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UNDERSTANDING THE INTERSTELLAR MEDIUM

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ABSTRACT

The Interstellar Medium – the medium between the stars is an active and dynamic medium and is a region of potential activity. Probing the ISM is interesting in itself. Understanding the gas and grains of the ISM provides vital clues on the evolution of the universe and our galaxy. The birth and death of stars takes place in the ISM. Spectral absorption features provide a wealth of information on the nature and composition of grains.

Keywords: *Interstellar Medium (ISM), dust grains, interstellar extinction, dust models.*

Introduction

On a clear, cloudless night, the starry sky is spectacular. The magnificent Sun we see with the naked eye is just a star in the sky – which has a history as well as a mystery. While Cosmology deals with the history, Astrophysics unravels the mystery.

Every year brings new and startling advances in astronomy. Better telescopes, better detectors, better pictures, newer ideas – they all contribute better to our understanding of the Universe. Our Universe appears to have had a beginning – The Big Bang! The realm of galaxies is extensive. The multitude of stellar nurseries – where cold

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and massive gas clouds collapse to form stars and then to a new solar system is fascinating. The Milky Way Galaxy, we live in, is just one of the billions of galaxies in the observable universe. The age of the universe is estimated to be around 13.7 billion years. Interestingly, there are more than 350 billion large galaxies in the universe and more than 25 billion cluster of galaxies! Each galaxy contains millions and millions of stars. Gravity binds them together. A voyage through the Milky Way galaxy alone would reveal nearly 200 billion stars including millions of black holes and neutron stars. The vast volume between the stars is not empty – it is a region of potential activity.

Photographs of rich star fields show dark patches in the regions where light from stars is heavily extinguished. The streak with no stars is called the 'dark dust lane'.

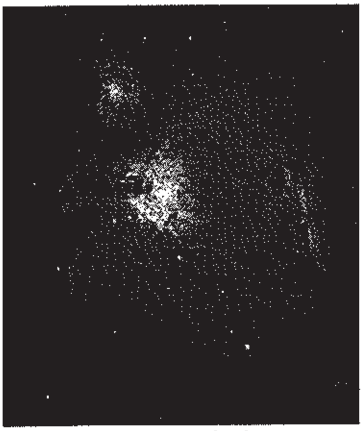
Early View of the Interstellar Medium

Early in the history of telescopic astronomy it was noticed that there were fuzzy patches in the celestial sky, in addition to countless stars [1-3]. These patches were called 'nebulae', which in Latin means 'cloud'. These nebulae were classified into different types:

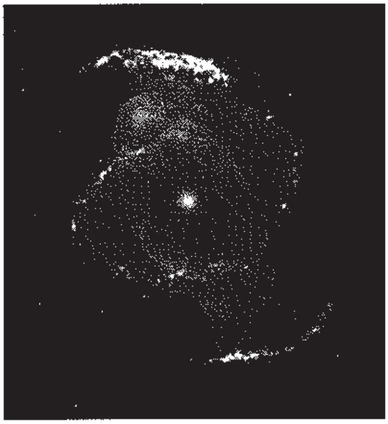
1. Diffuse Nebulae – which are amorphous, bright fuzzy blobs with one or more bright stars at the centre. These were ionized gas clouds lit up by very bright young stars. Ex. Orion Nebula (also known as Messier 42, M42, or NGC 1976 – discovered in 1610)
2. Planetary Nebulae – which are shells or rings of bright nebulosity surrounding a hollow centre. These turn out to be shells of matter thrown off by a dying star. Ex. Cat's Eye Nebula (NGC 6543), Dumbbell Nebula (NGC 6853)
3. Dark Nebulae – are dark clouds that block the stars behind them and redden those few stars that manage to be seen through them. They often look like 'holes' or 'gaps' in the Milky Way. These are relatively dense clouds of gas containing dust grains that absorb star light.
4. Emission Nebulae – are clouds of high temperature gas. They are usually the sites of recent and ongoing star formation. Ex. Carina Nebula (HH666)
5. Reflection Nebulae – are clouds of dust which reflect the light of a nearby star or stars. Reflection Nebulae are also the sites of star formation. They are usually blue, because the scattering is more efficient for blue light. Ex. Witch-head Nebula (IC2118)

6. Supernova Remnants are the remains of a supernova explosion. A supernova explosion occurs when a massive star ends its life in an amazing blaze of glory.

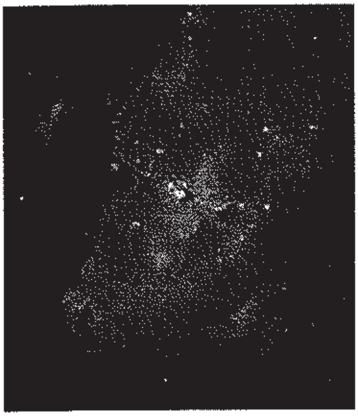
Reflection Nebulae and Emission Nebulae are often seen together and are sometimes referred to as Diffuse Nebulae. The Dark Nebulae is the origin of Interstellar Medium.



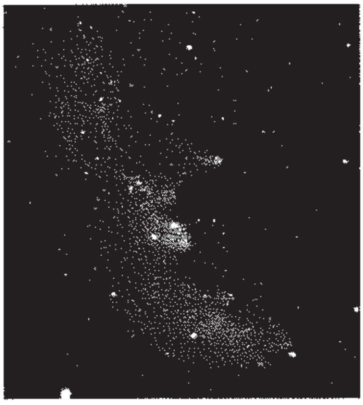
Orion Nebula



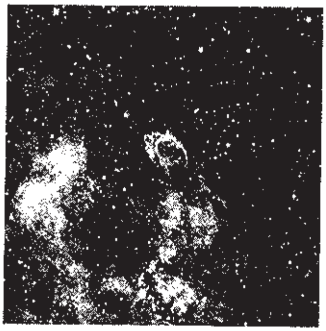
Cat's Eye Nebula



Eagle Nebula



Witch-head Nebula



Carina Nebula

Interesting facts about Interstellar Medium

The region between the stars, called the Interstellar Medium, is an active and dynamic medium. This region is very cool and has very low density. Typically, the temperature of the ISM ranges from about 10 K to 100 K. Interestingly, the interstellar medium is not empty. Studies reveal that 99% of the ISM is composed of gas, nearly 1% is dust and a very small fraction is made up of charged particles and magnetic field. The interstellar gas is primarily composed of atomic and molecular hydrogen (90%), Helium (9%) and the remaining 1% is the heavier elements. The interstellar gas is very dilute with an average density of about 1 atom/cc. This low density gas is typically found in two forms:

1. Cold clouds of neutral atomic or molecular hydrogen, which is the birth place of new stars.

2. Hot ionized hydrogen seen near hot young stars.

   The 21 cm. radiation from atomic hydrogen is used to study cold, dark regions of interstellar space. Spectral analysis is a tool to study the interstellar gas.

Observations infer that dust particles in the interstellar medium range in size from 0.001 μm to 1 μm. Dust grains interact in many ways with the ambient gas, the electromagnetic radiation and the magnetic field. Thus dust can modify the structure of stellar environment and influence its evolution. Dust scatters and absorbs the light of background stars. This leads to extinguishing and reddening of starlight.

Several attempts are made to understand the interstellar dust grains by probing the ISM. These studies reveal that dust grains have an active role in interstellar structure.

Effect of Dust on Stars

Stars emit light at many different wavelengths across the electromagnetic spectrum. Dust scatters and absorbs the light from stars changing the brightness and colour of starlight. Dust changes the colour of starlight by extinguishing shorter wavelengths more effectively. This is known as Interstellar Reddening.

Interstellar Dust Models

Several theoretical models are proposed to study the interstellar dust grains. The ideal interstellar dust model should fully specify the physical characteristics of the dust particles – their composition, geometry and size distribution. The dust related physical processes are absorption, scattering and emission of photons and photoelectrons. Knowing the physical properties of the ISM, one can calculate the evolution of grain population, changes in grain composition, geometry and size of the dust grains.

Knowledge of interstellar grains comes form various lines of evidence namely, interaction of dust grains with electromagnetic radiation, interstellar extinction, polarization and scattering of starlight.

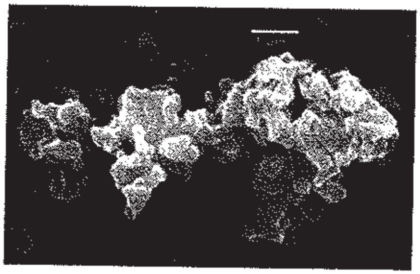
Early Dust Models

In literature, the *'Ice model'* was first proposed by Lindblad [4] in 1935 and later developed by Oort and van de Hulst [5] in 1946. The generic term *'ice'* is used to describe any volatile molecular solid composed of -CHON group of elements. Typically, interstellar ices appear to be ~70% of H_2O, with the remainder being made up of species such as CO CO_2, CH_3OH, CH_4, NH_3, N_2 and O_2.

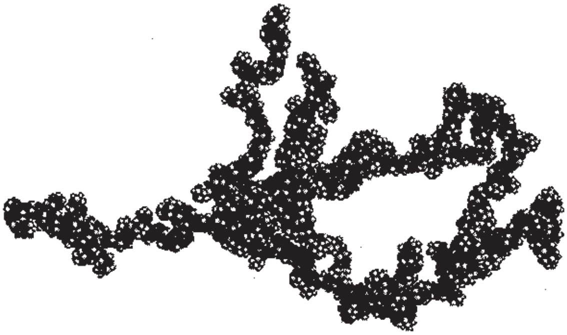
Construction of a Dust Model

Dust grains have irregular shapes and a very complicated internal structure. Typical steps in constructing a dust model are

1. Dust grains have to be of reasonable structure and chemical composition.
2. The model should be consistent with the interstellar extinction law.



Porous chondrite interplanetary dust particle



Fractal Interstellar Dust

Some Recent Dust Models

In recent years a number of different grain models have been proposed. All current models share some common features.

1. Interstellar dust grains contain carbon and silicon.
2. They also include Very Small Grains (VSG) and Poly-aromatic Hydrocarbons (PAHs).
3. The Dust model should fit the observed extinction curves.

The most commonly used Interstellar dust grain model was proposed by Mathis, Rumpl and Nordsiek [6] in 1977 and is popularly known as the MRN model. This model consists of two distinct populations with a mixture of bare spherical silicate grains and graphite grains with a power-law size distribution. This model provides an excellent fit to the average observed interstellar extinction curve. However, it is highly unlikely that interstellar grain is truly spherical in shape or that they are homogeneous in composition and structure.

Desert, Boulanger and Puget [7] in 1990 proposed a grain model consisting of three components –

1. Polycyclic aromatic hydrocarbon molecules (PAHs)

2. Very Small Grains (VSGs)

3. Big Grains

The PAH size distribution was not specified. A simple functional form was assumed for absorption by VSGs. The Big Grains were assumed to have scattering and absorption efficiency factors Q_{sca} and Q_{abs} given by simple functions of a/λ, where a is the radius of the grain and λ, the wavelength of light.

In 1994, Kim, Martin and Henry [8] used the maximum entropy method to obtain size distributions for mixtures of silicates, graphite and amorphous carbon grains.

Mathis [9] in 1998 proposed a grain model consisting of three components.

1. Small graphite grains to provide the 2175 A bump.

2. Small silicate grains to provide steep ultraviolet extinction.

3. Composite grains consisting of silicates and carbon.

Dielectric functions were adopted for silicates and graphites. Effective Medium Theory (EMT) was used to estimate the effective dielectric functions for composite grains. Assuming the grains to be homogeneous spheres, absorption and scattering cross-sections were calculated.

In 2001, Weingartner and Draine [10] and also Li and Draine [11] developed a grain model consisting of amorphous silicate grains and carbonaceous grains. The carbonaceous grains are taken to have the physical and optical properties of PAHs when small, and the physical and optical properties of graphite spheres when containing more than $\sim 10^5$ Carbon atoms.

Vaidya et al [12] have modeled the extinction curve using composite grains of host silicate material with graphite inclusions plus a small porous graphite grain to produce the 2175 Å feature.

In 2003, Clayton et al [13] used the "maximum entropy method" to feature dust grain size distributions to reproduce the interstellar extinction with mixtures of silicates, graphite and amorphous carbon grains.

Formation of Interstellar Dust

Studies infer that various stages are involved in the formation of interstellar dust grains.

- If a multi component system becomes cool enough, particular molecules begin to cluster and finally the macroscopic solid particles are formed. This process is called nucleation.
- The nucleation and grain growth occurs in the stellar outflows of cool red giants and super giants and also in novae and super novae ejecta.
- Solid particle in a gaseous medium, can in principle, be considered as a product of large number of chemical reactions resulting in the final macroscopic specimen.
- However the formation of solid particles in gaseous medium can be roughly considered as a two-step process ie

1) formation of critical cluster
2) growth of these clusters to macroscopic dust grains.

Nucleation of Critical Cluster:

The critical clusters for the condensates expected are very small having few monomers of the order of 10. Hence only few chemical reactions are required for a cluster to surmount the condensation barrier. The formation of critical cluster in the stellar outflow is stationary process. Until now only few limiting approaches are available for describing the the formation of the critical clusters like

1) Classical nucleation theory
2) Construction of individual chemical pathways from molecules to the macroscopic specimens

Most surprisingly, there are a few processes that cause the destruction of dust grains. These are

1) Photon-grain interactions (Photodesorption, sublimation, Coulomb explosion)

2) Atom/ion-grain interaction (sputtering)

3) Grain-grain interactions (coagulation, shattering, disaggresion, vaporization)

Conditions and Constraints for Construction of Interstellar Dust Models

Interstellar dust models are characterized by the abundance of different refractory elements that are locked up in the dust and also by composition, morphology and size distribution of individual grains.

The conditions to be considered are

1) specify the total mass of the different refractory elements

2) consider the morphology

3) size distribution of dust particles.

The interstellar dust model is needed to fit all observational constraints raised due to interaction of grain with the ambient gas and interstellar radiation field.

Constraints

The various constraints in structuring interstellar dust models are

1) extinction, obscuration and reddening of star light .

2) abundances of different elements and their observed depletions

3) polarization and alignment properties of grains

4) spectral absorption features

5) the continuum and line emission features

6) wavelength-dependence of albedo and phase functions

Most of the interstellar models have been constructed by deriving the abundances and size distribution of some well studied solids, such as graphite or silicates and using few observations such as, the average interstellar extinction, the polarization or the diffuse infrared emission as constraints. The model is then checked for consistency with other observational constraints such as wavelength-dependent albedo and interstellar abundances.

Significance of Dust in Astrophysics

1. Dust is a vital ingredient of the cosmos.

2. **Interstellar processes and Chemistry:**

   For many years, the only molecules known to exist in the interstellar space were radicals -CH, $-CH^+$ and -CN. These radicals were identified by their characteristic absorption lines in stellar spectra at blue-visible wavelengths. In the later years CH_4, CH_3OH, CO_2 and NH_3 were traced. Grains play a catalytic role. In recent years, polycyclic aromatic hydrocarbons (PAHs) were detected in the ISM by means of characteristic vibrational modes observed in the infrared. PAHs are planar molecules composed of benzene rings, with sizes typically of $\sim$1 nm. PAHs containing as many as 200 C atoms or more are believed to be very abundant in the ISM.

3. **Evolution of Stars:**

   Dust is intimately involved in the formation and evolution of stars and planetary systems. Stars are born within cocoons of dust and gas. The dusty outflows of evolved stars contribute significantly to the enrichment of ISM with heavy elements. Thus dust can modify the structure of stellar environment and influence its evolution.

4. **Biological grains:**

   In contrast to conventional models, it is proposed that interstellar dust is composed of materials of biological origin like bacteria, viruses, diatoms, proteins and polysaccharides. The search is on for such biological grains.

Evidence for Interstellar Dust

Nearly 1% of the ISM is contained in the form of interstellar dust having a radius of few microns. These grains are made up of graphites, carbonates, silicates, water molecules and their compounds. They do play an important role in the extinction of star light, thereby affecting our visual appearance. Interstellar dust grains redistribute the spectrum of the interstellar radiation field, which has contribution to diffuse background radiation.

The evidence for interstellar dust comes from

1) Interstellar Abundance.

2) UV absorption line studies.

3) Infrared emission features in the spectra of cool and luminous stars has shown presence of silicate particle in and above such stars.

Conclusion

Current research on interstellar grains involves a range of theoretical studies. It has been well established that extinction, the total property of absorption and scattering is a diagnostic tool to study the nature of dust grains. Recent research reveals that interstellar dust grains play a vital role in several branches of science and such studies are potentially interesting and are of immense importance.

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