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Laboratory Analogues of Cosmic Dust

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Abstract. Understanding the properties and the evolution of cosmic dust requires laboratory experiments for measuring basic physical and chemical data and simulating the interaction of dust grains with their cosmic environments. We give a short review of such laboratory experiments using analogue materials of cosmic dust.

1. Introduction

For astrophysical processes such as the formation of stars and planets, the properties of cosmic dust play a crucial role (see the contribution by A. Witt). Cosmic dust is a complicated system of grains of different sizes and morphologies built up from a variety of materials. Due to incorporation into different cosmic environments during their lifecycle, these small solids interact with atoms and molecules, ions, fields, electromagnetic radiation and cosmic rays. Consequently, they will experience a complex evolution of their chemical and physical structure which may lead to unusual properties compared to terrestrial solids (see, e.g. Dorschner & Henning 1995).

Laboratory measurements can deliver basic data of solid materials expected to be present in space, which are needed for the interpretation of astronomical observations and the modelling of astrophysical systems. Moreover, understanding the cosmic dust evolution itself requires simulation experiments for physical and chemical processes occuring to the dust grains. For both types of experiments, solid materials have to be produced, which imitate the properties of cosmic dust grains as good as possible, at least in the aspects important for the experiment. We call such materials "Cosmic Dust Analogues". In this short review, we will illustrate by a few examples the work done with such materials in many astrophysical laboratories. For further reading, we recommend the books edited by Ehrenfreund et al. (1999), and Greenberg & Li (1999).

2. Measurement of optical data

Most important for the development of astrophysical dusty systems such as stellar outflows, disks, and dense interstellar cloud cores are the optical properties of the dust. They determine the energy balance and the dynamics of the system to a large extent. Moreover, the emission and absorption by the dust is an important source of information in astronomical observations.

Emission, absorption, and scattering by small grains, however, is very complex because it is not only determined by the internal composition and structure of the material, but also by morphological factors such as grain size and shape, and by the environment (temperature, embedding medium). All of these aspects need to be studied experimentally, since both optical material data and computational models are available only in special cases (Henning & Mutschke 2000). The wide wavelength and temperature range of interest puts special challenges to the laboratory spectroscopist.

So, on the one hand, there is a need for systematic studies of the spectra of terrestrial natural and synthetic analogue materials, in order to understand the elementary excitations in materials of special composition and crystal structure. Such materials studied in detail in astrophysical labs comprise amorphous and crystalline silicates, oxides, sulfides and carbides (e.g. Mutschke et al. 1999), carbon in various amorphous and crystalline modifications (e.g. Mennella et al. 1995, Henning & Schnaiter 1999), and ices (e.g. Hudgins et al. 1993). Most of these studies aim at the derivation of the dielectric function of the material, which is one of the parameters determining the particle optical properties needed for radiative transfer models of dusty astrophysical systems. Databases of such optical constants have been developed for astronomical purposes (e.g. Henning et al. 1999).

On the other hand, in the last years some experiments have been started which focus on spectroscopy of particle ensembles under conditions comparable to those in space. These experiments so far can only be carried out on nanoparticles directly synthesized from the gas phase. Most favourable for this purpose are processes which imitate grain condensation e.g. in stellar outflows. In contrast to conventional measurements these experiments should avoid interaction between the particles or with other media.

One possibility on the way to spectroscopy of free particles is the isolation in noble gas matrices, which allows accumulation of particles from a beam up to a mass density even sufficient for infrared measurements. There is still an influence from the matrix in this type of measurement, but it is possible without laser equipment and in a very large spectral range. One example of such spectra recently obtained by Clément et al. (in preparation) is shown in Fig. 1. The future certainly will belong to laser spectroscopic techniques, utilizing e.g. free-electron lasers (see, e.g. von Helden et al. 2000) in connection with particle beams or traps.

3. Irradiation experiments

Irradiation of solids with energetic photons or particles causes structural changes by various types of interaction, the effectivity of which depends not only on the energy of the radiation. Bonds can be broken directly by resonant excitation of the electronic system or by displacing nuclei in collisions. These processes produce disorder, but depending on the mobility of the atoms they give the possibility for restructuring of the lattice. This mobility, on the other hand, is enhanced by energy transferred by non-resonant processes.

Evidently, UV radiation plays an important role for the evolution of organic and, in general, carbon-dominated matter. The production of organic molecules

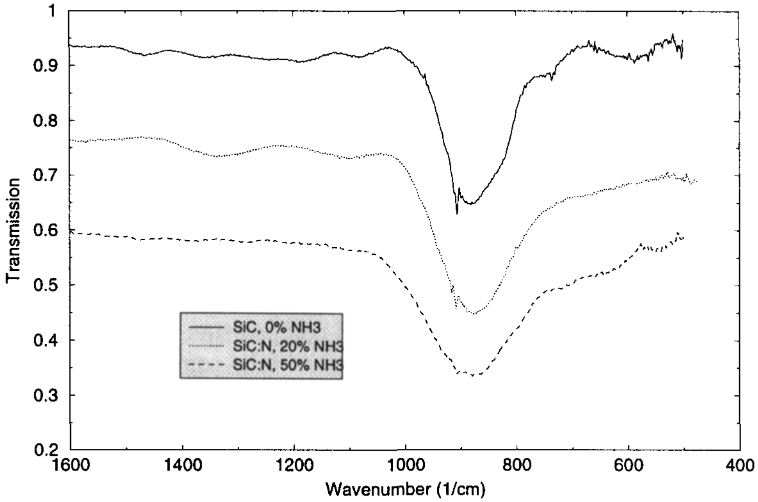

Figure 1. Infrared spectrum of nitrogen-doped SiC nanoparticles from gas pyrolysis, isolated in an argon matrix at 6 K.

in ice-layers by photolytic processes has a long tradition in laboratory astrophysics (Hagen et al. 1979, Gerakines et al. 1996). Further, graphitization of amorphous carbon by UV radiation plays a decisive role in the most recent structural model of the carbon nanoparticles responsible for the famous UV bump in the interstellar extinction curve (Mennella et al. 1998).

Another very recent problem are the structural changes between crystalline and amorphous silicate phases observed in different cosmic environments. Ions may play an important role in amorphization processes occuring to crystalline silicates (and other dust species) in the diffuse interstellar medium. In order to evaluate the efficiency of such processes in space, the interaction of silicate dust analogues with ions of different masses and energies and at various temperatures is currently studied in astrophysical laboratories. Recent results by Fabian et al. (in preparation) show that only relatively slow (less energetic or more massive - compare Table 1) ions can efficiently amorphize submicron crystalline silicate particles. These investigations are still at the beginning, but they will provide important insight into cosmic dust evolution in the future.

Table 1. Effect of ion bombardment on the crystal structure of silicate (enstatite) grains

Ion	Dose (cm^{-2})	T (K)	Amorphization
1 MeV He^+	$5{\cdot}10^{15}$	300	no
3 MeV C^+	$2{\cdot}10^{15}$	300	no
0.15 MeV He^+	$1{\cdot}10^{17}$	15	no
0.4 MeV Ar^+	$9{\cdot}10^{14}$	900	yes

4. Conclusions

Solid-state laboratory astrophysics currently benefits from and partly also triggered the revolutionary development of nanoparticle physics. New production methods as well as analytic techniques such as molecular beams, traps, and laser spectroscopy have been introduced and allow to study more detailed elementary processes occuring in the interaction of solids with gaseous species and radiation fields. Because of limited space we have omitted in our review the important field in which surfaces of solids serve as catalysts for molecular reactions, which is another application of cosmic dust analogues. Further, we did not mention the studies of particle interaction carried out in microgravity in order to explain the formation of planets and other large bodies. Certainly, these fields will contribute and already contribute not only to astrophysics but are an important part of general physics and materials science.

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