks around them which are called protoplanetary disks. Once the new star starts to warm the surrounding envelope, the ices are heated and molecules are desorbed back into the gas phase, probably according to their desorption temperatures. These freshly evaporated molecules drive a rich chemistry in the 'hot cores'. Hot cores are small (0.3 $\approx$ light years), dense ( $\approx 10^4 - 10^7$ cm$^{-3}$), and warm ( $\approx 100 – 200$ K ) clumps of material. Here, the chemical processes are different from those in the cold regions. In particular, small saturated molecules such as NH$_3$, H$_2$O, CH$_3$OH (methanol) are far more abundant in hot cores than the other regions. In addition, the larger molecules like methyl formate (HCOOCH$_3$), dimethyl ether (CH$_3$OCH$_3$), ethanol (C$_2$H$_5$OH), ethyl cyanide (C$_2$H$_5$CN) and even simplest amino acid named glycine (although evidence of glycine might not be conclusive as yet) are only found in these regions. Finally, the envelope is dispersed by winds and/or ultraviolet photons, leading to the appearance of photon dominated regions. Parts of the gas phase matter and the ice mantle are incorporated into the circumstellar disk and survive a longer period of time before being dispersed or assembled into the new planetary bodies. The planets are believed to be formed by
accumulating matter from the protoplanetary discs. Now the journey of stars and its planetary bodies (if any) begin. Depending upon the various physical parameters these stars have certain lifetime. At the end of their lifetime they explode and throw the matter back into the interstellar medium with increased abundance of heavier atoms. The story begins, rather, repeats once more.