**Gas and dust in the interstellar medium**

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Abstract. In this article I shall describe the gas and dust in the interstellar medium. I review the evidence for dust and describe its likely nature. Its many roles in the interstellar medium, especially its effect on interstellar chemistry in star-forming regions, are discussed. The nature of the molecular interstellar gas is described, and a brief account of the interstellar chemistry that produces these molecules is given. Several examples of the interaction between gas and dust in star forming regions are given to demonstrate the importance of these components of the Milky Way and other galaxies.

1. Introduction

The aim of this article is to describe the content of the cooler parts of the interstellar medium. Here the gas is mainly molecular and is always accompanied by dust grains. We discuss the evidence for the existence of interstellar dust, its probable nature, and the many roles that it fulfils in the interstellar medium. The wide chemical variety of the cooler interstellar gas is described and the chemical network that produces these molecules is outlined. The interaction between the gas and the dust is important, and in some circumstances may dominate the purely gas-phase reactions between atoms and molecules; this is particularly the case in the densest parts of the interstellar gas which are most likely to give rise to the formation of stars.

2. Cosmic dust

We begin with a discussion of the qualitative and quantitative evidence for cosmic dust, and of its roles in the interstellar medium and star forming regions in particular. General references for this section are [1], [2], [3] and [4].

The qualitative evidence for interstellar dust

Naked-eye observation of the night skies does not immediately suggest to us that interstellar space is full of dust and gas. True, the Pleiades constellation of bright stars has a haziness around it that we now interpret as starlight scattered by dust grains close to the stars. Further, the existence of planet Earth itself, now assumed to be the accumulation of uncounted numbers of cosmic dust grains, and the stream of interplanetary particles (about 100 tonnes per day) and occasional asteroids arriving at the Earth’s surface remind us that space contains a variety of solids of various shapes, sizes and compositions.

Nevertheless, evidence for the existence of cosmic dust is very clear. For example, William Herschel, who was among the first astronomers to study and catalogue the variety of objects outside the solar system, noted that some small regions of space seemed to have a complete absence of stars. He called these “holes in the sky”, and speculated that their cause was an obscuration of the background star field by foreground matter. It was some time before this idea could be confirmed and that these
“holes” were in fact caused by intervening clouds of dust and gas with number densities many times greater than the mean interstellar densities; the clouds completely extinguished the light of stars behind them.

Light scattered by dust, as seen by naked-eye in the Pleiades and by telescopes near many bright stars is also evidence of dust. But is the dust merely confined to regions of space near to stars and to “holes in the sky” or is it widespread? A general extinction of starlight throughout the Milky Way Galaxy (and in other galaxies too) shows that the dust is ubiquitous. A comparison of the expected intensity of starlight from a star at a known distance with that actually detected shows that the detected emission is always less than expected. The difference is attributed to interstellar extinction by dust, i.e. to the combined effects of absorption and scattering. Interstellar extinction measured in this way is found to be small in the infrared, to rise almost linearly in the visible regions of the spectrum, to have a peak in the near ultraviolet at a wavelength around 220 nm, then to rise strongly in the far UV, at least down to wavelengths as short as 100 nm. The precise shape varies along different lines of sight, though the general character is the same; the departures from the averaged interstellar extinction can be large.

We can use the averaged interstellar extinction curve, i.e. the wavelength dependence of the extinction, to infer possible physical and chemical properties of the dust grains in the low density interstellar medium through which these observations are made. Such considerations on their own do not give a unique description, but in general we find that the dust should be predominantly dielectric, and – from other considerations – both silicates and carbons are likely materials. The near-linear rise in the visible part of the spectrum implies the existence of some dust grains that are of a size comparable with the wavelength of visible light, i.e. about 500 nm, and the strong rise in the far UV shows that many small grains must also be present. Thus, a range of dust grain sizes is implied. The broad peak at a wavelength of 220 nm is usually attributed to small graphite particles, or to other carbonaceous materials.

Interstellar linear polarization is also detected in the starlight, and is interpreted as differential extinction through a medium in which asymmetric dust grains are partially aligned. Thus, one plane of polarization is more heavily extinguished than another (the difference typically being a few percent) Therefore, the detection of linear polarization is also evidence of the presence of dust grains, and that they must be in general asymmetric. Oblate spheroids with an axial ratio of 2:1 are sometimes adopted in model calculations. The alignment is generally attributed to the interstellar magnetic field acting on magnetic inclusions in the dust grain to suppress one component of the angular momentum of the rotating grain by dissipating energy through the magnetic susceptibility. The grains are not thought to be aligned like compass needles.

More specific information as to the nature of cosmic dust can be obtained from a consideration of elemental depletions. If we can measure spectroscopically the relative gas-phase abundances along a particular line of sight through the interstellar medium, then elemental under-abundances relative to a cosmic standard (such as the Sun) may be assumed to be present in the dust rather than in the gas. For example, along the line of sight towards the bright star zeta Ophiuchi the relative abundance of Fe atoms is less than 1 percent of that found in the Sun, while that of Ti atoms is less than 0.1 percent. This implies (on the basis of our assumption) that more than 99 percent of Fe atoms and about 99.9 percent of all Ti atoms are in dust grains. If we make similar considerations for all atoms likely to be in dust grains we can determine an overall chemical composition for the dust. Of course, this doesn’t correspond to a single compound as the dust is certainly a mixture of at least several different kinds of grains. Nevertheless, the evidence from considerations of depletion is at least consistent with the general conclusions from the study of interstellar extinction: the dust in low density regions of interstellar space is mainly various types of silicates and carbons.
**Infrared observations of interstellar dust**

Advances in astronomical technology over the last few decades have enabled detections to be made of *infrared emissions and absorptions* by dust. In general, all ultraviolet and visual starlight absorbed by dust grains is converted into heat and re-radiated (mainly as a continuum) in the infrared. Thus, dust grains maintained at a temperature of, say, 30 K by the absorption of starlight will radiate in the sub-millimetre wavelength range. Maps of the Milky Way galaxy in the sub-millimetre therefore reveal the active regions of star formation that are heavily obscured in the visual range by extinction due to dust. Dust grains that are sufficiently hot (perhaps because they are unusually close to bright stars) may also radiate in specific bands in the infrared associated with molecular bonds. For example, very small carbonaceous grains can be heated by a single UV photon to radiate in a set of IR bands at 3.3, 6.2, 7.7, 8.6, 11.3, and 12.7 microns associated with various kinds of C-H and C-C stretch modes in polycyclic aromatic hydrocarbons (PAHs). (Because no specific identification of the carrier of these bands has been made, these features are called the *unidentified infrared bands*, or UIBs). Silicate grains heated by the radiation of a nearby star may radiate in characteristic broad Si-O stretch bands near 10 and 20 microns. Temperatures about ~ 10^3 K are required to cause grains to emit in these near-IR bands.

Dust grains in cold clouds, distant from heating sources such as hot stars, are very cold, ~ 10 K, and cannot radiate in these near-IR bands. However, if there is a background source of continuum infrared radiation (such as a hot star embedded in a dust cloud, so that all starlight is re-emitted in the infrared), then the foreground dust grains may absorb continuum radiation at wavelengths corresponding to near-IR bands. Absorption spectra of foreground dust in dense clouds usually shows a strong and broad absorption feature at 3 microns associated with the O-H stretch mode in water ice. Evidently, the dust grains in dense clouds are coated with mantles of water ice. The ice is not pure, but contains CO molecules, detected by their C-O stretch mode at 4.7 microns, CO₂ molecules (4.3 microns), and several other species such as methanol, formic acid and methane. The precise chemical composition changes from one line of sight to another, evidently reflecting the local conditions. The chemical complexity of dust in dense clouds is clearly greater than in low density regions.

**Cosmic dust studied in the laboratory**

These “remote” detections of cosmic dust can now be supplemented by laboratory investigations of interplanetary dust and meteorites. These materials originated as interstellar dust, but were physically and chemically processed to some extent in the proto-solar nebula, during and since the formation of the Sun. Within the interplanetary dust are found the so-called “GEMS”, particles that are *Glasses with Embedded Metals and Sulfides*. These particles have the correct physical and chemical characteristics to account for many of the observed features of interstellar dust. Their sizes are such that they give rise to the near-linear rise of extinction in the visual region; they are silicates with absorptions near 10 and 20 microns; they have small magnetic inclusions and could be partially aligned by the interstellar magnetic field; and they are embedded in a layer of amorphous carbon presumably originating in the carbonaceous dust thought to be present in the interstellar medium. It seems likely, therefore, that these GEMS are un-processed interstellar dust, contained within the interplanetary matter. Meteorites, too, appear to contain un-processed interstellar dust. Primitive meteorites are found to contain particles of diamond, graphite, silicon carbide, and aluminium oxide. In all cases, the isotopic ratios in these materials indicate that the materials were formed in circum-stellar environments, suggesting that the dust grains were formed there, subsequently ejected into the interstellar medium, and incorporated into the interstellar cloud from which the Sun eventually formed. Although the interstellar medium is remote from the Earth and we have no possibility of exploring it directly, nevertheless the natural processes in the Galaxy conveniently deliver interstellar samples to our planet.
What is cosmic dust?

It is now possible to assign tentatively the various observed features of cosmic dust to particular components. The model that we adopt is that the dust grains are formed in the atmospheres of cool stars, ejected into the interstellar medium where they are subjected to physical and chemical processing and are ultimately destroyed by shattering and erosion in shocks. The main materials are assumed to be silicates and carbons.

The features of the interstellar extinction curve may be assigned as follows. The strong rise of extinction in the far-UV may be caused by scattering of radiation by nanometre-scale carbon particles. These particles may be the shattering fragments from colliding larger grains, or an extension of the PAH population. It seems unlikely that very small silicate dust grains contribute significantly, otherwise these grains would in emit in the 10 and 20 microns bands. This is not detected in the general interstellar medium. The broad peak in the extinction at a wavelength of 220 nm may be attributed to stacked PAHs, while the visual rise is due to silicate grains of the type found as GEMS in interplanetary particles. The low extinction in the infrared is attributed to band gap absorption in carbonaceous grains (sp$^2$ bonding, graphitic carbon).

The unidentified infrared emission bands between 3.3 and 12.7 microns are clearly related to spectroscopic features in carbonaceous material, though no precise identification has yet been made. Perhaps none should be expected: it may be unlikely that large carbonaceous species, formed through grain-grain shattering, will have the well-defined structures associated with laboratory molecular samples.

Infrared absorptions arise both in the silicate and carbonaceous dust, the former material absorbing strongly at 10 and 20 microns, while amorphous carbon (sp$^3$ bonding, aliphatic carbon) absorbs weakly at 3.4 microns. In denser regions, molecular ices absorb at wavelengths corresponding to stretch modes of molecules within the ice. The rotational structure associated with free-flying molecules is of course suppressed for molecules within the ice.

Open questions concerning dust

While our understanding of the nature of cosmic dust and its role in interstellar space has improved, there are several areas in which our knowledge is poor. What is the physical form of the dust? As we have seen, the possible chemical structures can be determined (silicates, carbons, etc.) the structure is not well-determined. Are dust grains monoliths, i.e. pure and uniform solids, or are they porous, open structures? It’s unclear which of these models is correct, and yet this question has a bearing on surface chemistry, the formation of ices, and on the survivability of dust grains in shocks. One possible measure of the surface to bulk ratio is the strength of absorption by OH dangling bonds that should exist at the surface of silicates both externally and – if porous – internally. This feature has not yet been detected. Are grains composites of various materials, or are the populations of silicates and carbons distinct? If grains are mixed composites, their optical properties will be significantly affected. The derived size distributions of the dust grain populations are merely mathematical fits to the extinction curve; while it is true that we need a range of sizes, it is clear the fit obtained is not unique. What are the physical processes determining the grain size distribution? How do those processes, and the consequent size distributions, change from one region of space to another? In the interstellar medium, dust grains are subject for very long periods to fluxes of energetic particles (the cosmic rays) and hard radiation (UV, X rays, and gamma rays). There must also be chemical processing of (at least) the surface layers. How do the optical and chemical properties of dust grains evolve in the interstellar medium? Can we detect this evolution? Part of the answer may lie in the wide variety of interstellar...
extinction curves detected along different lines of sight; do these reflect the local conditions? More work should be done in this area.

Other detected interstellar features may also be associated with cosmic dust. The diffuse interstellar bands are a set of several hundred unidentified absorption lines at wavelengths from 443 nm into the near-IR. They are seen along lines of sight in the low density interstellar medium in the spectra of bright stars. The strength of these bands correlates quite well with the strength of interstellar extinction along the same line of sight, and some of the bands are rather broad. It has therefore been suggested that the bands may arise as solid-state absorption features in cosmic dust; if so, they must be providing detailed information about the nature and properties of the dust. However, the suggestion has not been supported by further study. Strong solid-state absorption bands are expected to show emission wings, but these have not been detected in the interstellar medium. Current thinking is that the bands are optical transitions in large molecules, and that their breadth is determined by unresolved rotational structure. The molecules are required to be of such a size that they represent the nanometre scale end of the grain size distribution. They may be true molecules, with well-defined structure, or they may be fragments produced by dust grain shattering. The fact that no laboratory identification has yet been made of any of the large number of observed diffuse bands may simply be suggesting that the carriers have no well-defined structure.

The extended red emission is effectively an observed reduction in interstellar extinction as compared to the “averaged interstellar extinction”. It consists of a very broad and shallow emission feature, in wavelength several hundred nanometres wide and extending from around 500 nm to 700 nm. Since one is comparing observations with a notional average, the precise meaning of these observations is not clear. However, assuming that the feature is real then it seems likely that it, too, is associated with the solid state. Current thinking is that such a feature may arise in nano-particles, i.e. the very small end of the dust grain size distribution. Nano-particles of silicon have been shown to have optical structures of this kind.

The roles of dust grains in the interstellar medium

Dust grains are no longer considered merely as a feature inhibiting the study of stars and galaxies; dust is now recognised as playing a fundamental role in the evolution and current state of the Universe. The most obvious effect of dust grains is that they cause extinction of starlight. This means that regions of space are shielded from starlight and – as we shall describe below – a rich chemistry becomes possible because the photodissociation of molecules can be heavily suppressed. The molecules formed are important coolants, affecting the dynamical and thermal evolution of the gas in star formation. Dust grains, too, radiate at long wavelengths the UV and optical radiation they have absorbed, and contribute thereby to the cooling. Therefore, dust affects the star formation process. Dust grains, by their very existence remove from the gas the elements of which they are composed. Therefore, some elements (e.g. Fe, Si, and Ni) are very rare in the gas phase and contribute less to chemistry or to the level of ionisation than would otherwise have been the case. In regions pervaded by starlight, the photoelectric effect generates energetic electrons that form the main heating source; thus dust is the most effective means of coupling the energy in the starlight into the gas.

The surfaces of dust are chemical catalysts. We shall describe below the evidence that interstellar molecular hydrogen is formed efficiently in surface reactions on dust grains, and we shall note that nearly all of interstellar chemistry depends on the presence of molecular hydrogen. In this sense, one might argue that dust grains are an essential component of the present Universe; certainly, star formation in the Universe must have evolved differently before dust grains were abundant. Other species than H₂, too, must form similarly in reactions at the surfaces of dust grains; in low density regions of space these species may be mainly simple hydrides. In denser regions, the dust grains
provide a substrate on which molecular ices can form. These ices also remove molecules other than molecular hydrogen from the gas phase, and evidence for gas depleted of its heavy molecules is common. Such regions, therefore, have rather different and less effective cooling functions. These ices act as reservoirs of molecules that can be released back to the gas phase in warmer regions. Thus, dust grains can act both as sources and sinks of molecules. As we shall see below, more complex molecules can be created in solid state chemistry within the ices.

Dust grains generally carry electrical charges. In low density regions, the photoelectric effect may dominate, in which case the grains are positively charged. When starlight is suppressed by extinction, then dust grains tend to be a sink for electrons, and become negatively charged. In very dark clouds grains may become the main charge carrier, and therefore the main coupling agent between the interstellar magnetic field and the interstellar medium. The large mass of a dust grain compared to the mass of an atomic or molecular ion affects the ambipolar diffusion timescale, and therefore the influence of magnetic fields on the local dynamics.

Finally, dust grains are the raw material for planet formation. From an anthropic point of view, our origins are in interstellar dust. This is as good a reason as any for studying cosmic dust!

3. Interstellar gas

Cosmic dust and the cooler, denser interstellar gas are intimately mixed. The gas clouds in which the cooler (T < ~ 10^2 K) and denser (n_H > 10^2 cm^-3) gas is located occupy only a few percent of the interstellar volume, but account for nearly all of the interstellar mass. Our concern in this article is the relation between the gas and the dust, and therefore we are primarily concerned with the cooler and denser regions of interstellar space. Here, we merely note the existence of several important components of interstellar gas that fill the interstellar volume. The coronal gas occupies much of the volume; it is so-called because it has a very high temperature (~ 10^6 K), comparable to that of the solar corona. It is shock-heated by the hugely energetic winds of supernovae and is detected in X ray lines of highly ionised atoms such as OVI and NV. The proton density of the coronal gas is very low, < ~ 10^-2 cm^-3. Dust grains in such gas are rapidly destroyed by sputtering. Hot stars inside otherwise neutral regions maintain volumes of fully ionised gas around them. These ionised nebulae, or HII regions, have relatively high temperatures, ~ 10^4 K, and the density is that of the neutral region around them, generally > ~ 10^2 cm^-3. These rather beautiful objects occupy only a small volume of space. In general, dust tends to be eroded in such regions. Another component of interstellar gas is the intercloud gas. It is atomic and may be quite warm (~ 10^3 K) and of low density (< 1 H atom cm^-3). It is heated and partially ionised by X rays from hot stars. It does not comprise much of the interstellar mass, and we shall ignore it in subsequent discussions. General references for this section are [4], [5], [6] and [7].

Where are molecules found?

The main regions where gas and dust coexist are almost entirely neutral and cool. They are conveniently categorised as diffuse clouds and molecular clouds, though this is a gross (but useful) simplification. The gas is almost entirely hydrogen, with about 10 percent of helium by number; oxygen, carbon and nitrogen comprise about 0.1 percent by number, and all other elements are present only in trace quantities. In diffuse clouds, the number density of dust grains is low enough that starlight can readily penetrate. Radiation from hot stars can then ionise the minor elements of carbon, sulfur, and trace metals such as iron, silicon, magnesium, calcium, nickel and sodium. Cosmic rays ionise a small fraction, 0.01 percent, of the hydrogen, and much of the rest is molecular. A limited variety of molecules is present in diffuse clouds, (e.g. CO, CH, CN, CH^+, etc.) but most elements are in atomic form.
Molecular clouds are typically denser \( \left( n_{H} > 10^{5} \ \text{cm}^{-3} \right) \) and cooler \( (T \sim 10 \ \text{K}) \), and they contain so much dust that they are opaque to starlight. As their name implies, molecular clouds are almost entirely molecular. An active chemistry is required to maintain the detected relatively high abundances of these molecules. We shall describe that chemistry below. In these molecular clouds, the conditions may be such that molecules can freeze out on the surfaces of dust, and atoms collide and react at those surfaces, so that mantles of molecular ices can accumulate within the lifetime of the cloud.

In fact, molecules are found in a surprisingly wide variety of locations, in addition to molecular clouds. In the solar system, molecules are found in planetary atmospheres, in comets, asteroids, and interplanetary dust. Molecules (\( \text{H}_2 \) and \( \text{H}_2\text{O} \)) are found even on the Sun’s surface, in sunspots where the temperature is somewhat lower \( (\sim 4000\ \text{K}) \) than the mean surface temperature \( (\sim 5800\ \text{K}) \). Planet-forming disks around young stars are particularly dense regions of dust and molecules. Outflows from cool stars and ejecta from novae and supernovae are the main sources of the products of stellar nucleosynthesis, and are the main origin of dust and heavy elements for the interstellar medium. Molecules show a remarkable propensity to form and survive even in conditions that seem hostile. As a crude rule, if the gas number density is sufficiently large that collisions occur frequently enough \( (\text{say, } n_{H} > 1 \ \text{cm}^{-3}) \) and the temperature is sufficiently low that the collisions are not too violent \( (\text{say, } T < \sim 4 \times 10^{3}\ \text{K}) \) then molecules are likely to form in mostly neutral gas. Molecules are found in regions satisfying these conditions throughout the Milky Way Galaxy, and molecules are known to be present in galaxies at high redshift. The current record of detections is of \( \text{CO} \ (3-2), \ (6-5) \) and \( (7-6) \) in a galaxy at a redshift of 6.42, corresponding (on the Standard Big Bang Nucleosynthesis model) to an age of the Universe around 6 percent of its current value.

**Interstellar molecules**

A continually updated list of identified molecular species can be found at [www.cv.nrao.edu/~awootten/allmols.html](http://www.cv.nrao.edu/~awootten/allmols.html)

(Note that the word *molecule* in the astronomical context includes molecular ions and radicals). This list contains more than 120 molecular species, but does not include isotopic substitutions such as \( \text{D} \) for \( \text{H} \), \( ^{13}\text{C} \) for \( ^{12}\text{C} \), nor \( ^{18}\text{O} \) for \( ^{16}\text{O} \). Thus, ammonia has been detected with D replacing one or more H atoms (i.e. \( \text{NH}_3 \) appears in all the forms \( \text{NH}_2\text{D}, \ \text{NHD}_2, \ \text{and ND}_3 \)), and CO has been detected in all six varieties involving \( ^{12}\text{C}, \ ^{13}\text{C}, \ ^{16}\text{O}, \ ^{17}\text{O}, \ \text{and} \ ^{18}\text{O} \). Therefore, the list of actual detections is very much larger than 120 (especially because the most common interstellar molecules are hydrocarbons for which there are many opportunities for isotopic substitutions).

As we shall see when we discuss the interstellar chemistry that gives rise to this great variety of molecular species, the list of detected molecules implies the existence of a great many more species that have not so far been detected. This lack of detection may be because some molecular species are short-lived and consequently have a low abundance (e.g. \( \text{CH}_5^+ \)), or because transitions are difficult to excite at low temperatures (e.g. \( \text{O}_2 \)), or because the emitted wavelengths are in a spectral region difficult to observe. It may be that some molecular spectra have not been studied in the laboratory so that no reliable detection can be made. In terms of the chemistry, the existence of about 120 detected species probably implies the existence of about four or five hundred so far undetected species.

Many of the detected species are simple molecules familiar on Earth, such as carbon monoxide (\( \text{CO} \)), water (\( \text{H}_2\text{O} \)), ammonia (\( \text{NH}_3 \)), methane (\( \text{CH}_4 \)), methanol (\( \text{CH}_3\text{OH} \)), hydrogen cyanide (\( \text{HCN} \)), hydrogen sulfide (\( \text{H}_2\text{S} \)), or sulfur dioxide (\( \text{SO}_2 \)). However, there are some surprises. The existence of different species of molecular ions suggests that ion-molecule reactions are likely to be important in the chemistry, and we shall see that this is indeed the case. The existence of these ions demonstrates that a source of ionisation must be present; otherwise, these ions would rapidly recombine with electrons to form neutral species. This ionisation source is the flux of cosmic rays, energetic protons
and electrons (mainly), that can penetrate all but the very densest regions of interstellar space. There are some chemical surprises, too. The higher members of the carbon chain molecules, HC\textsubscript{n}N, \(n = 1-11\), were identified spectroscopically first in space, and their existence confirmed after synthesis in the laboratory. The appearance of these heavily unsaturated species in a hydrogen-rich environment was unexpected.

There is evidence that even larger molecules exist in the interstellar medium. As described earlier, the diffuse interstellar bands and the unidentified infrared bands both seem to require the existence of structures that are either large molecules or very small dust grains. These structures contain on the order of a hundred atoms. They are, therefore, likely to include hydrocarbons, since these molecules are easily capable of reaching such a size. In fact, it may be more that molecules of this size are not well-defined structures formed in a sequence of synthesis reactions, but are poorly defined degradation products of shattering that occurs in grain-grain collisions in interstellar shocks.

**Interstellar chemistry**

We describe here the chemistry occurring in molecular clouds from which starlight is effectively excluded by extinction caused by dust. These relatively dense and cool regions are almost entirely molecular. What are the processes that maintain the gas in this molecular state? The tendency of the cosmic ray flux is to reduce molecules to atoms, either directly by collisional ionization and dissociation, or indirectly by dissociative recombination of ions produced by the radiation. The cosmic rays also generate a weak UV radiation field inside the cloud, and this tends to dissociate molecules. So a complex chemistry is required to synthesize the variety of observed species.

In discussing this chemistry, we shall assume that the hydrogen is already almost entirely molecular. We are therefore considering molecule formation in a gas consisting of H\textsubscript{2}, with traces of the atomic species He, O, C, N, S, Mg, etc. The gas is irradiated with cosmic ray particles (mainly MeV protons and electrons), and contains within it dust grains of various sizes and materials.

**Gas phase chemistry**

Simple collisions between atoms rarely lead to reaction and the formation of a molecule since the interaction time is short compared to the time required for the interacting complex to eject energy either by radiating or by collision with a third body. In gas at atmospheric pressure, all collisions involve a third body, but in interstellar space densities are so low that only two-body collisions occur. For a rapid chemistry to occur, a third body is needed. In interstellar space, this means that reactions are usually exchange reactions or reactions occurring on the surface of dust grains (see below). Exchange reactions are of the type

\[
A + BC \rightarrow AB + C
\]

in which a new molecule, AB, is formed from the original molecule, BC. Such reactions are much more efficient if one of the partners is ionized. Direct exchange reactions of neutral atoms with H\textsubscript{2}, however, do not occur at the very low temperatures of interstellar space, so the obvious routes to chemistry – reactions of O, C, or N with H\textsubscript{2} - are suppressed (except in regions of high temperature, say, behind shocks or in stellar atmospheres).
The main scheme is driven by cosmic ray ionization of molecular hydrogen and helium:

\[ \text{H}_2 \rightarrow \text{H}_2^+ + e \]

\[ \text{He} \rightarrow \text{He}^+ + e \]

The \( \text{H}_2^+ \) ion reacts rapidly with another \( \text{H}_2 \) molecule to form a new ion, \( \text{H}_3^+ \),

\[ \text{H}_2^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{H} \]

and the \( \text{H}_3^+ \) ion is an effective proton donor in ion molecule reactions, creating a variety of new molecular ions from which new neutral species form. The large He ionisation potential ensures that reaction of molecules with \( \text{He}^+ \) occurs with such a large energy release that products usually dissociate, e.g. the reaction

\[ \text{He}^+ + \text{CO} \rightarrow \text{He} + \text{C}^+ + \text{O} \]

is usually the main loss mechanism for CO molecules.

Reaction sequences initiated by \( \text{H}_3^+ \) proton transfer reactions can generate an oxygen chemistry:

\[ \text{O} + \text{H}_3^+ \rightarrow \text{OH}^+ + \text{H}_2 \]

\[ \text{OH}^+ + \text{H}_2 \rightarrow \text{H}_2\text{O}^+ + \text{H} \]

\[ \text{H}_2\text{O}^+ + \text{H}_2 \rightarrow \text{H}_3\text{O}^+ + \text{H} \]

and the sequence of H addition reactions terminates here. It is followed by dissociative recombination

\[ \text{H}_3\text{O}^+ + e \rightarrow \text{OH} + \text{H}_2 \]

and \( \text{H}_2\text{O} + \text{H} \).

This sequence illustrates the essential features of interstellar gas-phase chemistry: if an ion can react with \( \text{H}_2 \) it will do so, given that \( \text{H}_2 \) is overwhelmingly abundant. When an ion is saturated with hydrogen then the most likely step is dissociative recombination with electrons, an extremely efficient reaction.

Similarly, proton donation to carbon atoms leads to the formation of \( \text{CH}_3^+ \) ions which can slowly associate with \( \text{H}_2 \) to form \( \text{CH}_5^+ \); both ions can recombine dissociatively with electrons to form a range of neutral species, from CH to CH₄. Nitrogen chemistry can be developed in a similar way, except that the initial step may be \( \text{H}_2^+ \) transfer (rather than proton transfer), and subsequent H additions lead to \( \text{NH}_4^+ \), from which the neutrals NH, NH₂, and NH₃ may be formed.

Reactions between the products of these initial sequences may then create many of the detected interstellar species. For example, CO is formed in part in the reaction

\[ \text{CH} + \text{O} \rightarrow \text{CO} + \text{H} \]
and reactions of NH with O, C, and N atoms may lead to the formation of NO, CN, and N2, respectively. More complex species may be formed by addition reactions of the type

$$\text{CH}_3^+ + \text{H}_2\text{O} \rightarrow \text{CH}_3\text{OH}_2^+$$

followed by dissociative recombination to form methanol

$$\text{CH}_3\text{OH}_2^+ + e \rightarrow \text{CH}_3\text{OH} + \text{H}$$

Schemes of this kind, capable of generating all the detected interstellar molecules, have been developed, and a database of chemical reactions likely to be important in the interstellar medium is available at the website www.rate99.co.uk; it lists about 4000 reactions between about 400 species. This reaction set also includes photodissociation and photoionisation reactions promoted by starlight; such reactions occur in diffuse clouds. The main difference in diffuse clouds, as compared to molecular clouds, ions such as C+, S+, and metal ions are the dominant form of those elements. In diffuse clouds, the carbon chemistry is initiated by the slow radiative association between the abundant species H2 and C+.

$$\text{C}^+ + \text{H}_2 \rightarrow \text{CH}_2^+$$

rather than the reaction of H3+ with C atoms.

**Surface and solid-state chemistry**

In the previous section we made the assumption that in molecular clouds nearly all the hydrogen is in the form of H2 molecules. In fact, gas phase routes for the conversion of hydrogen atoms to molecules do exist, but are too inefficient to account for the high abundances that are detected, especially in diffuse clouds where starlight is the main H2 destroyer. It has long been assumed, by default, that molecular hydrogen is formed in reactions at the surfaces of dust grains. The deduction made from observations of H2 is that the process must be an efficient one: most of the H atoms arriving at the dust grain surfaces must be converted into molecules and returned to the gas phase.

During the last decade, experimental and theoretical techniques have developed to such an extent that reliable investigations of this astronomical deduction can be made. The most successful programme of experiments has been carried out at Syracuse University, New York. In these experiments separate beams of cooled H and D atoms impinge on cold dust analogues to form HD, H2, and D2, and the product HD is counted in prompt desorption and in subsequent temperature programme desorption. These experiments have been performed for a variety of dust analogue materials, including amorphous silicates, carbons, and ices. The recombination efficiency is shown to be a sensitive function of surface temperature and is significant only within a rather restricted temperature range. It also depends on the substrate material.

Detailed theoretical studies of hydrogen recombination on graphite surfaces indicate that newly-formed hydrogen molecules should desorb with considerable internal and kinetic energies. An experiment at University College London uses a single H atom beam and bases its detection of product molecules by identifying H2 molecules in excited ro-vibrational states. The extent of the internal excitation is less than that predicted theoretically, suggesting that in the actual experiment there are additional mechanisms tending to quench the excitation.
These experimental and theoretical studies demonstrate the viability of the basic process by which hydrogen molecules can form on cold surfaces. However, the situation in interstellar clouds is that the surfaces are those of very small, discrete dust grains, not macroscopic laboratory samples. In space, the gas densities are low enough that the mean population of H atoms per grain is very small. In these circumstances, a statistical approach is required, and various studies of that kind are described in the accompanying chapter by Herbst. Also described there is a detailed theoretical model of astrophysical surface chemistry.

Our understanding of surface chemistry is improving, though we do not as yet have a complete description of how these processes operate in the interstellar medium. Nevertheless, the astronomical evidence that H2 forms by surface catalysis is compelling. Nor is H2 the only molecule to be formed in this way. Icy mantles on dust grains in a dense cloud can only grow within the lifetime of the cloud through hydrogenation of incident O atoms at the surface and retention of the product H2O molecule there.

Ice processing

As we have seen earlier, interstellar ices contain a variety of simple molecules, at least partially mixed in a solid solution. For example, CO in the ices can be shown spectroscopically to exist in different environments in the ice, including a polar environment (in which the CO environment is dominated by polar molecules, presumably H2O) and non-polar (in which the CO environment is dominated by non-polar or weakly polar molecules such as N2 or CO itself). In the interstellar situation, these ices are subjected to weak fluxes of highly energetic cosmic rays, or - less likely – intense UV radiation. Such an energy input can cause ionisation and dissociation of molecules within the ice and promote chemical reactions in the solid state. From an astronomical perspective, it seems clear that such solid-state chemistry is occurring and is important. For example, carbon dioxide, CO2, seems frequently to be the second most abundant molecular species in the ices, after water, at roughly 20 percent of H2O by number, and often exceeds the abundance of carbon monoxide, CO (especially on lines of sight toward bright stars). However, CO2 is extremely rare in the gas phase, and its abundance in the ices certainly cannot be accounted for by freezing-out of gas phase CO2 molecules. Hence, one infers that CO2 in the ice is formed as a result of the oxidisation of CO in situ. The reactions by which this occurs are currently unclear; either simple addition of O to CO or an exchange reaction of CO with OH is possible, where the O or OH is released by cosmic ray processing from H2O.

A second example concerns methanol, CH3OH. In some locations, methanol is detected in the gas phase with a relatively much higher abundance compared to that which can be established by gas phase chemistry. Methanol is also detected spectroscopically in ices within dense gas close to young hot stars, with an abundance that is only a factor of about 3 less than that of CO in the ice. In the gas phase, however, methanol is generally several orders of magnitude less abundant than CO. This suggests that there is a solid-state mechanism for hydrogenating CO to form CH3OH, and that in some circumstances the ices enriched in methanol are evaporated and the molecules injected into the gas phase. There have been a number of experimental and theoretical investigations of the hydrogenation of CO, but so far these have produced conflicting results. Nevertheless, on the basis of the astronomical evidence we can assert that such hydrogenation must be occurring, either in a direct addition of H atoms or in some more complex process.

Modelling the physics and chemistry of molecular clouds

Molecular clouds are the sites of star formation. A comprehensive picture of this fundamental astronomical process therefore includes the formation of the molecular cloud by collapse under gravity
from less dense and mainly atomic material. Chemistry provides the coolant molecules that radiate away the gravitational potential energy and maintain a low temperature during the collapse, so that thermal pressure does not rise and inhibit the collapse. Chemistry also controls the level of ionisation within the cloud; this ionisation determines how strongly the magnetic field is coupled to the gas and helps to resist the collapse. Therefore, in the initial stages of star formation several processes operate at both the microscopic and macroscopic levels.

How rapidly do these processes operate, and do they all have similar timescales? If one process, say the chemistry, has a shorter timescale than the others, then one could assume that the chemistry has arrived at a steady-state while the other processes are still evolving. While this would be a desirable simplification to the modelling, it appears not to be the case. The chemistry is essentially controlled by the cosmic ray ionization rate, and this give a timescale for the conversion of most of the atoms to molecules of about 0.3 My. The collapse is controlled by gravity, and an estimate of the collapse timescale is the pressure-free case of free-fall. The free-fall timescale is about 1 My for a gas number density of $10^4$ cm$^{-3}$. During the collapse, molecules are forming but also being lost by freeze-out on to dust grains. The timescale for freeze-out is about 0.3 My for a cloud of the same density. The cooling timescale, determined by the rate at which molecules can radiate energy out of the cloud, is about 1 My, and for the low ionisation level expected in molecular clouds the ambipolar diffusion timescale is about 0.4 My. Therefore, in a cloud of typical density for a star-forming region all the relevant timescales are comparable. This means that all processes: chemical, dynamical, gas-grain interactions, thermal, and magnetic support are strongly coupled and should in principle be computed in parallel.

4. The gas/dust interaction: examples from current research

In this section I shall discuss three examples of situations in astronomy in which the gas/dust interaction is particularly important. In the first, we consider the pre-stellar situation in molecular clouds in which clumpiness is evident. How does this clumpiness arise, and what role might it play in star formation? In the second situation we consider material in the vicinity of newly formed massive stars. Ices present in the collapsing cloud are evaporated by the rising temperatures and provide an integrated history of the collapse process. Can we use this chemical information to de-code the history? Finally, we shall mention a situation in which a collimated jet from a newly formed star impinges on a molecular cloud; can we use this jet as a probe to reveal the interior structure of the cloud?

Example 1: Dust and clumpiness in molecular clouds

The observational study of molecular clouds in molecular line emissions has been carried out almost entirely through single-dish observations. Typically, these give an angular resolution of a few arcminutes, corresponding of a spatial resolution on the order of 0.1 parsec for a nearby cloud that is at a distance of a few hundred parsecs. Not surprisingly, these studies have revealed structure with a size of a few tenths of a parsec in the clouds which themselves have a size of a few parsecs. However, the distribution of the molecules was surprising in that the CS emission contours traced the full extent of the cloud while the NH$_3$ emission contours were confined to small, denser regions near to infrared sources, i.e. newly-forming stars [8]. Intuitively, one expects the NH$_3$ contours to be widely distributed and CS contours to be confined to the higher density regions, since the critical density (at which the collisional excitation and radiative relaxation rates are equal) is larger for CS than NH$_3$. This has been interpreted [9] in terms of time-dependent chemistry: CS is an “early-time” molecule, while NH$_3$ is “late-time”. It is inferred, therefore, that these clouds had unresolved sub-structure that was transient on a timescale short enough for CS to appear while NH$_3$ appears only where the structure is denser, as it would be near star formation.
Such substructure has now been detected. Using telescopes with FWHM beamwidths of 45 and 50 arcseconds at the wavelength of C$^2$S emission observed Peng et al. [10] showed that Core D of TMC-1, previously assumed to be a single object, breaks up into a cluster of 45 dense cores, five of which appear to be unstable and likely to collapse to form low-mass stars. The high angular resolution provided by the Berkeley-Illinois-Maryland Array (BIMA) revealed [11] in the emission lines of three molecules (CS, N$_2$H$^+$, and HCO$^+$) very small scale structure that is different in the lines of each molecule. The difference in the microstructure can be most readily understood on the basis of time-dependent chemistry; the observations tend to pick out clumps in which particular molecules are rising to their peak abundances. Several of the cores they observed appear to be gravitationally unstable.

Thus molecular clouds appear to be highly dynamic objects with transient small scale structure, rather than the relatively smoothly distributed large-scale objects revealed in the low-resolution cases. What causes this small scale structure? The assumption usually made is that it is the result of hydrodynamic turbulence. Falle & Hartquist [12] have made a more specific suggestion: that the structure is set up by the passage of slow-mode MHD waves passing through the region. They have shown that in some circumstances these waves create density inhomogeneities in which the density is raised to between one and two orders of magnitude above the background density. It is tempting to associate the transient structures described by Morata et al. with such an origin.

Garrod et al. [13] have modelled the chemistry in such a transient core. In this calculation, the density and visual extinction are supposed to rise from a low density background condition to a maximum over a period of a million years, and then decay on a similar timescale. The initial chemistry is therefore essentially that of a diffuse cloud, but in the core that develops the chemistry is like that of a dense region. Freeze-out occurs in the densest regions, and ices are deposited; the ices are returned to the gas phase when the gas becomes once again of low density and low extinction. The observations of Morata et al. imply that a molecular cloud is made up of a population of cores at different stages of development. Therefore, Garrod et al. (in preparation) have used their time-dependent chemistry for a single transient core in a calculation that assembles a large number of transient cores, at random stages of evolution, and computes the molecular abundance contours. These simulated maps may then be viewed with angular resolutions corresponding to both low and high angular resolution cases of the observations. These artificial line maps have general characteristics that are in striking agreement with the observations. In the low resolution case, the artificial maps show that ammonia is concentrated in small regions, while the CS contours are widespread. This contrast, arising as previously described [9], is even more pronounced when the simulated maps are viewed with high angular resolution. When the critical densities of the emitting molecules are allowed for, the spatial separation of cores observed in CS, HCO$^+$ and N$_2$H$^+$ observed by Morata et al. is also found to be reproduced in the artificial maps.

Thus, there is now a theoretical understanding of the origin of the discrete cores found in L673. It is important to know whether this kind of structure is widespread, or confined to a few clouds such as L673 and TMC-1. The implications are that molecular clouds are clumpy, that the clumps are transient, that the timescale of this transience is comparable with the chemical timescale and the freeze-out timescale, and that the dynamics arise from MHD waves passing through this partially ionised region. Therefore, to model correctly the microscopic and macroscopic behaviours of molecular clouds to understand the cloud evolution in the early stages of star formation, it is important to take into account the coupling between all these factors. In particular, the chemistry in molecular clouds dominated by processes of this kind will be “young”. The gas-dust interaction is clearly important in these models, as material is assumed to be cycled into and out of the ices. The low mass star formation rate in such regions may be determined by the mass spectrum of clumps created by the MHD waves.
**Example 2: Regions of high mass star formation**

In the last section we have seen how the small scale structure within molecular clouds may be associated with the initial stages of the formation of low mass stars. The evolution of the structure from starless cores through a sequence of stages from protostar to a true star is roughly understood from the point of view of both theory and observations. Stars of high mass, however, evolve quickly and the opportunity of observing pre-stellar objects is consequently rare. High mass protostars tend to be deeply embedded in very dense and dusty environments, so the question arises: can we use information about this environment to learn about the history of the collapse?

This is the opportunity that is available from the study of so-called *hot cores*. These are small (< 0.1 pc), dense \( n_{\text{H}} \sim 10^7 \text{ cm}^{-3} \) and warm \( T_K \sim 200 - 300 \text{ K} \) regions of very high visual extinction (> \( 10^2 \) magnitudes) close to very young massive stars. They have a characteristic chemistry: they are rich in large hydrocarbons (such as alcohols, ethers, and ketones), in small hydrogenated species (such as ammonia, \( \text{NH}_3 \)), and very rich in deuterated species (even \( \text{ND}_3 \) has been discovered, a surprise since \( [\text{D}]/[\text{H}] \sim 10^{-5}! \)). Molecules such as methanol and ethanol may be many thousands of times more abundant in hot cores than is the case in molecular clouds. The hot cores are believed to be remnants of the collapsing cloud that were not incorporated into the newly forming star. They are, however, heated by the intense radiation of that star, and hence their temperatures are raised from the normal low values (~ 10 K) during the cloud collapse to the high values indicated above. The rise in temperature causes evaporation of the ices deposited and processed at low temperature. Thus, the gas phase chemistry reflects the cold conditions during the collapse and freeze-out phase, rather than the current warm conditions.

The warm up process of the star, initially at a temperature of ~10 K but rising to many thousands of Kelvins, cannot be instantaneous. It must occur over a finite period of time, and during that finite period the dust and gas temperatures in the high extinction hot core must also rise to the value we can detect now. Eventually, the influence of the stellar radiation field and stellar winds will clear the stellar environment of all debris, and the hot core will vanish. What happens during the warm-up phase? The ice is warmed at a rate that is in fact rather slow compared to the rate of warming in otherwise similar experiments of *Temperature Programmed Desorption* often conducted in the laboratory. If the ice were a pure solid, then as the temperature rose, evaporation would begin at a temperature corresponding to the binding energy of the molecules within the pure ice. However, the ice is chemically mixed, and physically the ice may have a complex morphology. How does the mixing and the morphology affect the desorption of molecules from the ice? Can we still hope to use the composition of hot cores as a descriptor of the conditions within the collapsing cloud?

McCoustra and colleagues at Nottingham University have made a series of experiments of Temperature Programmed Desorption from mixed ices involving molecules that arise in hot cores. The temperature range over which these experiments were made is from about 10 K up to about 160 K, at which all species evaporate. The case of a CO/\( \text{H}_2\text{O} \) ice is instructive [14]. While a pure CO ice would desorb at around 27 K, the CO/\( \text{H}_2\text{O} \) ice showed a very different behaviour. Instead of a single peak of desorption occurring around 27 K as the sample is slowly warmed, four desorption peaks were detected. The lowest temperature peak is indeed evaporation of the pure CO ice located on the top of the \( \text{H}_2\text{O} \) ice and a second peak is associated with the evaporation of CO molecules directly associated with the surface \( \text{H}_2\text{O} \) molecules. As the temperature continues to increase, CO molecules migrate into the interior of the amorphous \( \text{H}_2\text{O} \) ice and are trapped until \( \text{H}_2\text{O} \) crystallisation occurs; this occurs in the experiments at about 140 K, and opens up paths for trapped CO to migrate to the surface. A fourth and final peak in CO desorption occurs when the water ice itself desorbs, which in these experiments occurs at about 160 K.
Further experiments at Nottingham [15] have shown that other materials behave differently with respect to desorption from solid mixtures with H₂O. While water ice itself has a simple desorption behaviour and desorbs only at one (relatively) high temperature and some materials (e.g. CH₃OH, SO, NH₃) behave with respect to desorption like water, others (CS, N₂) behave like CO in CO/H₂O ice. Some species (e.g. OCS, H₂S, SO₂) are intermediate between these behaviours. Other species are classed as reactive or refractory. Viti et al. [16] have assumed that the ices that give rise to a hot core are well-mixed and that the various molecules behave as indicated from the Nottingham experiments; they have used these data in a model of a hot core in which the ices are deposited during the collapse phase and then released during a slow warming process. Desorption is then a complicated process in which, for example, CO molecules are desorbed in pulses at four different temperatures. This is also evident in the sulfur chemistry. H₂S is classified as an intermediate species and H₂S molecules are released in three pulses. Each pulse generates an increase in H₂S in the gas phase, and then a decline as the H₂S is processed by gas phase reactions into other species, principally SO, SO₂, and OCS. So, as H₂S shows a decline, these other species show a rise. These abundance steps are significant, and should be detectable. Thus, the chemistry provides a clock, and we may be able to use this clock to determine the warm-up time for the hot core, which is of course the same as the time required for a massive star to arrive at the Main Sequence. Therefore, chemistry is a useful tool to study hot cores, and hot cores themselves illustrate the importance of the gas/dust interaction in star-forming regions. On the basis of this picture, hot cores can – in principle - provide information about the pre-stellar conditions in regions of massive star formation, and the rise time of the temperature of a massive star as it evolves to the Main Sequence.

Example 3: Interactions between stellar jets and molecular clouds

It is a remarkable fact that low-mass stars at a very early stage in their formation develop high velocity jets that are extremely well collimated. The origin of these jets is unclear, but may be a consequence of magnetic reconnection occurring close to the newly formed and rapidly rotating protostar. The jets may penetrate considerable distances in the interstellar medium, up to a parsec or so. Though not detectable directly, their effects are seen where the jets impact on interstellar gas. The consequent shock creates high temperature ionised post-shock gas that radiates, for example, in forbidden lines such as [FeII] and [SII], and in Hα. These bright but “fuzzy” non-stellar emission sources are called Herbig-Haro objects. A linear array of HH objects illustrates the direction and extent of the jet. The termination of the jet occurs in a bow shock and HH object where the jet collides with a molecular cloud.

Over the last couple of decades, evidence has been accumulating that HH objects at the termination bow shock of a jet may be associated with molecular condensations in molecular clouds. These condensations were first detected in enhanced molecular line emissions from HCO⁺ and NH₃. However, it was clear from their narrow line widths that these condensations had not been directly affected by the shock, and it was suggested by Girart et al. [17] that UV radiation from the HH object might be promoting a photochemistry that gives rise to the chemical anomalies. If so, and if the mechanisms could be properly described, then the stellar jet/HH object system forms a microprobe of molecular clouds. These ideas have been subjected to theoretical and further observational study.

The chemical enhancements can now be understood on the basis of the following model. Unprocessed ices formed on dust grains in transient cores within a molecular cloud (perhaps similar to the cores of Example 1, above) are assumed to be released to the gas phase by radiation from the HH object. The UV dissociates CO and ionizes atomic carbon to give a source of C⁺ where normally none would exist. This C⁺, and other ions, can drive a characteristic chemistry in this molecule-rich environment. In particular, C⁺ reacts directly with H₂O (released from ices) to form HCO⁺. Theoretical studies of this cosmic chemistry show that the abundances of HCO⁺ and NH₃ should indeed be significantly
enhanced over those expected in a dense cloud. Also, a variety of other species, including CH$_3$OH, H$_2$CO, SO, and SO$_2$ were predicted to be enhanced in abundance over those typical of quiescent interstellar clouds. For example, enhanced C$^+$ leads to enhanced CH$_3$$^+$ which then associates with gas phase H$_2$O to form the ion CH$_3$OH$_2$$^+$; this ion dissociates with electrons to give CH$_3$OH. There was found to be qualitative agreement between observations and these model predictions of the photochemical signature induced by the HH object.

More detailed observational and theoretical studies [18] of one particular condensation (associated with HH2) confirm the general picture, but place tighter constraints upon it. This particular condensation has peak density of 3 × 10$^5$ cm$^{-3}$ and a visual extinction of a few magnitudes. It is irradiated by the flux from the HH object, but this can be no more than a thousand times as intense as the general background interstellar radiation field. The irradiation time must be short, about 100 years; the implication is that the HH object is approaching the condensation rapidly. In a recent survey [19], nearly all HH objects were found to have an associated condensation detectable in HCO$^+$ emission. This suggests that the filling factor associated with these condensations in molecular clouds is high. The most recent observational work [20] indicates that the interaction between the HH object and the molecular cloud is probably more complex than described above. In addition to the photochemical effects described above, there are – not surprisingly in such a dynamically active region – locations where both shock and alternative radiation effects may be apparent. However, the gas/dust interaction plays a part in all types.

5. Conclusion

Evidently, dust has many crucial roles to play as a component in the present Universe. The direct interaction of gas and dust is one of the most important microscopic processes in regions of high density. Our understanding of this interaction is now developing rapidly, and makes possible the application of the science of surfaces and the solid-state to star-forming regions.

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