

Experimental Insights Into the Formation of Fullerenes and Carbon Nanotubes in Interstellar Space

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Introduction: The detection of the fullerenes C₆₀ and C₇₀ in space has transformed our understanding of chemical complexity in the interstellar medium (ISM) [1]. It also raises the question of the origins of these large, carbon-bearing species, as well as the possibility of even larger molecules in astrophysical environments. While the presence of C₆₀, C₆₀⁺, and C₇₀ in the ISM is well established, there is significant controversy concerning the formation mechanism of this new class of molecules in environments that are hydrogen-rich. Several mechanisms have been previously proposed to explain fullerene formation, including photoprocessing of polycyclic aromatic hydrocarbon (PAH) molecules and destruction of hydrogenated amorphous carbon (HAC) grains [e.g. 2-3]. Our previous work [4] demonstrated that fullerenes such as C₆₀ form from thermal decomposition of silicon carbide (SiC) grains. Here we report on the follow-up analysis of SiC thermal decomposition. This work is part of an effort to identify larger carbon nanostructures in the ISM.

Sample and Method: A 3C-SiC powder (the same polytype as presolar grains [5]) with a particle size < 80 nm was obtained from US Research Nanomaterials to serve as an analog presolar grain sample. The SiC sample was deposited onto a Norcada microelectromechanical systems (MEMS) chip (model HTN-0101H), which was then inserted into a Hitachi “Blaze” sample holder [6]. A controller box powers the MEMS chip, which is operated through a Labview interface. Variable ramp rates, set points, and isothermal holds are achievable with the Blaze holder and MEMS platform.

The SiC sample was heated in-situ to 1050 °C using the 200 keV Hitachi HF5000 scanning transmission electron microscope (S/TEM) located at the Lunar and Planetary Laboratory (LPL). The HF5000 is equipped with a cold field-emission gun, a 3rd-order spherical-aberration corrector for STEM mode, bright field and dark-field STEM detectors and an Oxford Instruments X-Max N 100 TLE EDS system with dual 100 mm² windowless silicon-drift detectors ($\Omega = 2.0$ sr). These heating experiments are designed to simulate shocks occurring in post-AGB stellar envelopes, where fullerenes are observed.

Results and Discussion: Our newest experimental findings reveal that heating the analog SiC grains yields a growth of hemispherical C₆₀-sized nanostructures perpendicular to the SiC crystal surface – additional evidence for C₆₀ formation, as we previously found. The carbon hemispheres are < 1 nm in diameter, and are single-walled. These nanobud structures, upon a heating duration greater than a few minutes, transform into multi-walled carbon nanotubes (MWCNTs). The MWCNTs observed in the TEM experiment are composed of >4 graphene layers, with dimensions of ~4 nm in length. The MWCNTs also are capped, with each graphene layer of the tube curved at the end. These structures are larger than any of the currently-observed interstellar fullerene species, both in overall size and number of constituent carbon atoms.

These experimental results suggest that such MWCNTs are likely to form in post-AGB shocks. As the post-AGB wind impacts the dust envelope surrounding the star, we hypothesize that the Si atoms leech from the SiC crystal, first forming reduced carbon layers in the form of graphene on the SiC grain surface. Due to the surface curvature and imperfections in the SiC grains, the graphene sheets then distort to form the C₆₀-sized carbon nanobuds. The nanobuds may form C₆₀, which leaves the grain surface, or act as growth sites to form larger MWCNTs. The structures, along with the smaller fullerenes, are subsequently injected into the ISM, where they have high radiation stability [7]. We will discuss the implications of these findings to presolar grain studies and the potential for these nanostructures as carriers of the Diffuse Interstellar Bands (DIBs).

References:

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