INTERSTELLAR MATTER

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INTRODUCTION:

Within the last few years, the field of Astronomy has widened considerably and has opened up many interesting new areas for theoretical research. This came about partly because of the success of making observations from above the atmosphere and partly due to advances in the instrumentation. What I shall discuss here are the advances in our knowledge of interstellar matter. In particular, I would like to bring out some new observational results, both on the dust and the gas component, that has come out in recent years and which poses challenging problems for a theoretical astrophysicist.

DUST COMPONENT:

We will first consider the dust component or interstellar grains. The direct evidence for the existence of dust comes from the photographs of the milky way. One can see clearly in these photographs dark and conspicuous markings. The presence of dust of sizes of the order of a few tenths of a micron in front of a star can do many things. It can absorb or scatter the stellar radiation. It can also emit its radiation in the infrared region of the spectrum at its own equilibrium temperature. The importance of the latter process was not very much appreciated until infrared observations revealed its presence.

The reddening curve essentially seems to be the same for different regions of space in the wavelength region between 0.3 to 1 μm, and so one can talk of a mean reddening curve. The earlier rocket observations (Stecher 1969) and later observations (Code 1969) from OAO-2 (Orbiting Astronomical Observatory launched in December 1968) of the reddening curve for wavelengths smaller than 0.3 μm were consistent in showing that the reddening curve continues to increase even upto 1100 Å and that there is a conspicuous bump around 2200 Å. Before these ultraviolet observations, it was generally felt that the reddening curve for wavelengths smaller than 0.3 μm will be an extrapolation of the observed curve upto about 0.3 μm. However, the rapid increase in the reddening curve for wavelengths less than 0.3 μm was a surprise. In August 1972, another satellite called Copernicus was launched by the Princeton group and they have further extended the reddening curve upto about 1000 Å (York et al 1973). The curve still seems to be increasing fast with no indication of either flattening or falling down. This result is again a surprise. How the curve looks like at wavelengths between 1000 and 912 Å is anyone's guess at the present time. The cutoff at 912 Å occurs because of the absorption by interstellar neutral hydrogen. These observations indicate that the dust is very efficient in obscuring light in the far ultraviolet region i.e. even upto 1000 Å. The most plausible and accepted hypothesis for the explanation of the reddening curve is the absorption and scattering by small particles of sizes of the order of 0.1 μm or less. An exact characterization of these grains requires many parameters like size distribution, chemical composition, distribution, formation etc. The principal types of particles that have been proposed are iron, dirty ice, graphite, Platt particles (complex molecular aggregates), silicate, core-mantle grains etc. (Greenberg 1968; Wickramasinghe and Nandy 1972). None of the proposed models can explain the whole range of the reddening curve, the main drawback being that the models do not give as much extinction as observed in the far ultraviolet region. This led workers to try for multi-component models. These models gave reasonably good fit with the observations of OAO-2 upto 1100 Å. The results of Copernicus has further put severe limitations on these multi component models. It may be pointed out that in bringing multi-component models, one is essentially introducing additional parameters like size distribution of each component, percentage abundance of each component etc. So it may not be very surprising that these models can explain the whole reddening curve as there are many variable parameters which could be adjusted. Therefore, the various calculations done so far have been done purely on an ad hoc basis. It might however be noted that the graphite and silicate materials have a feature around 2200 Å which could explain the observed bump in the reddening curve. Here I may mention the most recent result of Day and Huffman (1973), who have made extinction measurements on small graphite particles and show that graphite particles could account for the observed extinction in the far ultraviolet.

In addition to the reddening curve, we have two more observations on grains. One finds that the stellar radiation is polarized. Also the scattering by the grains gives rise to a general diffuse background radiation. The observed interstellar polarization gives evidence for the non-spherical nature of the grain oriented either by the magnetic field or by some other mechanism (Purcell 1969). The magnetic field required to orient the grains to produce the observed amount of polarization seems to be consistent with the value determined from other observations. The measured diffuse background radiation in the visible and ultraviolet region of the spectrum gives a relation between the albedo and phase function, which has to be satisfied by any grain model (van de Hulst and de Jong 1969). Not all the models considered seem to satisfy this requirement. In order to test the applicability of any model, it is necessary and essential to apply multiple tests (Krishna Swamy and O'Dell 1967). This will considerably reduce the number of allowed models. Unfortunately at the present time, most of the models are tested only with regard to the reddening curve. In addition to satisfying some of the observations mentioned already, one has also to worry about the origin and stability of the grain.

It is also possible to get some information about the chemical composition of the grain from the infrared region of the spectrum. Depending upon the composition of the grain, one will have different bands in the infrared region. For example, if the dust constitutent is mostly H_2O, one expects to observe a band at 3.1 μm. On the other hand, two broad features at 10 and 20 μm seem to have been detected from interstellar matter, which have been attributed to silicate material (Hackwell et al 1970). Therefore, it appears that the composition of the grain partly or wholly may be silicate in nature.

In conclusion, it may be said that none of the existing models can explain satisfactorily all the available observations on grains. The results of OAO-2 and particularly those of Copernicus demand a fresh look into the whole problem of interstellar grain.

Another result which has yet no explanation is about the diffuse absorption features observed in the spectra of interstellar-reddened stars (Bromage 1972). There are about 25 of them at the present time. They mostly lie in the region 4500-6000 Å. One feature at 4430 Å, which has been studied in some detail, seems to indicate that it is closely associated with the interstellar grains. A number of explanations have been proposed to explain the origin of these diffuse features, but none is fully satisfactory.

Another aspect of the dust component which I would like to briefly touch upon refers to thermal emission from grains. Within the last few years, infrared observations have shown that strong infrared radiation is generally associated with various kinds of astrophysical objects (Neugebauer et al 1971). These include infrared stars, T-Tauri stars, giant and supergiant stars, nebulae, novae, galaxies, comets etc. Some of these results were of course unexpected. The most plausible explanation to date for the origin of this excess infrared radiation is the thermal re-radiation by the grains. It essentially means that the grains absorb short wavelength energy from the source and attain an equilibrium temperature when absorption and the infrared emission are balanced. This mechanism implies that dust seems to be present in almost all the objects. In some of the objects, we also have other evidence for the presence of dust in them. However, the question of how the grains are formed in these objects is still not clear. At least in cool stars, one finds that conditions are good enough that particles may condense (Hoyle and Wickramasinghe 1962 ; Donn et al 1968). But in hotter stars, the grains have to be produced in the material well away from the star, which means in the shell. However, the process of nucleation, which gives rise to particles of about a few tenths of a micron, is not understood. There is some indication that the dust material in some of these objects might be silicate in nature, from the detection of spectral features at 10 μm and 20 μm (Woolf 1972). I would not like to go into detail on all the work of Infrared Astronomy except to discuss briefly the implications of the detection of unexpected strong infrared radiation from a number of planetary nebulae. These objects have expanding spherical shells around them. They have a star of very high temperature (~ 50,000 to 100,000°K) at the centre of the shell. The density in the nebulae is typically of 10^4 atoms/cm^3 and it is completely ionized. The electron temperature is about 10^4°K. These objects are supposed to be highly evolved and so it was believed that dust cannot exist in these objects. If the observed infrared radiation is interpreted as due to thermal emission from dust, it gives evidence for the first time about the presence of dust in these objects. This interpretation leads to many interesting and fundamental problems.

INTERSTELLAR MOLECULES:

Since 1940, it is known that the molecules are also present in interstellar space. This essentially comes from the detection of absorption lines of the bands of CH, CH^+ and CN. Only within the last few years (since 1968) the whole subject of interstellar molecules has exploded, in the sense that a large number of simple and complex molecules have been found to exist in interstellar space (Rank et al 1971). This unexpected and startling discovery has come mainly from the detection of microwave lines arising from these molecules. Complex organic and inorganic molecules, which could not be even thought of before to be present in interstellar space, have been detected. To name a few, molecules like formaldehyde (H_2CO), cyanoacetylene (HC_3N), formic acid (HCOOH), methyl alcohol (CH_3OH), methyl acetylene (CH_3C_2H) etc. have been identified. So far, about 25 molecules have been detected. One expects to observe many more molecules in due course of time. The simple molecules CH, CH^+ and CN were identified earlier as their electronic bands lie in the visible region of the spectrum. Already the bands of H_2 and CO molecules have been identified in the far ultraviolet spectrum (Carruthers 1970; Smith and Stecher 1971; Spitzer et al 1973; Jenkins et al 1973). The discovery of the presence of a large number of different kinds of molecules in interstellar space has raised many important questions. One such important question is the mechanism of their formation. All the existing mechanisms are grossly inadequate even for simple molecules. The mechanism of formation of molecules is intimately connected with the lifetime of these molecules in interstellar space. The increase in the reddening curve upto 1000 Å means that the available energy around 1000 Å is much smaller than the values used earlier. This should increase the lifetime of molecules considerably from those previously calculated. In any case, the mechanism of formation of molecules in interstellar space is a problem where the collaboration of astronomers, physicists and chemists is needed.

The observed lines from many of the complex molecules also show overpopulation of certain levels (possibly due to maser action), time variations and apparent abundance of some complex molecules relative to simpler molecules. The understanding to some of these has still to come.

Lastly, the outstanding problem of the origin of life is a mystery till today. The presence of complex organic and inorganic molecules in interstellar space might also provide some clue to this pressing problem.

INTERSTELLAR GAS :

Although neutral atomic hydrogen is the most dominant gaseous matter in interstellar space, it is very hard to observe, as there is no easy way of detecting it. It was actually detected in 1951 from the hyperfine structure in the ground state which gives rise to a transition at 21 cm, which lies in the radiofrequency region. Most of our knowledge about structure of our Galaxy and other galaxies has come from an analysis of these 21 cm observations of neutral hydrogen (Kerr 1969). In addition to neutral hydrogen, interstellar space is also sprinkled with other atomic species like Ca, Na, K, Ti, Fe etc. It is believed that all the elements that exist in our solar system are also present in the interstellar medium and with abundances comparable to it. However, lines from only a few elements have been detected, as the strongest lines of most of the elements lie in the ultraviolet region of the spectrum. Already many new lines arising from various elements have been detected and more will come within the next few years. The great importance of determining the abundances of individual elements and their isotopes, particularly those which can be destroyed at temperatures obtaining in the interior of stars, is obvious. I would not like to go into a detailed discussion of each one of them, except to say a few words about deuterium. Deuterium has also a ground-state hyperfine transition at 91.6 cm, similar to 21 cm line of hydrogen. This line was looked for by many observers but with negative results until recently. For the first time the line of deuterium seems to have been detected from the Galactic center (Cesarsky et al 1973). In addition, molecules containing deuterium, for example DCN, have also been detected. The deuterium present in interstellar space has to be primordial as there is no way of producing it. The observations however seem to be consistent with the production of deuterium in the big bang theory. There is also the possibility that it may be produced by some unknown phenomena.

CONCLUSIONS :

The whole subject of interstellar matter has to be looked upon on a new perspective. Until a few years ago, all of the information came essentially from the study in the visible and radio wavelength regions. The extension of observations to ultraviolet, infrared, and also millimetre wavelength regions has given us a vast amount of unexpected and new information about the various aspects of interstellar matter, and have posed difficult problems for an astrophysicist. Here I have tried to stress some of these. We should however keep in mind that all the results obtained so far are based on the present day techniques, where there is a lot of scope for improvement. Therefore, we may hope to expect many more results of fundamental nature in the years to come. In the end, it may be pointed out that it is also important to carry out laboratory work under physical conditions appropriate to that of interstellar space. Such studies may help us in our understanding of some of the existing puzzles in this field.

References :

Bromage, G.E. 1972, *Ap. and Space Sci.*, **15**, 426.

Carruthers, G. R. 1970, *Ap. J. (Letters)*, **161**, L81.

Cesarsky, D. A. Moffet, A. T., and Pasachoff, J. M. 1973, *Ap. J. (Letters)*, **180**, L1.

Code, A. D. 1969, *P.A.S.P.*, **81**, 475.

Day, K. L., and Huffman, D. R. 1973, *Nature (Phys. Sci.)*, **243**, 50.

Donn, B., Wickramasinghe, N. C., Hudson, J. P., and Stecher, T. P. 1968, *Ap. J.*, **153**, 451.

Greenberg, J. M., 1968, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (University of Chicago Press, Chicago), Ch. 6.

Hackwell, J. A., Gehrz, R. D., and Woolf, N. J. 1970, *Nature*, **227**, 822.

Hoyle, F., and Wickramasinghe, N. C. 1962, *M.N.R.A.S.*, **124**, 417.

Hulst, H. C. van de, and de Jong, T. 1969, *Physica*, **41**, 151.

Jenkins, E. B., Drake, J. F., Morton, D. C., Rogerson, J. B., Spitzer, L., and York, D. G. 1973, *Ap. J. (Letters)*, **181**, L122.

Kerr, F. J. 1969, *Ann. Rev. of Astro. and Ap.*, **7**, 39.

Krishna Swamy, K. S., and O'Dell, C. R. 1967, *Ap. J.*, **147**, 937.

Neugebauer, G., Becklin, E., and Hyland, A. R. 1971, *Ann. Rev. of Astro. and Ap.*, **9**, 67.

Purcell, E. M. 1969, *Physica*, **41**, 100.

Rank, D. M., Townes C. H., and Welch, W. J. 1971, *Science*, **174**, 1083.

Smith, A. M., and Stecher, T. P. 1971, *Ap. J. (Letters)*, **164**, L43.

Spitzer, L., Drake, J. F., Jenkins, E. B., Morton, D. C., Rogerson, J. B., and York, D. G. 1973, *Ap. J. (Letters)*, **181**, L116.

Stecher, T. P. 1969, *Ap. J. (Letters)*, **157**, L125.

Wickramasinghe, N. C., and Nandy, K. 1972, *Rep. on Prog. in Phys.*, **35**, 157.

Woolf, N. J. 1972, in *Proc. of the Conf. on Interstellar Grains and Related Topics*, Eds. J. M. Greenberg and H. C. van de Hulst.

York D. G., Drake, J. F., Jenkins, E. B., Morton, D. C., Rogerson, J. B., and Spitzer, L. 1973, *Ap. J. (Letters)*, **182**, L1.

(*Continued from page 8*)

While concluding this article, we note that astronomy is a neglected field in most Indian universities. This is a sorry state of affairs in the present space age when every scientist, at least every physicist, should have a basic knowledge about our astrophysical environment. The universities have therefore a special responsibility in the task of spreading the message of astronomy among the academic community. We hope that with the continuing support of the Osmania University authorities and the University Grants Commission, the Centre of Advanced Study in Astronomy will be able to play a positive role in the near future.