Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 55 (2015) 705–715

Advances in Space Research (a COSPAR publication)

www.elsevier.com/locate/asr

Hydrocarbon analogs of cosmic dust to trace the solid carbon abundance in the interstellar medium ☆

Kamel A.K. Gadallah *

Astronomy & Meteorology Department, Faculty of Science, Al-Azhar University, Nasr City, PO Box 11884, Cairo, Egypt
Astrophysical Institute and University Observatory, Friedrich Schiller University, Schillergsschen 2/3, 07745 Jena, Germany

Received 9 April 2014; received in revised form 16 October 2014; accepted 17 October 2014
Available online 24 October 2014

Abstract

The spectral changes of hydrogenated amorphous carbon (HAC) could show variable distributions of solid carbon abundance in the interstellar medium (ISM). The variable optical properties of HAC analogs, produced by the laser ablation in a high vacuum, depends on the variation in its atomic and electronic structures. The fraction of hydrogen atoms in HAC increases proportionally with the laser's power. The available solid carbon tied up in the interstellar HAC, being the carrier of the interstellar 3.4 μm and 4.6 μm^{-1} bands, is indicated by the strength of these bands. Comparing the strength of these bands with those of laboratory data indicates that the amount of carbon in HAC analogs is not inherently sufficient. The lack in the solid carbon (locked solid carbon) in these analogs can be analytically estimated to facilitate the simulation of cosmic carbon dust. The results show a reduction in the locked solid carbon when the fraction of hydrogen atoms in HAC analogs increases. When this fraction becomes approximately 0.52 relative to the total number of hydrogen and carbon atoms, there is no lack of carbon in HAC analogs. The interstellar distribution of variable solid carbon abundance is attributed to the modification of cosmic HAC, which occurs as a result of the variation in its hydrogen atom fraction and the UV processing taking place in the interstellar environments. This distribution reveals more solid carbon abundances reside in the dust phase and may assist in resolving the carbon crisis.

Keywords: Astrochemistry; Carbon abundance; Interstellar dust

1. Introduction

Solid carbonaceous materials are extremely important components of dust grains in the diffuse ISM (Greenberg and Li, 1999; Ehrenfreund and Charnley, 2000). Some of these materials with different fractions of sp^2 and/or sp^3 hybridization have been considered in the ISM such as the graphite, diamond, aliphatic hydrocarbons, polycyclic aromatic hydrocarbons (PAH), amorphous carbon (AC), hydrogenated amorphous carbon (HAC), and others (e.g., Pendleton and Allamandola, 2002; Tielens, 2008).

In the mid-IR range, vibration absorption features were detected at the 3.4 μm band, which is attributed to C–H stretching mode, and at the 6.85 and 7.25 μm bands, which are attributed to C–H bending (deformation) modes. In the Milky Way, all these modes were observed along lines of sight in the local diffuse ISM (Pendleton et al., 1994; Whittet et al., 1997) and toward the galactic center (Tielens et al., 1996; Chiar et al., 2000, 2002, 2013). They were also observed in dense and dusty galactic nuclei of Seyfert and ultraluminous infrared galaxies (Mason et al., 2004; Spoon et al., 2004; Risaliti et al., 2006; Dartois et al., 2007; Dartois and Muñoz-Caro, 2007; Kondo

☆ This template can be used for all publications in Advances in Space Research.

* Address: Astronomy & Meteorology Department, Faculty of Science, Al-Azhar University, Nasr City, PO Box 11884 Cairo, Egypt.
E-mail address: Kamel.Gadallah71@gmail.com.

http://dx.doi.org/10.1016/j.asr.2014.10.022

et al., 2012), and in cometary and interplanetary dust particles (Muñoz Caro et al., 2008; Matrajt et al., 2013). The optical and structural evidence from the experimental and theoretical studies indicates that the structure of such interstellar carbonaceous grains is predominantly amorphous (e.g., Jäger et al., 1999; Henning et al., 2004; Jones and Nuth, 2011). Furthermore, based on the depth of the corresponding features at 3.4, 6.85 and 7.25 μm, the best candidate material is likely to be a HAC material (Duley et al., 1998; Dartois et al., 2005; Mennella et al., 2002). Comprehensive studies recently conducted by Jones (2012a,b,c) show the structural and optical properties of HAC based on its compositional, optical, and size-dependent properties, respectively. In these studies, the evolution of HAC, in a mixture of aliphatic and aromatic carbon, has been described in the mid-infrared and VIS–UV wavelength ranges. Since the first astronomical detection by Stecher (1965) until the modern astronomical data (Sofia et al., 2005; Fitzpatrick and Massa, 2007), the 4.6 μm^{-1} (217.5 nm) UV bump was observed in interstellar extinction curves toward many lines of sight in the diffuse ISM. The shape of this curve is related to the ratio of the total to selective extinction, $R(V)$, (Whittet et al., 2004; Fitzpatrick and Massa, 2007). In laboratory astrophysics, UV-irradiated HAC could be the carrier of the interstellar UV bump, due to the $\pi - \pi^*$ transition, once HAC dust grains have been exposed to the interstellar UV radiation during the lifetime (10^7 yr) of the diffuse ISM (Mennella et al., 1996; Gadallah et al., 2011, 2012b). Based on the physical description of the electronic structure of carbon materials as well as the laboratory simulations of the UV-processed HAC, the model of the bump carrier carbons by Mennella et al. (1998) is able to match the width and position of this bump.

In the ISM, the cosmic elemental carbon abundance represents the total carbon in both the gas- and dust-phases. Since the evolution of the solid carbon materials (the carbon dust phase) was predicted in different environments such as the diffuse ISM, circumstellar media and the solar system, their optical and structural properties were widely described in several studies (e.g., Mennella, 2010; Godard et al., 2011;Compiègne et al., 2011; Dalle Ore et al., 2011; Gadallah et al., 2011, 2012a, 2013; Chiar et al., 2013). The carbon abundance in the solid-phase in the ISM will be summarized in Section 2.

In this work, HAC analogs investigate the influence of the hydrogen fraction on the optical properties of the corresponding interstellar HAC, which shows the distribution of solid carbon abundance in the ISM. Various carbon abundances are analytically linked to the variation in the intensity of the 3.4 μm and 4.6 μm^{-1} bands in the diffuse ISM. In Section 3, additional details of the experimental setup are provided where the laser ablation technique was used to produce HAC analogs having a range of the hydrogen atom fraction. In details, the laboratory results come in Section 4. Regarding HAC analogs, the calculation of the lack of carbon (or locked solid carbon) needed to reproduce the strength of the interstellar bands is discussed in Section 5. Finally, the conclusions are summarized in Section 6.

2. The solid-carbon abundance

In astrochemical models, the extent of the cosmic carbon budget is still ambiguous. The discrepancy between the amount of carbon available in the ISM and that needed in models to reproduce the observed wavelength-dependent extinction causes the so-called "carbon crisis." From the observation of CII, Cardelli et al. (1996) found that the carbon abundance in the gas phase is about 140 ± 20 ppm from the total, 225 ± 50 ppm, leaving 80 ± 55 ppm for the dust phase. In order to solve this crisis, some theoretical models (Kim and Martin, 1996; Mathis, 1996) suggested that higher carbon abundance resides in the dust grain. In the composite fluffy dust model presented by Mathis (1996), almost 160 ppm of carbon atoms is required in the dust phase. In Dwek et al. (1997), this model was improved considering 70 ± 20 ppm of carbon which is locked up in PAHs. Kim and Martin (1996) improved the grain size distribution in the ISM from diffuse to dense environments as a function of $R(V)$, requiring higher carbon abundances (240–310 ppm) in the dust phase to match the interstellar extinction curves. These higher abundances are close to those in Parvathi et al. (2012) toward several sight lines depending on a higher reference abundance of 464 ppm of elemental carbon. It was thought that there was not enough depleted-carbon to produce the optical properties of carbon dust (Kim and Martin, 1996; Mathis, 1996; Dwek et al., 1997). In recent models (i.e. Draine, 2003; Compiègne et al., 2011), approximately 200 ppm of carbon atoms needs to be available in the interstellar carbon dust to carry out the dust extinction. From the observed spectra of the dominant ion of carbon (strong transition of CII at 1334 Å) in diffuse neutral sight lines, Sofia et al. (2011) found that more carbon could reside in dust than was previously thought.

The depletion of some elemental abundances is correlated to the change in their solid-phase abundance in the interstellar dust grains (Jenkins, 2009). The elemental abundances in the proto-sun (Lodders, 2003) and in young F and G stars (Sofia and Meyer, 2001) have been considered as a reference to estimate the solid abundance. In the recent study by Parvathi et al. (2012), the lower limit of the interstellar cosmic carbon abundance is 464 ppm, which represents the higher carbon abundance in the gas-phase toward HD 206773. Therefore this study shows higher variable values in the population of the solid carbon abundances. Once dust passes through a medium such as the interstellar shock, the carbonaceous dust is more rapidly destroyed than silicate dust during their re-evaluation lifetimes as explained in the study by Jones and Nuth (2011) and Chiar et al. (2013). As a result of the evolutionary dust in the ISM, the population of the solid carbon with different abundances is attributed to the destructive