Highlights of Spanish Astrophysics VI, Proceedings of the IX Scientific Meeting of the Spanish Astronomical Society held on September 13 - 17, 2010, in Madrid, Spain. M. R. Zapatero Osorio et al. (eds.)

Short-lived nuclides and stellar grains preserved in primitive meteorites, and cometary matter: some reasons to promote future sample return missions

Josep M. Trigo Rodríguez[1]

[1] Institute of Space Sciences (CSIC-IEEC), Facultad de Ciencias, Torre C-5 pares, Campus UAB, 08193 Barcelona

Abstract

Primitive meteorites contain clues on the astrophysical environment in which the solar system formed. The processing of chemical and isotopic signatures in the protoplanetary disk were preserved in the components of undifferentiated meteorites known as chondrites. The meteoritical evidence inherent to these primordial materials strongly supports that the solar system formed in a stellar association, probably under the presence of some intermediate or even massive star. Chondritic minerals also contain the fingerprints of stellar nucleosynthesis. Short-lived nuclides and stellar synthesized grains from nearby stars were incorporated into the solar nebula before the condensation of the first minerals from the hot vapor phase. Therefore, the isotopic ratios preserved in chondrites provide clues on the stellar sources that produced these nuclides, being supernovae and Asymptotic Giant Branch stars two likely contributors. A recent model has concluded that the inferred SLNs initial ratios in chondrites seems to be consistent with a 6.5 solar masses AGB star. To answer this question additional clues need to be obtained from the study of stellar grains and organic components preserved in pristine chondrites, Interplanetary Dust Particles, and future sample-returned materials from primitive asteroids and comets.

1 Introduction

Primitive chondrites contain short-lived nuclides (SLNs) that were incorporated to the solar nebula at the time of condensation of the first minerals from the vapor phase. The study of the isotopic ratios preserved in primitive meteorites provides clues on the stellar sources that produced these SLN, being supernovae and Asymptotic Giant Branch stars (AGBs) two possible contributors. A comparison between the inferred SLNs initial ratios in chondrites seems to be consistent with a model of a 6.5 solar masses AGB star where 1 part of its released gas is diluted in 300 parts of original solar nebula material. Is this an evidence that the solar system formed in a stellar association with at least one massive star? To answer this question additional clues can be obtained from stellar grains preserved in chondrites and Interplanetary Dust Particles (IDPs). All together provides information on the stellar sources that enriched the protoplanetary disk- forming materials. The survival of such stellar grains demonstrates that the solar nebula was not so hot as first researchers proposed in the 60s of last century. However, detection of small grains is challenging and perhaps hides important secrets. On the other hand, the preservation of some classes of stellar grains in meteorites has been strongly biased by physico-chemical processes suffered in their parent asteroids: metamorphism, aqueous alteration, etc. An evaluation of the primordial presolar grain abundances in the protoplanetary disk at the time these materials formed would allow a comparison with the derived from astrophysical models. Different research techniques to gain insight on these processes by studying fresh meteorites, and cometary particles will be described. I will particularly answer why the study of 81P/Wild 2 comet particles recovered by Stardust (NASA), IDPs captured in the stratosphere, or materials from primitive asteroids or comets are valuable targets of opportunity in planetary sciences.

2 Identifying primitive chondrites: why we need future sample-return missions?

Among the most primitive meteorites are these called generically chondrites. These can be considered sedimentary rocks composed of primeval aggregates that were forming part of the protoplanetary disk, containing glassy spherules, and other inclusions compacted in a fine-grain matrix. Additionally to their unique chemical and isotopic signatures, isotopic dating of different nuclides has provided formation ages 4.567 Gyr ago [2]. These components were forming part of the protoplanetary disk and, consequently, can provide information about the processes occurred in the Early Solar System (hereafter ESS) that I'll discuss in Section 3.

Up to date 14 chondrite groups have been identified (see e.g., [21]) designated with a one or two letter symbol and have a characteristic chemical composition. A few chondrites are also considered "ungrouped" as they have distinctive chemical signatures from the rest of groups. The chemical differences identified among the chondrite groups led to the idea that each group represents rocks coming from a different reservoir. This idea has been recently reinforced because relatively few chondrite breccias exist that contain clasts belonging to different chondrite groups [3]. Primitive asteroids are covered by rubble produced by continuous impacts that have excavated and fragmented their surfaces.

Inside each chemical group there are meteorites that belong basically to 6 different petrologic types. Types 1 and 2 are restricted to those groups affected by aqueous alteration at low temperatures. It is believed that these groups come from small asteroids that never suffered significant radioactive heating. Type 3 is represented by meteorites that are in the intersection of two processes: aqueous alteration and thermal metamorphism. In general type 3 chondrites experience little aqueous alteration and metamorphism, so they are considered the most pristine chondrites available in meteorite collections. Thermal metamorphism increasingly affected petrologic types 3 to 6, type 6 being the most affected by in-situ parent body heating. A comprehensive review on the thermal metamorphism experienced by all chondrite groups has been recently published by [8], while the effect of aqueous alteration in the survival of presolar silicates has been treated in [18].

The degree of thermal metamorphism and aqueous alteration is highly variable in the different chondrite groups, so it is not trivial to speak about pristine candidates. Those chondrite groups considered chemically primitive as are the CI and CMs suffered extensive aqueous alteration as reported in [17] and [14], but for the most part escaped thermal metamorphism (only a few CMs evidence heating over several hundred Kelvin). This factor is crucial as the CI and CM groups of chondrites are water-rich, and secondary minerals can form easily as consequence of the alteration of primary minerals. These minerals preferentially precipitated after water-soaking of their parent bodies, mostly growing among the pores of the matrix. These meteorites can contain up to 12% of water by weight, which, given the obvious rocky nature of these rocks, is bound in secondary minerals. These aqueously altered minerals are mainly clays with serpentine, carbonates, sulfates, sulfides, phosphates, and oxides. Other groups, like e.g. CO, CV, and CR chondrites suffered much less severe aqueous alteration, but some CRs are moderately aqueously altered. Among these groups, CO and CV are particularly good candidates to find presolar grains as they experienced moderately small heating. Thermal metamorphic grades for both groups are ranging from low (3.0) to nearly type 4 [15]. Consequently, chondrites that we could consider pristine, i.e., unaltered in their parent bodies are quite rare. Just to cite two widely recognized examples one is the CO chondrite ALHA77307 shown in Fig. 1, while another is the CM-like ungrouped Acfer094 [14]. To find pristine chondrites among the different groups of ordinary chondrites (H, L, and LL groups) is also complicated, but some examples exist like e.g. LL3.0 Semarkona, and LL3.1 Bishunpur [11].

Obviously, a precise chemical characterization of each chondrite is required before claiming that a particular specimen is pristine. We should note that chondrites are typically fragile, particularly those more porous and primitive. It is remarkable that the typical delivery mechanism is a collision with their parent body, and as these meteorites have Cosmic Ray Ages (CRAs) of million of years, the progenitor meteoroids in solar orbit are subjected to additional collisions. Consequently, our terrestrial sample is biased towards the toughest rocks, so is not surprising that the most primitive groups of chondrites are underabundant in our meteorite collections [19]. For this main reason, future sample-return missions are required to gain information about how representative are our samples of the primitive asteroids and comets out there. At the same time, the returned samples will provide additional clues on the first stages of the ESS as was the case of the successful Stardust mission to comet 81P/Wild 2 [5].

3 Clues on astrophysical processes occurred in the ESS

It was originally believed that the components of chondrites were condensed from a hot nebula vapor, loosing their record of their original stellar sources. The chemical composition of the solids initially present in this collapsing cloud likely reflected the products of stellar evolution

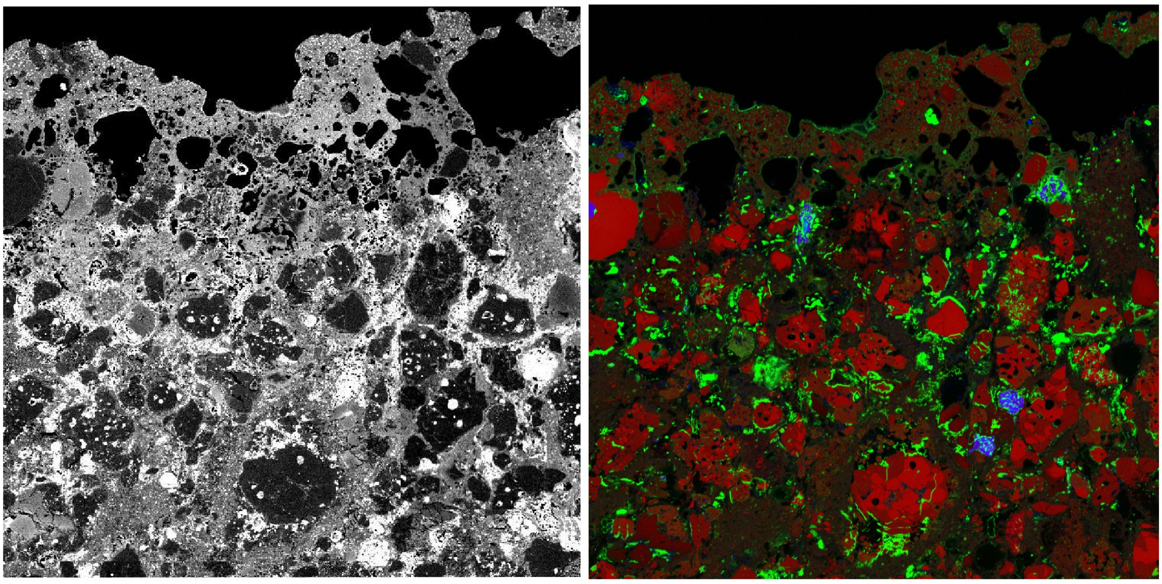

Figure 1: *Left*: A 1 mm^2 scanning electron microscope (SEM) image of a thin section of CO chondrite ALHA77307. *Right*: Composite RGB ion microprobe image (where red=Mg, green=Ca and blue=Al) built to identify the main minerals forming the chondrules, refractory inclusions and fine-grained matrix of this pristine meteorite found in Antarctica. Note that the vesicular fusion crust of about 150 microns in depth appears on top in order to exemplify that the thermal wave produced during atmospheric entry doesn't alter the meteorite inner components. This is because the extremely low thermal inertia of these porous materials.

and outflow that occurred during Galactic history [6]. The isotopic composition probably was also marked by the local environment where the solar system formed. Particularly the abundances of short-lived radionuclides (SLN, with half lives shorter than ~ 2 Myr), inferred to have been present in the early solar system (ESS), provide a constraint on the birth and early evolution of the solar system. Their short half lives do not allow the observed abundances to be explained by continuous Galactic uniform production, implying that some nucleosynthetic event must have occurred very close in time and space to the forming Sun. This is currently considered a clear evidence that our solar system formed in a stellar association or a cluster. Such anomalies have been mostly measured in Ca-Al rich inclusions (CAIs) and chondrules.

The CAIs are the oldest materials known, and are basically formed by refractory minerals like e.g. spinel, melilite, and hibonite. They are probably heated materials from the original CI-composition dist clumps that accreted in the protoplanetary disk. Interestingly, CAIs retained a variety of isotopic anomalies being rich in ^{16}O, ^{26}Al, ^{53}Mn, ^{41}Ca, and ^{87}Rb [9]. CAIs, and other refractory inclusions were probably stored in the inner edge of the protoplanetary disk, nearby or inside the reconnection ring formed by the intense magnetic field of the protosun, and subjected to periodic heating by flares that explain the so-called Wark-Lovering rims observed in sectioned CAIs [16]. These authors were also suggesting such a model to produce chondrules, but it has been recently shown that these glassy spherules

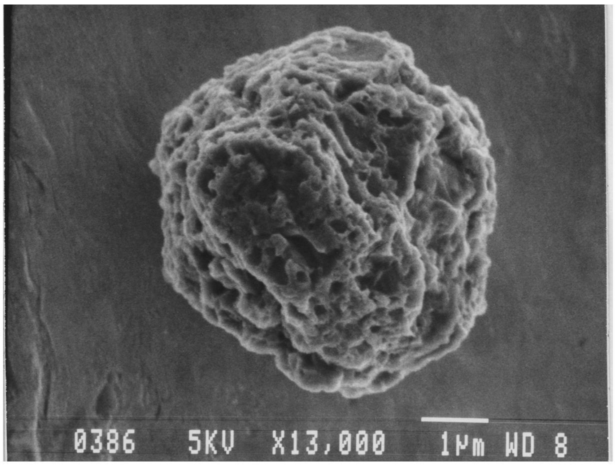

Figure 2: SiC grain. Courtesy Sachiko Amari.

can be formed in the shock fronts produced in gravitationally unstable disks at the typical heliocentric distances of the Main Belt [4].

In this context, it has been recently suggested that a 6.5 solar masses AGB star of solar metallicity played a role in the Solar System enrichment in SLNs. By comparing the SLNs abundances in primitive meteorites with the isotopic pattern modeled for the surrounding environment of that type of AGB star was found that the model matches the abundances of ^{26}Al, ^{41}Ca, ^{60}Fe, and ^{107}Pd inferred to have been present in the solar nebula by using a dilution factor of 1 part of AGB material per 300 parts of original solar nebula material. It is remarkable that such a polluting source does not overproduce ^{53}Mn, as supernova models do, and only marginally affects isotopic ratios of stable elements [20].

SLNs are not the only stellar materials preserved in primitive materials. Stellar-synthesized (presolar) grains have been identified in the matrices of chondrites, in IDPs, and in comet 81P/Wild 2 [5]. Chemical procedures were first used to extract these grains from chondrites. In this way were separated diamonds, SiC (see Fig. 2) and other chemically resistant grains contained in chondrites (see reviews by [22, 13]). However, such refractory grains are not the only presolar grains contained in chondrites as we can see in Table 1. Recent use of the nanoSIMS (Secondary Ion Mass Spectrometer) for studying the polished thin sections of primitive chondrites has allowed the in-situ identification of several hundred presolar silicates in an increasing number of meteorites and cometary materials. These presolar silicates are identified by the large isotopic anomalies exhibited relative to the other components of the matrix that are surrounding them [12, 10].

A surprising result of Stardust mission to comet 81P/Wild 2 was the identification of crystalline silicates among the particles returned to Earth in aerogel. These particles were necessarily formed in the inner disk, so important turbulence processes were operating in the protoplanetary disk. Solar wind was able to transport micron-sized silicates from the central star to the Kuiper Belt region where 81P/Wild 2 formed [5]. Other clues on interstellar and outer-protoplanetary disk processes are probably in the fine-grained materials that are

Table 1: Main types of stellar grains found in chondrites with measured abundances larger than 1 part per million (ppm). Additionally to these types other like e.g. silicon nitride, Ti and Fe-carbides, kamacite, and silicates like e.g. olivine have been identified in chondrites in abundances below few parts per billion. Data adapted from [22].

Grain type	Typical size (μm)	Abundance (ppm)	Stellar sources[a]
Diamond	0.002	1,000	SNe, AGB?
Silicon carbide	0.1–20	10	AGB, SNe, J-stars, Novae
Graphite	1–20	1–2	RG, AGB, SNe
Oxides	0.15–3	1	SNe, AGB

[a]The acronyms listed here are: Supernovae (SNe), Asymptotic Giant Branch (AGB), and novae

forming comets and carbonaceous asteroids, but many remain to be deciphered. Organic compounds are common in the matrices of CI, CM and CR chondrite groups that were presumably formed just behind the snowline. Most organics are insoluble Polyciclic Aromatic Hydrocarbons (PAHs) with considerable astrophysical interest, but aliphatic hydrocarbons, carboxylic acids and amino acids are also present in substantial amounts. In particular, the D content measured in the insoluble inorganic material (IOM) of the CI, and CM chondrite groups suggests that the water contained did not form at large radial distances [1]. The extreme D, and ^{15}N isotopic variations with respect to solar identified in these chondrites are associated with hotspots of interstellar origin. However, our sampling of primitive bodies is highly biased. An exciting recent discovery has been extreme deuterium excesses measured in IDPs of presumable cometary origin [7]. This is suggesting that outer solar system bodies can provide new clues on the processes occurred in the outer part of the protoplanetary disk. Obviously, future missions to comets could provide additional information, particularly how complex is cometary matter and how are they sampling other regions of the outer solar system. This could be mainly achieved on the basis of cryogenic sample-return.

4 Conclusions

Protoplanetary disk materials are currently available for study in our laboratories, just forming part of undifferentiated solar system bodies. The chemical and isotopic properties exhibited by chondritic asteroids and comets indicate that building materials of these bodies preserve signatures from the early solar system. However, the available samples are very limited as consequence of strong biasing associated with the fragile nature of these materials and the natural processes required to be delivered to Earth. For these reasons, other minor bodies should be explored by future space missions in order to gain insight into the astrophysical processes occurred in the ESS. Particularly future sample-return missions like e.g. Marco Polo-R, and Osiris-REX could provide fresh materials from primitive carbon-rich asteroids. Some significant progress would be achieved in the next future in the following areas:

1. Stellar environment where the solar system formed: was inside a cluster or an association?

2. Origin of isotopic anomalies in minerals: were SLNs detected in primordial materials produced by a supernova, an AGB star, or both?

3. Heating processes in the origin of CAIs: peak temperatures reached, and vapor phase interchanges.

4. Shock waves in gravitationally unstable disks, and formation timescales of chondrules.

5. The magnitude of turbulence in the protoplanetary disk: implications for the composition of Kuiper Belt comets.

6. Interstellar medium and outer disk chemistry: inherited isotopic signatures.

References

[1] Alexander, C.M.O'D., Newsome, S.D., Fogel M.L., Nittler, L.R., Buseman, H., & Cody, G.D. 2010, Geoch. Cosmoch. Acta, 74, 4417

[2] Amelin, Y., Krot, A.N., Hutcheon I.D., & Ulyanov, A.A. 2002, Science, 297, 1678

[3] Bischoff, A., Scott, E.R.D., Scott, E.R.D., Metzler, K., & Goodrich, C.A. 2006, in Meteorites and the Early Solar System II. Lauretta, D.S., and McSween H.Y., eds., p 679, Univ. of Arizona, Houston

[4] Boss, A.P., & Durinsen, R.H. 2005, ApJ., 621, L137

[5] Brownlee, D., et al. 2006, Science, 314, 1711

[6] Carlson R.W., & Lugmair, G.W. 2000, in Origin of the Earth and the Moon, Canup R.M., & Righter K. eds., p. 25, The University of Arizona Press, Tucson

[7] Duprat, J., Dobrica, E., Engrand, C., Aleon, J., Marrocchi, Y., Mostefaoui, S., Meibom, A., Leroux, H., Rouzaud, J.-N., Gounelle, & M. Robert, F. 2010, Science, 328, 742

[8] Huss, G.R., Rubin, A.E., & Grossman J.N. 2006, in Meteorites and the Early Solar System II. Lauretta, D.S., and McSween H.Y., eds., pp. 567-586. Univ. of Arizona, Houston

[9] MacPherson, G.J. 2003, in Treatise on Geochemistry vol.1. Meteorites, comets and planets. Davis, A.M., ed., p. 201, Elsevier

[10] Mostefaoui, S., & Hoppe, P. 2007, ApJ., 613, L149

[11] Mostefaoui, S., Marhas K.K., & Hoppe, P. 2004, in LPSCXXXVI, abstract #1593

[12] Nguyen, A.N., & Zinner, E. 2004, Science, 303, 1496

[13] Ott, U. 2007, Space Sci. Rev., 130, 87

[14] Rubin, A., Trigo-Rodríguez, J. M., Huber, H., & Wasson, J.T. 2007, Geoch. Cosmoch. Acta, 71, 2361

[15] Russell, S.S., Huss, G.R., Fahey, A.J., Greenwood, R.C., Hutchison, R., & Wasserburg, G.J. 1998, Geochimica et Cosmochimica Acta, 62, 689

[16] Shu, F.H., Shang, H., Gounelle, M., Glassgold, A.E., & Lee, T. 2001, ApJ., 548, 1029

[17] Trigo-Rodríguez, J. M., Rubin, A., & Wasson, J.T. 2006, Geoch. Cosmoch. Acta, 70, 127

[18] Trigo-Rodríguez, J. M., & Blum, J. 2009, Publ. Astron. Soc. Australia, 26(3), 289

[19] Trigo-Rodríguez, J. M., & Blum, J. 2009, Plan. Space. Sci., 57, 243

[20] Trigo-Rodríguez, J. M., García-Hernández, D.A., Lugaro, M., Karakas, A. I., van Raai, M., García Lario, P., & Manchado, A. 2009, Meteorit. & Planet. Sci., 44, 627 1

[21] Weisberg, M.K., McCoy, T.J., & Krot, A.N. 2006, in Meteorites and the Early Solar System II. Lauretta, D.S., and McSween H.Y., eds., p. 19. Univ. of Arizona, Houston

[22] Zinner, E. 2003, in Treatise on Geochemistry Vol.1, Meteorites, comets and planets, Davis, A.M., ed., p. 17, Elsevier