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THE NATURE OF INTERSTELLAR DUST AS REVEALED BY LIGHT SCATTERING

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(Invited paper)

ABSTRACT. Interstellar dust was first identified through the extinction that it causes of optical starlight. Initially, observational and theoretical studies of extinction were made to identify simple ways of removing the effect of extinction. Over the last few decades it has become clear that dust has a number of very important roles in interstellar physics and chemistry, and that through these roles dust affects quite fundamentally the evolution of the Milky Way and other galaxies. However, our detailed knowledge of the actual material of dust remains relatively poor. The use of accurate models for the interaction of electromagnetic radiation with particles of arbitrary shape and composition remains vital, if our description of dust is to improve.

My talk will give a general survey of interstellar dust for those working in other areas, and as an introduction to the session on interstellar dust.

Interstellar visual extinction was detected as early as the 19th century [1] and was attributed early in the 20th century to scattering and absorption by particles of sub-micron size [2]. In the context of astronomy of the time, cosmic dust was regarded simply as an annoying impediment to obtaining a clear view of the stars at optical wavelengths. Simple procedures were introduced [3, 4] to estimate the amount of dust towards a particular object, so that a "non-extinguished" (i.e. true) spectrum of the object could be inferred, the main study of astronomy then being stellar atmospheres and the structure and evolution of stars. Polarization and scattered light measurements were used to extend the information gained from these extinction studies. When astronomical measurements in the ultraviolet and infrared regions of the spectrum became possible, extinction and polarization studies were also used to constrain the inferred models of dust. But the actual nature of the dust was not tightly constrained by these models, nor did the presence of dust have any serious implications for the rest of astronomy.

However, during the last half-century the realization grew that dust was not merely a passive component of the interstellar medium, i.e. an irritating "astronomical fog", but an active constituent with many important roles to play. It is now clear that without the contributions that dust makes to the physics and chemistry of the Milky Way, our galaxy would not have its present form, and - to take an Earth-centred view - we humans could not exist. It's obviously important to understand the contributions that dust makes to the evolution of the galaxy as fully as possible. These roles depend sensitively on the actual

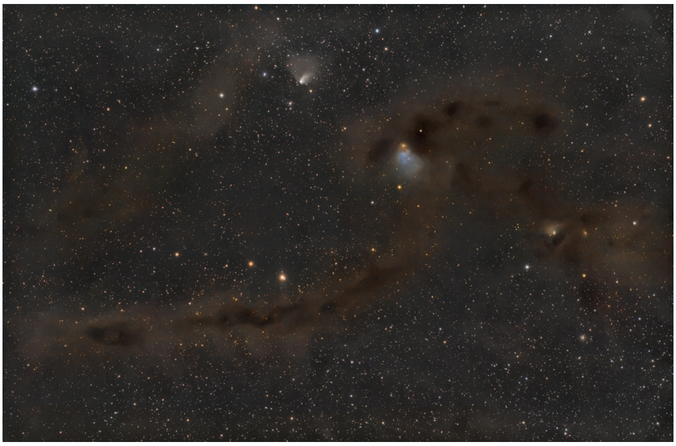

Figure 1. Interstellar clouds of gas and dust absorb the optical radiation from the rich star-fields in the background. Copyright Steve Cannistra.

physical and chemical nature of the dust. Thus, it has become essential to develop the best possible dust models. Therefore, the most accurate computational methods (such as those codes discussed and developed by experts at this meeting) need to be used to describe the interaction between radiation and the dust particles; the methods must be able to deal with particles of arbitrary shape, size distribution, porosity, structure, and composition [5]. While some indications as to the nature of interstellar dust can be made from collected interplanetary particles, especially in terms of their isotopic abundances (with implications concerning their origins in supernovae or other objects), conclusions as regards the physical nature of the dust grains are confused by the amount of physical and chemical processing the dust grains may have received during the formation of the Solar System. Hence, the most reliable (and readily available) source of information for the nature of dust, whether in our own galaxy or nearby galaxies, or in those at high red-shift, lies in the interaction of dust with electromagnetic radiation at all wavelengths. This interaction includes both absorption and emission of radiation. Fig. 1 illustrates the absorption of starlight from a rich background star-field by dust in foreground clouds of dusty gas. Fig. 2 illustrates the infrared emission from dust warmed by starlight, in the vicinity of the centre of the Milky Way Galaxy.

The roles of dust in the interstellar medium are many and varied [6]. Obviously, if some of the atoms of certain elements are locked into solid form, fewer of those atoms are available in the gas phase. Some elements, such as silicon, are normally inferred to be almost entirely locked up in dust, so that if gaseous silicon is present in atoms or molecules then it suggests that dust grains are being eroded in shocks. The extinction caused by dust reduces the local intensity of starlight and suppresses photoprocessing of molecules; this allows an extensive and significant chemistry to develop in well-shielded regions. This chemistry would otherwise be inhibited by the radiation field [7]. The molecules formed in this chemistry are coolants for the gas and can permit the collapse of a low temperature interstellar cloud to occur by radiating away the gravitational potential energy of the cloud

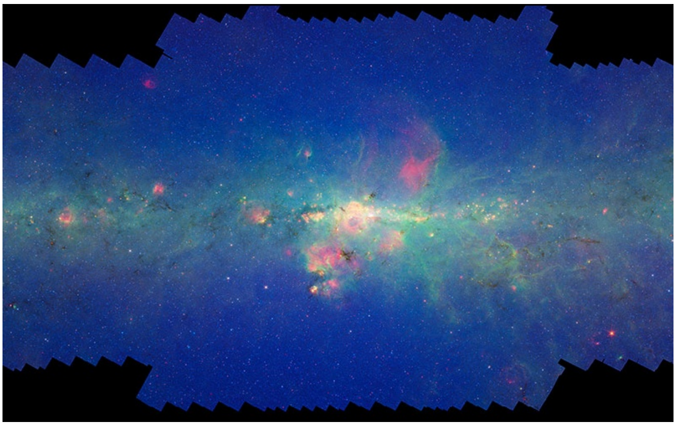

Figure 2. The Spitzer Space Telescope's infrared view of the centre of the Milky Way Galaxy, in a false colour representation. The red regions represent infrared emission (much of it at about 24 microns) from dust that has been warmed by radiation of newly-formed but still optically-obscured stars. The green filaments represent radiation (at around 8 microns) from large molecules/small dust grains called Polycyclic Aromatic Hydrocarbons. Credit: GLIMPSE, MIPSGAL, NASA, JPL-Caltech, Univ. Wisconsin.

[8]. Dust grains can accept electrons and thereby modify the charge balance remaining in the gas; therefore dust grains can affect the (largely ion-molecule) gas-phase chemistry producing coolant and tracer molecules. Charged dust grains are coupled to the neutral gas by collisions and by electromagnetic forces to the magnetic field lines, thus affecting the ability of neutral gas to move across field lines, contributing to a kind of magnetic pressure. Dust grains provide surfaces on which chemistry can occur; the molecule H_2 is certainly formed in this way [9] and H_2 is the fundamental molecule that drives almost all of interstellar chemistry. It is very likely that the surfaces of bare dust grains also stimulate other chemical reactions forming hydrides such as NH_3 and H_2O. Thus, all of interstellar chemistry in the Milky Way and other galaxies depends on the presence of dust, and on its physical and chemical nature.

In regions where the dust extinction is sufficiently high, then dust grains are observed to become coated with mantles of dirty ice. The composition of this ice can be determined by infrared spectroscopy and varies from one line of sight to another [10]. However, it is predominantly composed of frozen water, carbon monoxide and dioxide, with traces of methanol, formaldehyde, ammonia and other species. The ice changes the optical and chemical properties of the dust, and itself is capable of being chemical processed thermally, by fast particle interaction, or by UV excitation. Molecules of a relatively complex nature (alcohols, ketones, aldehydes, etc.) can be released to the gas phase when the ices evaporate in warm regions [11]. Such chemical complexity is argued by some to have relevance to pre-biotic chemistry; it could not occur without the presence of dust grains.

In this paper, I shall review some recent observational and modelling work. Observational studies are now emphasising dust in external galaxies, including some galaxies at high red-shift. There have been a number of space missions concentrating on observations in the infrared (e.g. Akari, Spitzer, Herschel) that have produced new information concerning dust. Ground-based millimetre-wave facilities are also providing key information about dust, and the forthcoming (2011) Atacama Large Millimetre Array will revolutionise much of astronomy, including dust studies.

In spite of the importance of dust for astronomy, there is only a rather broad consensus on the material nature of dust. Generally, models invoke dust grains of silicates and carbons, with a component of large molecules or small grains often assumed to be in the form of polycyclic aromatic hydrocarbons. I shall discuss some models of dust as revealed by recent observations. I shall also describe a model in which some carbon is assumed to be deposited in layers on silicate grains [12]. This layered model has predictive properties; for example, it has an intrinsic time-dependence, so that the nature of the carbon layer and its interstellar extinction on a particular line of sight will evolve in time [13]. The model predicts the nature of the carbon surface; this also allows more precise predictions of the chemical activity of the dust grain surfaces.

I shall also describe recent work [14] that suggests that stored chemical energy may affect the emission of radiation from sub-micron particles.

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