Probing the Evolution of Cosmic Dust with X-rays

X-ray irradiation may have played a significant role in chemical evolution of the early universe.

For most of the twentieth century, the presence of interstellar dust – mixed with gas – has been an accepted concept in astronomy, but that dust was regarded mainly as an irritating fog that prevented a clear view of the stars. Most early efforts were hence directed towards developing simple methods for dust extinction, so that the true intensity and spectrum of an unshielded star could be estimated from the observed obscured star. In the past half century, it has become increasingly accepted, however, that dust has many and important roles in astronomy, and is a crucial component of the Milky Way and other galaxies. Without dust, for example, our galaxy would not have evolved as it has, stars would not have their present forms and planets would not exist.

The most obvious role of dust is that it can shield regions from ambient starlight. Molecules, such as carbon oxide in cloud interiors, are thus protected from photodissociation by ultraviolet (UV) starlight and have a long lifetime; a complicated chemistry can hence arise in cloud interiors. Cosmic dust also enables interstellar chemistry of two kinds to occur through its interaction with the gas. First, the presence of dust promotes reactions between atoms and molecules adsorbed on the surfaces of bare dust grains. Surface reactions of this type are important because they provide, in particular, almost all hydrogen molecules that are essential partners in the gaseous-phase network.

Second, the observations of particular astronomical locations lead to a conclusion that dust grains therein accumulate mantles of ices containing a few fairly simple molecules – mainly water, carbon oxide and dioxide, with other simple molecules in smaller proportions. These unprocessed ices are certainly interesting; their chemical complexity can be greatly enhanced, apparently through solid-state chemistry in some form, with more complicated products enriching the gaseous phase. These more complicated product species, such as ethanol, acetic acid and glycol aldehyde, are detected in relatively large abundance in various interstellar locations, especially in regions of star formation, and are considered relevant to the emerging subject of astrobiology.

In space, ices of simple species can be cooked in various ways to produce species that are more complicated. The cooking can be driven by cosmic rays (swift particles – mainly protons, α-particles and electrons) and – energetic radiation (particularly UV photons and X-rays). The more complicated species might be retained in the ice to serve as precursors for prebiotic chemistry in larger bodies, such as planets, or released when the ices become warmed with the radiation of a newly forming star. All these processes are replicable in laboratory experiments.

Aiming to simulate the irradiation of ice mantles to study the formation of complicated organic molecules with X-radiation in circumstellar regions, an international team composed of researchers from Taiwan, Italy and Spain performed experiments using **TLS 08B**; this beamline provides photons in energy range 250-1250 eV. Synchrotron sources are ideal because of their great intensity and wide wavelength coverage. The rationale for the use of X-rays is based on the observationally derived evidence that X-ray emission is an almost universal characteristic of stars. For solar-type stars, the X-ray emission evolves with the age of the star, becoming less intense as the star ages. At early stages in the life of a star, such an X-ray component can be even more intense than UV emission.

In the first work,[1] the aforementioned researchers irradiated pure carbon-oxide ice, as CO is among the most abundant constituents in the chemical inventory of space, both in gaseous and condensed phases. Although CO_2 was the major product in excitation experiments of both types, the overall chemical evolution differed significantly between the experiments. **Figure 1** shows infrared (IR) spectra in the relevant range, in which signals of photochemical products are evident.

In the second work,[2] solid CO mixed with H_2O was irradiated with X-rays; the diffusion barrier of CO in water ices was found to be significantly less (~160 K) than current values of surface-diffusion barrier exploited in astrochemical models. Even if initially segregated, CO molecules can thus disperse in their embedding water ices at temperatures exceeding 10 K. The dust grains that are originally incorporated into protoplanetary disks are essentially of an interstellar

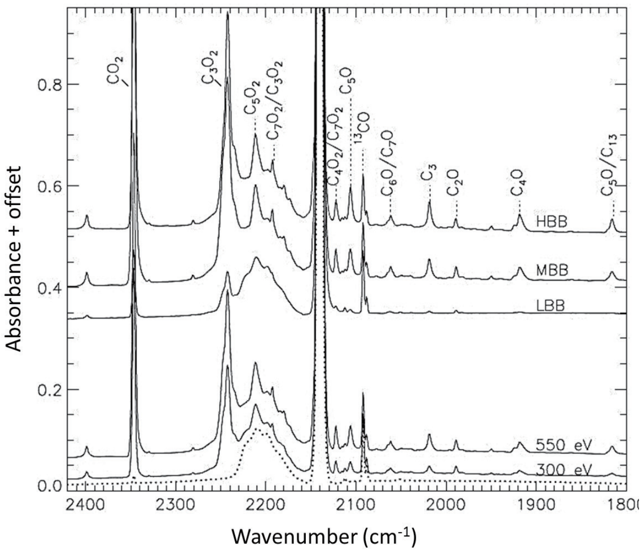

Fig. 1: IR spectra of an initial CO ice sample (dotted line) and obtained after irradiation at 300 eV, 500 eV and broad-band emission (250-1250 eV) with small, medium and large photon flux. [Reproduced from Ref. 1]

nature, but have been severely modified through the filter of star formation. The key issue is the extent of such processing that is imprinted on the growth, crystallization and settling of the dust grains. In the third experiment, the authors considered the effects of soft X-radiation on iron-free magnesium-silicate materials produced via a sol-gel technique; the soft X-radiation modified the structure of the silicate sample. The Si-O stretching signal shifted by approximately 0.2 µm towards greater wavelength, becoming weaker and broader with the duration of irradiation, shown in **Fig. 2**.

Icy surfaces are prevalent in cold regions of space. These ices are exposed to varied energetic sources, including UV photons, electrons, ions and X-rays. The nature of interstellar and circumstellar ices is difficult to constrain, as it depends on various physicochemical processes. Walsh *et al*. (2012) showed that the midplanes of circumstellar disks are shielded from UV radiation beyond 10 au, whereas X-radiation of greater energy can penetrate more effectively and might lead to an appreciable contribution to the molecular complexity in the disk midplane beyond 10 au. X-radiation might also affect the dust substrate supporting the ice. The reported work[3] demonstrated that X-rays can alter the silicate structure, possibly because of the loss of the local residual order of the silicate. All work on X-radiation of materials of astrochemical interest taken together provides an opportunity to rethink the importance of chemical evolution triggered by X-radiation in the early stage of protostars. (Reported by Yu-Jung Chen, National Central University, and Yu-Jong Wu)

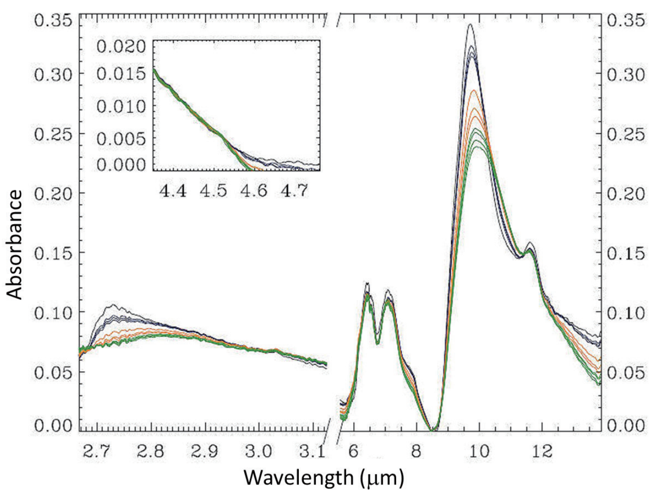

Fig. 2: IR spectra of silicate. The black line is the silicate spectrum before irradiation. The blue, orange and green lines are spectra after irradiation with weak, medium and strong X-ray rates, respectively. [Reproduced from Ref. 3]

This report features the the collaborative work of Angela Ciaravella, Yu-Jung Chen, Cesare Cecchi-Pestellini, Guillermo M. Muñoz Caro and their coworkers published in Astrophys. J. ***819****, 38 (2016);* ***820****, 25 (2016);* ***828****, 29 (2016).*

The research team members, Y.-J. Chen, G. M. Munoz Caro, A. Ciaravella and C. Cecchi-Pestellini (from left to right) performed the experiment at **TLS 08B1**.

TLS 08B1 BM-AGM

- Photoprocess of Solid States at Low Temperature
- Astrophysics, Astrochemistry

| References |

1. A. Ciaravella, Y.-J. Chen, C. Cecchi-Pestellini, A. Jiménez-Escobar, G. M. Muñoz Caro, K.-J. Chuang, and C.-H. Huang, Astrophys. J. **819**, 38 (2016).
2. A. Jiménez-Escobar, Y.-J. Chen, A. Ciaravella, C.-H. Huang, G. Micela, and C. Cecchi-Pestellini, Astrophys. J. **820**, 25 (2016).
3. A. Ciaravella, C. Cecchi-Pestellini, Y.-J. Chen, G. M. Muñoz Caro, C.-H. Huang, A. Jiménez-Escobar, and A. M. Venezia, Astrophys. J. **828**, 29 (2016).