

CARBONACEOUS DUST IN PLANETARY SYSTEMS: ORIGIN AND ASTROBIOLOGICAL SIGNIFICANCE

G. M. Muñoz Caro and J. Martínez-Frías

Planetary Geology Laboratory, Centro de Astrobiología (CSIC/INTA), associated to the NASA Astrobiology Institute, Ctra de Ajalvir km. 4, 28850 Torrejón de Ardoz, Madrid, Spain, Email: munozcg@inta.es, martinezfrías@mncn.csic.es

ABSTRACT

A brief overview of astrobiologically relevant organic species detected in small solar system bodies, in particular meteorites, is provided. Such organic molecules, however, are only a minor component of the carbon in these objects. Many of them, like amino acids, probably the most interesting family of molecules for astrobiology, have not yet been detected in the interstellar medium. Most of the carbon is present as the so-called macromolecular organic material, both in meteorites and interplanetary dust particles. We show that material is analogous to hydrogenated amorphous carbon, a hydrocarbon widely studied by chemists. A form of hydrogenated amorphous carbon is also observed in grains toward the diffuse interstellar medium, and even in Seyfert 2 galaxies, although with different chemical properties. Therefore, in our attempt to trace the evolution of carbonaceous matter as the local interstellar cloud collapsed leading to the formation of the solar nebula, we focus on the study of an ubiquitous form of carbon, namely hydrogenated amorphous carbon.

1. INTRODUCTION

From an astrobiological point of view there is an intriguing temporal link on Early Earth between the origin of life and meteorites. The sequence of events that led to the emergence of self-replicating organisms is poorly known but the late heavy bombardment of Earth by remnants of planetary formation might have played a crucial role [1]. It has been estimated that the mass of asteroids and comets reaching the Earth after core formation was $0.7\text{--}2.7 \cdot 10^{22}$ kg, and that comets represented less than 10^{-3} by mass of the impacting population. These values have significant implications for both early solar system dynamics and the emergence and early evolution of life on our planet [1]. Although it has been recently suggested a Hadean (4.6–3.9 Ga) origin of life (probably prior to 4.1 Ga) [2], the most probable time for life's origin is

estimated to be between 4 Ga and 3.8 Ga years ago (microorganisms have flourished in the oceans since at least 3.8Ga [3]). The most important episode of meteoritic impact cratering of the Earth appears to have occurred approximately 3.9 Ga, 500–600 million years after accretion [4].

With the exception of lunar and martian meteorites, practically all meteorites are assumed to come from asteroids. The asteroid belt is principally divided into two groups: the light S type (rich in silicates) asteroids within 2.6 AU and the dark C-types (carbonaceous) outside, comprising 20% and 75% of the belt, respectively. Obviously there are many subdivisions of the regions [5,6]. Astrobiologically, it is important to note that: a) carbonaceous chondrites are the closest spectral analogs available in laboratory of the carbonaceous asteroids that impacted the Earth during the Hadean eon [7]; b) most of the extraterrestrial carbon accreted by Earth is carried by the 40,000 tons of ≈ 0.2 mm micrometeorites [8], as well micron-sized interplanetary dust particles (IDPs), that enter the atmosphere every year. Petrological and geochemical studies carried out on micrometeorites indicate that the majority are carbonaceous [9,10], and c) according to [11], the abundance, compositional types and diversity of amino acids, sugars and other molecules discovered in carbonaceous chondrites support the possibility that these meteorites could have seeded our planet, with extraterrestrial organics required for the origin of life.

IDPs are either of asteroidal or cometary origin. Their small size hinders the detection of specific organic molecules. Comets are known to be rich in organic matter, presumably less altered than meteoritic carbon, but cometary organics remain poorly characterized. Therefore, the next section is dedicated to summarize the composition of organic carbon in meteorites.

2. ORGANIC MATTER IN CARBONACEOUS CHONDRITES

Carbonaceous chondrites are primitive and undifferentiated meteorites that include different clans and groups (CI, CM, CR, CB, CO, CV, CH, CK, C ungrouped) [11]. Most carbonaceous chondrites consist of spherical glass-like chondrules [12,13], embedded in a fine-grained groundmass. The chondrules and the CAIs (calcium-aluminum-rich inclusions) are at present the oldest-known material that formed in the solar nebula [14]. Among the most studied carbonaceous chondrites are Orgueil (>12 kg), fell in France in 1864, Murray (around 12.6 kg), fell in the US in 1950, Allende (>2000 kg), fell in Mexico in 1969, and of course Murchison (>100 kg), fell in Australia in 1969. The Murchison (CM2) organic inventory has become an essential reference to which other extraterrestrial organic matter may be compared. A recent very interesting carbonaceous chondrite is the Tagish Lake meteorite which fell in Canada on January 18, 2000 onto the frozen surface of Tagish Lake; its organic content [15] provides unique insight to an outcome of early solar system chemical evolution not seen so far.

Usually, carbonaceous chondrites contain up to 3 wt% of organic carbon [16]. The carbon in carbonaceous chondrites is present in several forms, with specific source regions. Materials such as silicon carbide and graphite condensed from the atmospheres of stars that existed long before our Sun. Cameron [17] was one of the first to hypothesize that carbonaceous chondrites could potentially harbor presolar grains. Diamonds were the first presolar grains isolated from meteorites and today we know that more than 3% of the total amount of carbon present in these meteorites is in the form of carbon rich presolar grains [18]. Families of carbon compounds include [19] alcohols, aldehydes, amides, amines, amino acids, carbonates, carboxylic acids, heterocycles, hydrocarbons, ketones, phosphonic acids, sulfonic acids, sugars and sugar-related compounds, being the most dominant form of carbon a high-molecular weight macromolecular material [20–22]. Although these compounds occur within the fine-grained inorganic meteorite matrix which displays signs of alteration by liquid water on the parent asteroid, it has been recently identified a preferential association with clay minerals [23,24]. The discovery is extremely important given the well known ability of clays to adsorb organic molecules and catalyse mutual reactions. Organic-inorganic interactions may have played a role in the assembly of increasingly complex organic entities 4.6 billion years ago [15,25]. Thus, it is important to coordinate the studies of organic and inorganic (mineralogy, crystal structure) compounds [26]. In broad terms, four different synthetic routes have been proposed to explain the formation (and characteristics) of the carbon compounds [19]: (1) interstellar ion-molecule reactions, (2) Fischer-Tropsch-type catalytic processes, (3) Miller-Urey-type reactions, and (4) hydrothermal transformation mediated by clays.

Probably one of the most interesting topics related with the research of organic compounds in meteorites (with fascinating astrobiological implications), corresponds to the study of the extraterrestrial amino acids as building blocks of proteins. The search for amino acids in meteorites began in the 1960s. Since then, around 70 amino acids have been identified in meteorites among the 159 possible C2 to C7 isomers [11,16,27,28]. Kvenvolden et al. [29] identified five protein and two non-protein amino acids and four of the protein amino acids were racemic. These same authors detected a further protein amino acid (aspartic acid), and 10 more non-protein amino acids, four of which were present as racemic mixtures. Later analyses [30] verified the presence and racemic nature of the protein amino acids and identified some leucines [25]. However, only eight of the 20 amino acids that life is using have so far been identified in meteorites [11]. As it is well known, in all living organism, only the L-enantiomers of chiral amino acids are utilized as building blocks for proteins and enzymes. An abiological synthesis of chiral amino acids will always yield a 'one to one' mixture of the D- and L-enantiomers. Indigenous L-enantiomeric excesses is present at least in some of the carbonaceous chondrites [24,31,32]. Modest L-enantiomeric excesses of 2-9% in 2-amino-2,3-dimethylpentanoic acid, α -methyl norvaline and isovaline, have been reported [31]. In accordance with the excellent paper by Cohen & Chyba (2000) [33] there are two main ways to explain the formation of amino acids into meteorite parent bodies. The first is through the Strecker synthetic process [34] in liquid water on the parent body itself. The second method is incorporation of amino acids into the parent body through accretion of previously synthesized molecules from the interstellar medium. The latter possibility is supported by experimental simulations of ice photo- and thermal processing of interstellar ices, leading to the formation of amino acids [35,36], although such processes might as well occur in the outer regions of circumstellar disks. Recently, diamino acids (i.e. amino acids with two NH₂ groups) produced in such experimental simulations [35], were also detected in Murchison [37].

As previously defined, the variety of organic compounds of carbonaceous chondrites constitute a valuable record of organic chemical evolution in the universe, which probably reflects a long cosmic history from stellar nucleosynthesis through complex stages of interstellar, nebular, and planetary processes that preceded life [15]. In the last section, we approach the question on the origin of carbon matter in small solar system bodies by studying in some detail the chemical structure and composition of an ubiquitous form of carbon matter, amorphous carbon.

3. AMORPHOUS CARBON IN SPACE

Amorphous carbon consists of an amorphous matrix composed of sp^2 , sp^3 , and even sp^1 , hybridized carbon atoms. Here *a*-C refers to amorphous carbon with less than 20% hydrogen. Hydrogenated amorphous carbons

(*a*-C:H) contain 20–60% hydrogen and have a low C-C *sp*³ content. The *sp*²/*sp*³ ratio, the hydrogen content, and the degree of *sp*² clustering determine the macroscopic properties of amorphous carbon [38].

The infrared spectrum due to the absorption of grains toward diffuse clouds in the interstellar medium (ISM) shows a prominent band at 3.4 μm (CH stretch in aliphatics), and bands at 6.85 and 7.25 μm (CH bending modes). These features are very well matched with the laboratory spectrum of *a*-C:H made from photoprocessing of simple aliphatic species at interstellar conditions [39,40]. Carbonaceous grains in the diffuse ISM are expected to be composed of an *a*-C:H polymer consisting of small aromatic units (1–2 rings) linked by aliphatic bridges with ratio CH₂/CH₃ ≈ 2, and low oxygen content [39,40].

Below, we provide evidence, based on infrared and Raman spectroscopy, for the presence of (hydrogenated) amorphous carbon in the insoluble organic matter of carbonaceous chondrites, such as Orgueil and Murchison, and IDPs. The results concerning IDPs were adapted from [41].

In Raman spectroscopy, the G mode is related to the in-plane bond-stretching motion of pairs of C *sp*² atoms, both in aromatic rings and olefinic chains [38]. These authors show that the D peak is a breathing mode of A_{1g} symmetry involving phonons near the K zone boundary, which becomes active in the presence of disorder. The intensity of the D peak is strictly connected to the presence of sixfold aromatic rings.

The first order Raman D and G bands of insoluble organic matter in Orgueil and four IDPs (Y, K2, K3, and N) are shown in Fig. 1, after subtraction of the continuum. The lorentzian fits of the D and G bands separately, and the sum of both lorentzians are also shown. Table 1 provides the parameter values for the fits of Orgueil, Murchison (from Murchison spectrum published in [42]), and the 4 IDPs. These are the D and G line positions and full widths at half maximum (FWHM), and the intensity ratio I(D)/I(G). The average parameter values obtained for the spectra of 11 IDPs [43], as reported in [44], are included. For each parameter, the maximum and minimum values are given in parenthesis. The Raman parameters of IDPs indicate that amorphous carbon is an important component of their carbon fraction. Using the equation valid for amorphous carbon

$$\frac{I(D)}{I(G)} = C'(\lambda) \cdot L_a^2 \quad (1)$$

where $C'(514 \text{ nm}) \approx 0.0055$ [38], the aromatic domain size, L_a , corresponding to the average IDP value of $I(D)/I(G) \sim 1$ (Table 1), is 1.35 nm (5 to 6 rings in diameter, or a total number of ~ 30 rings). For the $I(D)/I(G)$ values of IDPs with the highest deviation, 0.66 and 1.39 (Table 1), the corresponding L_a values are 1.1 and 1.6 nm (i.e. a total number of about 20 to 42 rings). The infrared spectra of IDPs (not shown) are also well fit with amorphous carbon, and provide information on the aliphatic component and the organic func-

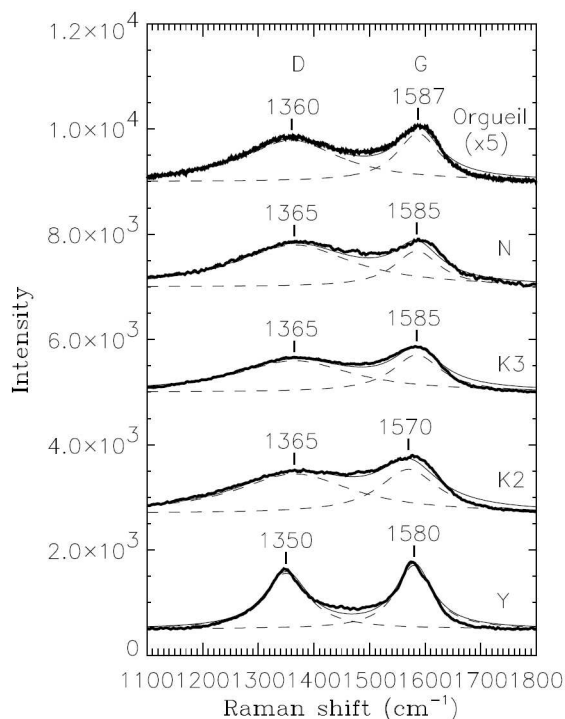


Figure 1. First order D and G bands after baseline correction (thick trace) and lorentzian fits (thin trace) for the Orgueil meteorite and 4 IDPs. The intensity of the spectra was shifted for intercomparison.

tional groups. From infrared and Raman spectroscopy of IDPs it is concluded that the bulk of the carbonaceous IDP component consists of *a*-C, or *a*-C:H for IDPs showing a prominent 3.4 μm infrared feature, with aromatic units of 20 to 40 rings in total, linked by aliphatic chains with CH₂/CH₃ ratios between 2.8–5.5, depending on the particle (for IDPs containing *a*-C:H) or a carbon *sp*³-skeleton (for IDPs containing *a*-C). This material presents relatively low O/C and N/C contents relative to organic residues made from ion or photoprocessing of interstellar ice analogs.

In general, the carbonaceous phase in IDPs show broader D and G bands than meteorites [42]. From Table 1, the FWHM of the D and G bands corresponding to Orgueil and Murchison are close to the lower limit for IDPs. The values of L_a (obtained from the $I(D)/I(G)$ values and eq. 1) for Orgueil and Murchison, respectively 1.3 and 1.1 nm (30 and 20 rings in total), fall within the IDP values. Previous determinations of L_a in these meteorites range from 8–60 rings in total for Murchison [45], 15 and 10 rings for Orgueil and Murchison respectively [46], to 4 rings for Murchison [47]. Similar to IDPs, both Raman and infrared spectra of insoluble organic matter in Orgueil and Murchison are consistent with that of *a*-C:H, although with a lower CH₂/CH₃ ratio, closer to the ISM value around 2. This conclusion is consistent with earlier characterizations: Ref. [48] describes the insoluble organic matter of Murchison as a structurally complex, extensively cross-linked, and highly ar-

Table 1. Lorentzian fit values for the D and G bands corresponding to line position, full width at half maximum (FWHM), and intensity ratio $I(D)/I(G)$.

Object	D line position (cm^{-1})	G line position (cm^{-1})	D line FWHM (cm^{-1})	G line FWHM (cm^{-1})	$I(D)/I(G)$
Y	1350	1580	96	80	0.88
K2	1365	1570	256	130	0.90
K3	1365	1585	256	108	0.84
N	1365	1585	256	100	1.17
Orgueil	1360	1590	220	94	0.87
Murchison	1360	1587	124	86	0.66
11 IDPs (average) ¹	1362 (1345-1393)	1584 (1562-1594)	296 (141-476)	104 (72-159)	1.02 (0.66-1.39)

¹ Average values of Raman parameters corresponding to 11 IDPs [43], reported in [44].

matic macromolecule. The O/C and N/C values found for Murchison are 25% and 2.9% [48].

In conclusion, amorphous carbon is abundant in the diffuse ISM, comprising 5%–30% of the carbon cosmic abundance [49]. It was also observed in lines of sight toward Seyfert 2 galaxies with spectra similar to that of the diffuse ISM [39]. As we explained above, Solar System objects like meteorites and IDPs also contain amorphous carbon. Nevertheless, the structure and composition of the material varies. Below, we attempt to sketch a possible evolutionary scenario of amorphous carbon in space.

a-C:H observed in the ISM is likely produced in the ejecta of stars, given the large collisional timescales of the ISM [40]. The fact that *a*-C:H with similar spectral infrared features is observed in Seyfert 2 galaxies, with environmental conditions that differ from the diffuse ISM in our Galaxy, indicate this material is very stable, and resists the hard interstellar UV and proton irradiation field [40]. Indeed, *a*-C:H is harder, denser, and more resistant to chemical attack than any other solid hydrocarbon ([50] and ref. therein). Could *a*-C:H in carbonaceous chondrites and IDPs have originated from diffuse ISM carbon dust? The infrared spectrum of an interstellar *a*-C:H analog annealed to ≈ 800 K [40], resembles the spectra of Orgueil and Murchison, as a fraction of the aliphatic C converted into aromatic C. However, that is not compatible with the observed O/C in these meteorites (see above), since interstellar *a*-C:H does not seem to contain much O and N. In the case of IDPs, the CH_2/CH_3 ratio is significantly larger than that of interstellar carbon dust. A possibility is that heteroatoms were later incorporated onto annealed interstellar carbon grains as accretion took place in the solar nebula. Another possibility is that the observed *a*-C:H in IDPs and meteorites is the result of thermal annealing (leading to carbonization) of the originally organic material, highly rich in O and N, formed by UV and ion processing of ice in the solar nebula [41]. The amino acids and other organic species found in meteorites might be, at least partially, original products of such ice processing in the outer regions of the disk. The latter hypothesis agrees with $^{15}\text{N}/^{14}\text{N}$ and D/H ratios measured in Solar System objects, which suggest formation temperatures of 50 K for comets and 80 K for meteorites,

i.e. higher than the typical dense cloud temperatures of 10–20 K [51].

One of the goals of the NASA Astrobiology Institute Roadmap is "understand how life emerges from cosmic and planetary precursors". Within this goal, three specific points are faced: a) to identify the different sources of organic compounds required for the origin of life, b) to resolve the origins and evolution of functional biomolecules, and c) to resolve the origins of cellularity and protobiological systems. Two hundred years of convergence between Earth and meteoritical studies, along with the spectacular scientific and technological advance in space sciences of the last half century, have permitted us to start to figure out how this happened, even before having a clear definition of what life is.

Acknowledgements

We thank the Centro de Astrobiología (CAB) for financial and institutional support, with special thanks to Prof. J. Pérez Mercader. G.M.M.C. is grateful to the Ramón y Cajal program.

References

1. Dauphas N. and Marty B. Inference on the Nature and the Mass of Earth's Late Veneer from Noble Metals and Gases, *J. of Geophysical Res.*, Vol. 107, no. E12, 5129 (2002).
2. Battistuzzi F. U., Feijao A., and Hedges S. B. A genomic timescale of prokaryote evolution: insights into the origin of methanogenesis, phototrophy, and the colonization of land *BMC Evolutionary Biology*, Vol. 4, 44, 2004.
3. Mojzsis S. J., et al. Evidence for life on Earth before 3,800 million years ago, *Nature*, Vol. 384, 55–59, 1996.
4. Kring D. A. and Cohen B. A. Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga, *J. Geophys. Res.*, Vol. 107(E2), 10.1029/2001JE001529, 2002.
5. Carroll B. W. and Ostlie D. A. *An Introduction to Modern Astrophysics*, Addison-Wesley Publishing Company, Inc., 1998.

6. Vinter Ch. and Larsson S.L., 2001
<http://www.fys.ku.dk/~vinter/projekt/main13.pdf>
7. Gaffey M. J., Burbine T. H., and Binzel R. P. Asteroid spectroscopy: Progress and perspectives, *Meteoritics*, Vol. 28, 161–187, 1993.
8. Kress M. and Brownlee D. *Chemical alteration of extraterrestrial organics during atmospheric entry of micrometeorites*. 34th COSPAR Scientific Assembly, The Second World Space Congress, 10-19 October, 2002, Houston, TX, USA., (abstract), 2002.
9. Kurat G., Koeberl C., Presper T., Brandstatter F., and Maurette M. Petrology and geochemistry of Antarctic micrometeorites, *Geochim. Cosmochim. Acta*, Vol. 58, 3879–3904, 1994.
10. Engrand C. and Maurette M. Carbonaceous micrometeorites from Antarctica, *Meteorit. Planet. Sci.*, Vol. 33, 565–580, 1998.
11. Andersen A. C., and Haack H. Carbonaceous Chondrites: Tracers of the prebiotic chemical evolution of the Solar System 2005, *International Journal of Astrobiology*, Vol. 4, 13–17, 2005.
12. Hewins R. Chondrules. *Ann. Rev. Earth Planet. Sci.*, Vol. 25, 61–83, 1997.
13. Boss A. and Durisen R. Chondrule-forming shock fronts in the solar nebula: A possible unified scenario for planet and chondrite formation, *Astrophys. J.*, Vol. 621, L137–L140, 2005.
14. MacPherson G. J., Simon S. B., Davis A. M., Grossman L., Krot A. N. *Calcium-Aluminum-rich Inclusions: Major Unanswered Questions*. In: Chondrites and the Protoplanetary Disk, eds. Krot, A. N.; Scott, E. R. D.; Reipurth, Bo, Vol. 342, Astronomical Society of the Pacific, 225–251, 2005.
15. Pizzarello S., Huang Y., Becker L., Poreda R. J., Nieman R. A., Cooper, G. and Williams M. *The Organic Content of the Tagish Lake Meteorite*, Vol. 293, 2236–2239, 2001.
16. Botta O. and Bada J. Extraterrestrial organic compounds in meteorites, *Surv. Geophys.*, Vol. 23, 411–467, 2002.
17. Cameron A. *Interstellar grains in museums?* In: Interstellar Dust and Related Topics, H. van de Hulst (ed.), Dordrecht, Reidel, 545–547, 1973.
18. Huss G. and Lewis R. Presolar diamond, sic, and graphite in primitive chondrites: Abundances as a function of meteorite class and petrologic type, *Geochim. Cosmochim. Acta*, Vol. 59, 115–160, 1995.
19. Llorca J. Organic matter in meteorites International, *Microbiology*, Vol. 7, 239–248, 2004.
20. Cooper G., Kimmich N., Bellsie W., Sarinana J., Brabham K., and Garrel L. Carbonaceous meteorites as a source of sugar-related organic compounds for the early Earth, *Nature*, Vol. 414, 879–882, 2001.
21. Hollis J., Lovas F., and Jewell P. Interstellar glycolaldehyde: The first sugar, *Astrophys. J.*, Vol. 540, L107–L110, 2000.
22. Hollis J., Jewell P., Lovas F., and Remijan A. Green bank telescope observations of interstellar glycolaldehyde: Low-temperature sugar, *Astrophys. J.*, Vol. 613, L45–L48, 2004.
23. Sephton M. A. Meteorite composition. Organic matter in ancient meteorites *Astronomy & Geophysics*, Vol. 45, Issue 2, 2004.
24. Pizzarello S., Zolensky M., and Turk K. Non-racemic isovaline in the Murchison meteorite: Chiral distribution and mineral association. *Geochim. Cosmochim. Acta*, Vol. 67, 1589–1595, 2003.
25. Sephton M. A. Organic compounds in carbonaceous meteorites, *Nat. Prod. Rep.*, Vol. 19, 292–311, 2002.
26. Rull Pérez F. and Martínez Frías J. Identification of calcite grains in the Vaca Muerta mesosiderite by Raman spectroscopy, *J. Raman Spectrosc.*, Vol. 34, 367–370, 2003.
27. Cronin J. and Chang S. *Organic matter in meteorites: Molecular and isotopic analysis of the Murchison meteorites*. In: J. Greenberg, C. Mendoza-Gomez, and V. Pirronello (eds.), *The Chemistry of Life's Origin*, 209–258, Kluwer Academic Publishers, 1993.
28. Ehrenfreund P., Irvine W., Becker L., Blank J., Brucato J., Colangeli L., Derenne S., Despois D., Dutrey A., Fraaije H., Lazcano A., Owen T., and Robert F. Astrophysical and astrochemical insights into the origin of life, *Rep. Prog. Phys.*, Vol. 65, 1427–1487, 2002.
29. Kvenvolden K., Lawless J., Pering K., Peterson E., Flores J., Ponnampereuma C., Kaplan I. R., and Moore C. Evidence for extraterrestrial amino-acids and hydrocarbons in the Murchison meteorite, *Nature*, Vol. 228, 928, 1970.
30. Oró J., Gibert J., Lichtensteink H., Wikstrom S., Flory D. A. Amino acids, aliphatic and aromatic hydrocarbons in the Murchison meteorite, *Nature*, Vol. 230, 105–106, 1971.
31. Cronin J. and Pizzarello S. Enantiomeric excesses in meteoritic amino acids, *Science*, Vol. 275, 951–955, 1997.
32. Pizzarello S. Chemical evolution and meteorites: An update. *Orig. Life Evol. Biosphere*, Vol. 34, 25–34, 2004.
33. Cohen B. A. and Chyba C. F. Racemization of meteoritic amino acids, *Icarus*, Vol. 145 (1), 272–281, 2000.

34. Peltzer E. T., Bada J. L., Schlesinger G., and Miller S. L. The chemical conditions on the parent body of the Murchison meteorite: Some conclusions based on amino, hydroxy and dicarboxylic acids, *Adv. Space Res.*, Vol. 4, 69–74, 1984.
35. Muñoz Caro G. M., et al. Amino acids from ultraviolet irradiation of interstellar ice analogues, *Nature*, Vol. 416, 403–406, 2002.
36. Bernstein M. P., Dworkin J. P., Sandford S. A., Cooper G. W., and Allamandola L. J. Racemic amino acids from the ultraviolet photolysis of interstellar ice analogues, *Nature*, Vol. 416, 401–403, 2002.
37. Meierhenrich U. J., et al. Identification of diamino acids in the Murchison meteorite, *PNAS*, Vol. 101 (25), 9182–9186, 2004.
38. Ferrari A. C. and Robertson J. Interpretation of Raman spectra of disordered and amorphous carbon, *Phys. Rev. B*, Vol. 61, no. 20, 14095–14107, 2000.
39. Dartois E., Muñoz Caro G. M., Deboffle D., and d’Hendecourt L. Diffuse interstellar medium organic polymers, *A&A*, Vol. 423, L33–L36, 2004.
40. Dartois E., Muñoz Caro G. M., Deboffle D., Montagnac G., and d’Hendecourt L. Ultraviolet photoproduction of interstellar medium dust, *A&A*, Vol. 432, 895–908, 2005.
41. Muñoz Caro G. M., et al. Nature and evolution of the dominant carbonaceous matter in interplanetary dust particles (IDPs): Effects of irradiation and identification with a type of amorphous carbon, *submitted to A&A*, 2006.
42. Raynal P. I., Quirico E., Borg J., d’Hendecourt L. *Micro-Raman survey of the carbonaceous matter structure in stratospheric IDPs and carbonaceous chondrites*, Lunar and Planetary Science XXXII, Houston, Texas, abs. 1341, 2001.
43. Wopenka B. Raman observations on individual interplanetary dust particles, *Earth. Planet. Sci. Lett.*, Vol. 88, 221–231, 1988.
44. Ferini G., Baratta G. A., and Palumbo M. E. , A Raman study of ion irradiated icy mixtures, *A&A*, Vol. 414, 757–766, 2004.
45. Kerridge J. F., Chang, S., and Shipp R. Isotopic characterization of kerogen-like material in the Murchison carbonaceous chondrite, *Geochim. Cosmochim. Acta*, Vol. 51, 2527–2540, 1987.
46. Derenne S., et al. *Abundance, size and organization of aromatic moieties in insoluble organic matter of Orgueil and Murchison meteorites*, Lunar and Planetary Science XXXIV, League City, Texas, abs. 1316, 2003
47. Hayatsu R. and Anders E. Organic compounds in meteorites and their origins, *Top. Curr. Chem.*, Vol. 99, 1–37, 1981.
48. Cody G. D., Alexander C. M. O’D., and Tera F. Solid-state (^1H and ^{13}C) nuclear magnetic resonance spectroscopy of insoluble organic residue in the Murchison meteorite: A self-consistent quantitative analysis, *Geochim. Cosmochim. Acta*, Vol. 66, no. 10, 1851–1865, 2002.
49. Duley W. W., Scott A. D., Seahra S., and Dadswell G. Integrated absorbances in the 3.4 micron CHn band in hydrogenated amorphous carbon, *ApJ*, 503, L183, 1998.
50. Walters J. K., et al. The effect of temperature on the structure of amorphous hydrogenated carbon, *J. Chem. Phys.*, Vol. 101 (5), 4288–4300, 1994.
51. Aléon J. and Robert F. Interstellar chemistry recorded by nitrogen isotopes in Solar System organic matter, *Icarus*, Vol. 167, 424–430, 2004.