

# Carbonaceous Chondrites: Tracers of the prebiotic chemical evolution of the Solar System

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## Abstract

The astrobiological relevance of carbonaceous chondrites is reviewed. It is argued that the primitive meteorites called carbonaceous chondrites provide a unique source of information about the materials and conditions in the Solar System during the earliest phases of its history, and its subsequent evolution. Presolar dust grains extracted from the carbonaceous chondrites provide direct information on the previous generations of stars that provided the materials present for planet formation. The organic material found in carbonaceous chondrites consist of amino acids, carboxylic acids and sugar derivatives. Part of the amino acids found show L-enantiomeric excesses, which indicates that homochirality on Earth could be a direct result of input from meteoritic material to the early Earth.

## 1 Introduction

Meteorites provide a record of the prebiotic history of the Solar System during the evolution of the early Earth when life emerged. Meteorites provide the only available information on the timescales of nebular and planetary formation. Primitive meteorites (chondrites) provide important information about the chemical composition of the Solar System at its time of formation.

A rare but important subclass are the carbonaceous chondrites, they contain small amounts of interstellar dust grains that have survived the formation of the Solar System as well as a variety of organic compounds including amino acids. The most pristine of the carbonaceous chondrites have never been heated about 100° C which makes it very likely that part of the organic compounds is of an interstellar origin. The carbonaceous chondrites could therefore be a very important source of the organic material for the early Earth.

Meteorites are divided into three major classes according to their metal content; stones, stony-irons, and irons. Further subdivision is essential, because there is considerable diversity within these classes. The stony meteorites are by far the most numerous group of meteorites accounting for more than 90% of the observed falls. They are divided into chondrites, which are primitive (undifferentiated) meteorites containing chondrules, and achondrites which are evolved (differentiated as the result of heating) meteorites derived from the mantles of differential asteroids. The achondrites are the meteorites that most closely resemble certain terrestrial and lunar rocks. Chondrites are divided into three groups based on chemical composition: ordinary, enstatite and carbonaceous. Some of the carbonaceous chondrites have been exposed to aqueous alteration, that have resulted in complete recrystallization and thus removed any traces of chondrules.

## 2 Carbonaceous chondrites

The carbonaceous chondrites have compositions that are consistent with a primitive origin, i.e. Solar composition of non-volatile elements, so no igneous fractionation of the meteorite can have taken place after the formation in the Solar nebular. It is a rather rare type of meteorites with only 37 falls being recorded since 1806. The majority of the carbonaceous chondrites consist of spherical glass-like chondrules embedded in a fine-grained matrix. The matrix has had a gentle thermal history and is believed to be the (relatively unprocessed) original dust from which the planets formed.

Carbonaceous chondrites are classified in several subgroups on the basis of differences of inclusions, of water content and of hydrous phases. On average they contain up to 3 weight percent of organic carbon (Botta and Bada, 2002). More than 3% of the total amount of carbon present in these meteorites are in the form of carbon rich presolar grains (Huss and Lewis,

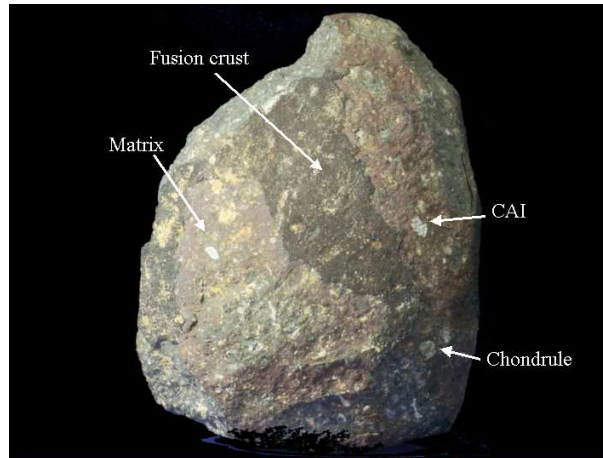


Figure 1: A fragment of the carbonaceous chondrite Allende that fell in Mexico in 1969. The meteorite is composed of dark fine grained dust, mm-sized spherical inclusions (chondrules) and white inclusions know as calcium-aluminum-rich inclusions (CAIs). The CAIs formed 4567 My ago and are the oldest known solids formed in the Solar System. Carbonaceous chondrites have preserved organic matter from the early Solar System, they probably originate from the outer part of the asteroid main-belt.

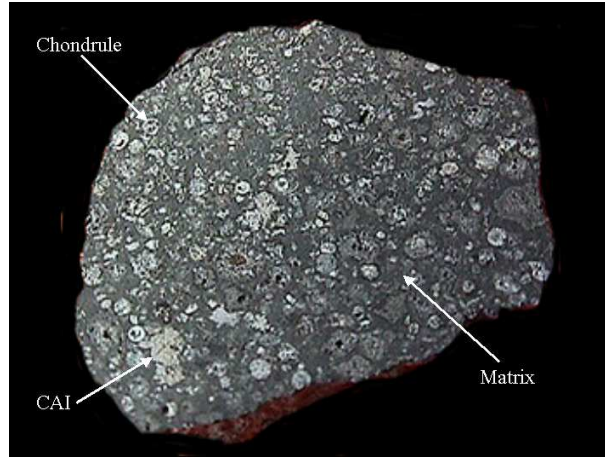


Figure 2: A polished slice the Allende meteorite disclosing the included chondrules. Chondrules are silicate and metal droplets which date back to the period when the Solar System formed. The chondrules cooled on a timescale of minutes and later stuck together with other minerals to form chondrites.

1995). Also present, is a soluble fraction of organic compounds, where the majority are comprised of polycyclic aromatic hydrocarbons (PAHs) (Botta and Bada, 2002; Gardinier *et al.*, 2000). In the quest for understanding the origin of life in the Universe carbonaceous chondrites are therefore important and easy accessible source of information.

The three most studied carbonaceous chondrites are Murchison (>100 kg) which fell in Australia in 1969, Allende (>2000 kg) which fell in Mexico in 1969 and Murray (~12.6 kg) which fell in the US in 1950. 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. These four meteorites differ in composition in such a way that it is very unlikely they all originate from the same parent body. There has therefore over the years been many different suggestion for possible parents bodies such as e.g. the asteroid 511 Davida and cometary nuclei (Hiroi *et al.*, 2005; Botta *et al.*, 2002a).

### 3 Chondrules and Calcium-Aluminum rich Inclusions

Astrobiologically relevant information about the early conditions in the Solar System can be obtained by considering the millimeter- to centimeter-sized chondrules and calcium-aluminum-rich inclusions (CAIs) within the carbonaceous chondrites. The chondrules and the CAIs are at present the oldest Solar System material known. The CAIs can be seen on Fig.1 and 2 as "white spots", while the chondrules are easily seen in Fig. 2 and 3, as spherical inclusions. The chondrules, the CAIs and the micron- and smaller-scale matrix particles appear to have been the major solid constituents of the Solar nebular, at least inside Jupiter's orbit. Their formation and assembly into chondrites provides strong constraints on processes occurring during the earliest phases of the Solar System formation.

Chondrules with relict unmelted grains or igneous rims record multiple melting events. They consist of ferromagnesian silicate particles. There are two main types of chondrules, type I which are poor in FeO and volatiles and type II which are FeO rich and have approximately Solar composition. The abundance of chondrules in the chondrite meteorites implies that melting of small particles was a common phenomenon in the early Solar System (Hewins, 1997). Understanding chondrule formation therefore has potential astrophysical and/or planetary significance.

Chondrules are currently believed to have formed 2-3 Myr after the CAIs (Hewins, 1997). However, recently Bizzarro *et al.* (2004) reported that chondrule formation processes recorded by the Allende and other chondrites could have persisted for 2-3 Myr starting contemporaneously with CAI formation in the early Solar System. This finding is consistent with both the X-wind model (Shu *et al.*, 2001) or shock wave models (Boss and Durisen, 2005) as an explanation for chondrule formation. Alternatively, chondrule formation could be reconciled with an origin as ejecta from colliding planetesimals in the accretion disk (Sanders, 1996), providing that accumulation and melting of asteroids occurred <0.2 Myr after CAI formation. Since the study by Bizzarro *et al.* (2004) indicates recurrent formation of chondrules over nearly 3 Myr it could indicate that a number of distinct processes and/or heat sources were involved in the formation history of these objects.

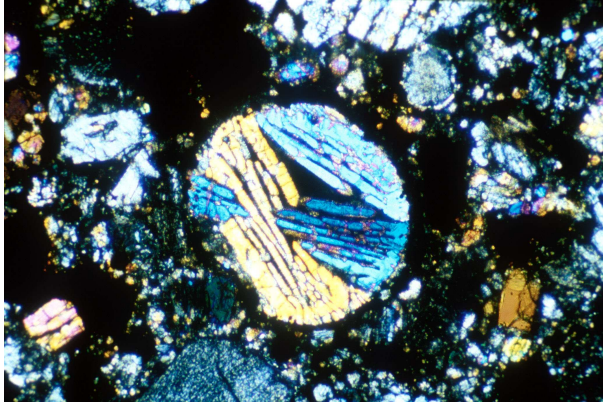


Figure 3: Close up photo of a chondrule from the Allende meteorite. The chondrule is shown in polarized light which makes it easy to distinguish the constituent minerals. Most chondrules consist of olivine or pyroxene and are believed to have formed by shock melting of the primordial dust during the very earliest part of the Solar System formation.

## 4 Presolar grains

Cosmic dust condenses primarily in the extended atmospheres of evolved stars (e.g. red giants), that slowly lose mass (Andersen *et al.*, 1999), or in novae and supernovae events. The elemental abundance available in the parent star determines the chemical composition of the condensed dust. Carbon-rich dust condense primarily in carbon stars, while silicates dominate in oxygen-rich stellar atmospheres. In oxygen-rich environments the excess oxygen to that locked in CO bearing molecules forms Si-O networks involving, e.g. Mg and Fe. The condensed dust is ejected into the interstellar medium (ISM) mainly as a result of the radiation pressure on the dust particles followed by the complete transfer of this momentum to the gas.

Carbonaceous dust in the ISM is expected to occur in diverse forms, consisting for example of amorphous carbon (AC), hydrogenated amorphous carbon (HAC), coal, soot, quenched-carbonaceous condensates (QCC), diamonds, fullerenes and other compounds (Henning and Salama, 1998). The presence of a minor fraction of some of these constituents (star dust) in carbonaceous chondrites is an important supplement to traditional astronomical observations. The strongest argument supporting that these grains are

formed outside the Solar System is their peculiar, non-solar isotopic composition.

Understanding the way that grains form and for how long they can survive in the ISM is relevant in an astrobiological context, because grain surfaces are very likely the place where chemical processes related to the prebiotic formation of molecules relevant to the origin of life on Earth can occur.

The survival and presence of genuine star dust in meteorites was not expected in the early years of meteorite studies. In the 1950s and 1960s, Solar System formation models assumed that the material from the early Solar nebular was processed and homogenized (Suess, 1965). Cameron (1973) was one of the first to speculate that carbonaceous chondrites could potentially harbor presolar grains. Finding the grains turned out to be very difficult and it lasted almost 20 years before the first presolar grain type carrier was located (Lewis *et al.*, 1987; Anders and Zinner, 1993).

Diamonds were the first presolar grains isolated from meteorites and they account for more than 99% of the identified presolar meteoritic material with an abundance that can exceed 0.1% of the matrix (Huss and Lewis, 1995). Later silicon carbide (SiC), graphite, corundum ( $\text{Al}_2\text{O}_3$ ), spinel ( $\text{MgAl}_2\text{O}_4$ ) and silicates have been identified, as well as small amounts of silicon nitride ( $\text{Si}_3\text{N}_4$ ), hibonite ( $\text{CaAl}_{12}\text{O}_{19}$ ) and  $\text{TiO}_2$ . Presolar graphite grains also often enclosed small carbide and Fe-Ni metal particles (Lodders and Amari, 2005). To date several thousand individual SiC and a few hundred graphite grains have been analyzed. The nm-size of the presolar diamonds prevents individual grain analysis, so although the diamonds are the most abundant of all the presolar grains and were discovered first, they are the least understood (Jørgensen and Andersen, 2000; Andersen *et al.*, 1998).

Presolar meteoritic grains have opened the possibility of studying stellar dust grains directly in the laboratory, providing an important complement to astronomical observations. The identification of the presolar origin of the grains is based on their highly anomalous isotopic composition which in general agrees with those expected for stellar condensates (Zinner, 1998).

The unusual isotopic properties of individual grains of silicon carbide, graphite, aluminum oxide, spinel and silicon nitride have been important in unraveling the history of the Solar System. Some grains have formed in carbon stars, some in nova or supernovae while others are of indeterminable origin. The data derived from these grains have formed the basis for studies on the development of element formation by stellar nucleosynthesis and of the migration of stars within the Galaxy (Clayton and Nittler, 2004).

## 5 Amino acids

In the 1960s radioastronomy indicated the presence of carbon-rich molecules in space. At that time, scientist had been examining and detecting organic compounds in meteorites for over a century. Kvenvolden *et al.* (1970) determined that the amino acids and hydrocarbons discovered in the Murchison meteorite had formed before the meteorite reached Earth. This was largely based on the racemic nature of the organic compounds, their isotopic composition and the presence of organic compounds rare or absent on Earth. Additional work by Oró *et al.* (1971) confirmed the racemic nature of the organic molecules in the Murchison meteorite. Epstein *et al.* (1987) examined the isotopic compositions of amino acids and other organic molecules, confirming their extraterrestrial origin and suggesting they formed in interstellar clouds. Around 70 amino acids have been identified in meteorites among the 159 possible C<sub>2</sub> to C<sub>7</sub> isomers (Cronin and Chang, 1993; Botta and Bada, 2002; Ehrenfreund *et al.*, 2002). Only eight of the 20 amino acids that life is using have so far been identified in meteorites.

The observed variations in abundance and molecular structure with increasing carbon number in the carbonaceous chondrites suggest synthesis routes involving small free radical initiators and intermediates (Cronin and Chang, 1993). These routes tend to produce all possible structural isomers at lower carbon numbers by more or less random synthesis. Primary reactions in the ISM most likely produced a mixture of nitriles and other compounds. When exposed to liquid water on the meteorite parent body, the nitriles would converge to various carboxylic acids, including amino acids (Botta and Bada, 2002; Botta *et al.*, 2002b; Ehrenfreund *et al.*, 2002). During nebular processing, the distance to the young Sun determines how much (if at all) the organic material is thermally altered within the Solar nebula. The original interstellar characteristic of organic material accreted into solid objects in the cool outer regions of the forming Solar System are expected to be rather well preserved.

Amino acids are particularly interesting since they provide a means of discrimination between a biological and non-biological origin of amino acids in meteoritic extracts. In all living organism on Earth, only the L-enantiomers of chiral amino acids are used 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 (a racemic mixture). The attempts to detect enantiomeric excesses in meteoritic amino acids (Engel and Nagy,

1982; Engel and Macko, 1997) has been very difficult due to the many possibilities of terrestrial contamination (Bada *et al.*, 1983). However, it now seems established that indigenous L-enantiomeric excesses is present at least in some of the carbonaceous chondrites (Cronin and Pizzarello, 1997; Pizzarello *et al.*, 2003; Pizzarello, 2004). Cronin and Pizzarello (1997) reported modest L-enantiomeric excesses of 2–9% in 2-amino-2,3-dimethylpentanoic acid,  $\alpha$ -methyl norvaline and isovaline, the first two have no known biological counterparts and the third has a restricted distribution in fungal antibiotics, indicating that the result of these experiments is not due to contamination.

There have also been claims of the presence of structures believed to be primitive life-forms, such as bacteria (Zhmur and Gerasimenko, 1999). Mautner *et al.* (1995) and Mautner (2002) have shown that bacteria and algae can live in nutrients extracted from the Murchison meteorite, which has been interpreted as evidence that carbonaceous asteroids can support and disperse microorganisms.

## 6 Sugars

Interstellar glycoaldehyde ( $\text{CH}_2\text{OHCHO}$ ), the simplest possible aldehyde sugar, is to date the only sugar yet detected in space (Hollis *et al.*, 2004). Glycolaldehyde is an important bio marker since it is structurally the simplest member of the monosaccharide sugars. There is currently no consensus as to how any such large complex molecules are formed in the interstellar clouds. It may be that the typical environment of dense interstellar clouds is favorable to glycolaldehyde synthesis by means of the polymerization of formaldehyde ( $\text{H}_2\text{CO}$ ) molecules either on grain surfaces or in the gas phase (Hollis *et al.*, 2000).

Cooper *et al.* (2001) have found a variety of polyhydroxylated compounds such as sugars, sugar alcohols and sugar acids in amounts comparable to the amino acids which were found. Polyhydroxylated compounds are vital to all known lifeforms where they are components of nucleic acids (RNA, DNA), cell membranes and also act as energy sources.

## 7 Summary

Carbonaceous chondrites contain the oldest known material in the Solar System. The discovery of presolar grains in these meteorites have given new insight into the formation and survival of star dust in the interstellar medium (ISM) as well as to the heating and mixing process in the early Solar System nebular. The studies of chondrules and CAIs indicate which distinct process and heat sources were involved in the formation history of the Solar System. The abundance, composition and variety of amino acids and sugars discovered in carbonaceous chondrites support the possibility that carbonaceous chondrites could have seeded the early Earth, especially near the end of the heavy bombardment 3.8 Gyr ago, with extraterrestrial organic compounds required for the origin of life.

The gas phase species and the less well characterized, but complex organic solids in the ISM point toward a sort of universality of organic chemistry. Many of the organic molecules found in carbonaceous meteorites, suggest that the basic building blocks of life were present during the formation of the Solar System.

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