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Gamma-ray Bursts and X-ray melting of material as a source of chondrules and planets(*)

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Summary. — The intense radiation from a Gamma-Ray Burst (GRB) is capable of melting stony material at distances up to 300 light years which subsequently cool to form chondrules. These conditions were created in the laboratory for the first time when millimeter sized pellets were placed in a vacuum chamber in the white synchrotron beam at the European Synchrotron Radiation Facility (ESRF). The pellets were rapidly heated in the X-ray and gamma-ray furnace to above 1400 °C melted and cooled. This process heats from the inside unlike normal furnaces. The melted spherical samples were examined with a range of techniques and found to have microstructural properties similar to the chondrules that come from meteorites. This experiment demonstrates that GRBs can melt precursor material to form chondrules that may subsequently influence the formation of planets. This work extends the field of laboratory astrophysics to include high-power synchrotron sources.

PACS 98.70.Rz – γ-ray sources: γ-ray bursts.
PACS 96.50.Mt – Meteorites micrometeorites and tektites.
PACS 97.82.Jw – Infrared excess; debris disks: protoplanetary disks; exo-zodiacal dust.
PACS 07.20.Hy – Furnaces; heaters.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Chondrules are millimetre sized, spherical objects that constitute the major component of chondrite meteorites that originate in the region between Mars and Jupiter and which fall to Earth. The meteorites are the debris from a collision that destroyed a planet. The composition of the meteorites contain information on the material that formed the planet and hence chondrules are considered to be an important stage in the

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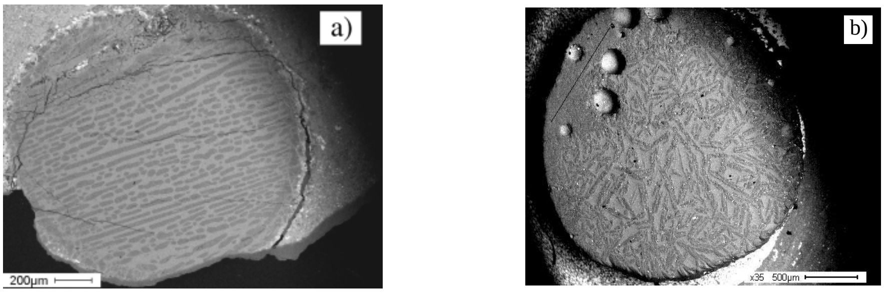

Fig. 1. – Backscattered electron microscope images of (a) a chondrule from the Allende meteorite and (b) a melted sample from the synchrotron run with randomly oriented olivene crystals and Type 1A precursor composition. Phases with higher atomic number are brighter in color. The dark grey grains are elongated olivine crystals in (a) and the brighter regions are the interstitial glassy material.

processes leading to the formation of planets. Many proposals [11] have been made for the transient heat source that melted the precursor material to form chondrules. The main processes include nebular lightning, shock waves and activities associated with the young Sun. Almost all proposed heat sources are local to the solar nebula. One exception is the proposal [3-6] that the chondrules were flash heated to melting point by a nearby GRB when iron in the precursor material efficiently absorbed X-rays and low-energy γ-rays. The distance to the source could be up to 300 light years ($\sim 100\,\text{pc}$) for a GRB with an isotropic output of 10^{46} J [9]. This distance limit was obtained using the minimum value of $2 \times 10^6\,\text{J}\,\text{kg}^{-1}$ required to heat and melt the precursor grains [13] and is equivalent to an enormous energy deposition of $10^8\,\text{J}\,\text{m}^{-2}$.

The timing, duration and conditions that led to the formation of chondrules in the solar nebula are poorly understood. The properties and thermal histories of the chondrules have been inferred from an extensive series of experiments [1]. Their mineralogy is dominated by olivine ($(\text{Mg,Fe})_2\text{SiO}_4$) and pyroxene ($(\text{Mg,Fe})\text{SiO}_3$) both being solid solutions with a wide range in composition. This diversity is consistent with the melting of heterogeneous solids or dust balls. The chemical composition, crystal structures and morphologies of chondrules have been used to limit the temperature cycle. The chondrules were rapidly heated in a few seconds, kept at maximum temperature between 1400 °C and 2000 °C for about ten seconds and cooled at a rate of a few thousand degrees per hour. The temperature cycle can be produced by a GRB and the afterglow [6]. A backscattered electron microscope image of a barred olivene chondrule from the Allende meteorite is shown in fig. 1a.

2. – Experimental method

It is now possible to create the astrophysical conditions near a GRB source in the laboratory due to the development of powerful synchrotrons. The ESRF has a 6 GeV synchrotron capable of generating the required power. A wiggler device was inserted and used to create X-rays in the range 3–200 keV. The 24-pole wiggler has a characteristic energy of 29 keV at a minimum wiggler gap of 20.3 mm. The composition of chondrules varies widely and a classification system based on the iron content is often used [11]. Type IAB chondrules have low iron content while type IA and type II have increasing amounts of iron. The pellets were made from a mixture of elemental oxides with weight percentages as given in [4, 5]. The powder was pressed into cylindrical pellets of diameter 3 mm and height of 3 mm. Each pellet was placed in a graphite crucible inside an

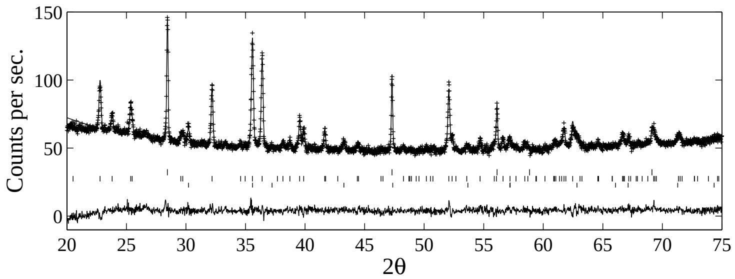

Fig. 2. – X-ray diffraction pattern of a type II sample. The data are plotted with crosses and the calculated profile is shown as a continuous line. The three sets of vertical bars in the middle of the figure are the calculated reflection positions for silicon (top), olivine (middle) and magnetite (bottom). The residuals between the data and the calculated profile are shown at the bottom of the figure indicating a very good match.

evacuated container and inserted into the path of the white X-ray beam. The size of the beam was 2 mm × 1.5 mm. The synchrotron beam entered the vacuum chamber through a Kapton window of thickness 0.05 mm. The pressure in the container was between 10^{-2} and 10^{-3} mbar, which is typical of planetary forming systems. During the heating cycle the temperature of the pellet was measured using a pyrometer with a range from 1000 °C to 3000 °C. The pellets were rapidly heated in the X-ray and γ-ray furnace to temperatures above 1400 °C. The melted samples were kept at the maximum temperature for a duration of 10 s to 300 s and cooled when the power in the beam was reduced by widening the magnets of the wiggler. The beam was removed when the temperature dropped below 1000 °C. The samples cooled rapidly to yield 2–3 mm diameter black spherules.

A Huber model 642 Guinier X-ray powder diffractometer with monochromatic Cu Kα_1 radiation was used for powder diffraction. The crystal phases were identified using the JCPDS Powder Diffraction File [4, 5]. Crystal structures were refined using Rietveld analysis in the range $20° < 2\theta < 100°$ using Rietica. For angular calibration and quantitative phase analysis, a known mass of high-purity silicon (9% to 16% by mass depending on the sample) was added as an internal standard to the powdered sample.

3. – Results

A total of 24 samples were melted and cooled in the radiation beam. A backscattered electron microscope image of one sample is given in fig. 1b.

There was a general tendency for the microstructure of the samples to reflect the liquidus temperature [11]. Type IA samples have the highest liquidus temperature of 1692 °C. The type IA samples were predominantly porphyritic in texture with smaller crystals while IAB were about equal mixture of porphyritic and acicular olivine whereas acicular olivine predominated in type II. The type IA samples had more nuclei throughout the partial melt at the start of cooling on which the crystals could grow [11]. The greater number of nucleation sites resulted in more crystals with smaller dimensions. Type II samples had the least number of nucleation sites resulting in fewer but larger crystals. The faster the cooling rate the more imperfect the crystals that formed. There is not a perfect match between the microstructure of chondrules (fig. 1a) and the samples produced in the synchrotron beam (fig. 1b). The final texture of samples depends on a range of factors [11] such as the precursor composition, maximum temperature, rate of cooling and duration of heating at maximum temperature. Further experiments are needed to explore a wider range in parameter space to obtain more observational constraints on the process.

The Rietveld plot of one sample is given in fig. 2. The sample in fig. 1b had olivine with weight percentage of 56.6% with the remainder being amorphous while the type II sample had olivine (86.2 wt-%), magnetite (7.2 wt-%) with the remainder being amorphous. The stoichiometry of the olivine is $Mg_{1.92}Fe_{0.08}SiO_4$, (*i.e.* almost pure forsterite) for the type IA sample (fig. 1b) and $Mg_{1.72}Fe_{0.28}SiO_4$ for the type II sample (fig. 2).

4. – Discussion

This experiment demonstrates that GRBs can melt precursor dust balls to form chondrules in nearby planetary forming systems. Once formed, the chondrules can move through the gas more freely and coagulate to form the building blocks of planets [2]. GRBs with durations greater than 2 s are associated with supernovae in massive stars and the formation of Kerr black holes [7, 10]. The discovery of more than 100 extra-solar giant planets has opened a range of questions regarding the mechanisms of planetary formation [12]. The probability that any planetary forming system will be blasted by a nearby GRB has been estimated [5, 6] to be about 0.1%. In the solar neighbourhood, 7% of stars with high metallicity harbour a planet whereas less than 1% of stars with solar metallicity seem to have a planet [12]. The high frequency of planetary systems implies that more than GRBs are involved and other processes may include nebular lightning and shock waves. However it has recently been shown [8] that a GRB and its post-burst emission can also cause charge separation and lightning storms in a protoplanetary nebula. This new process can melt chondrules and significantly increase the probability of interaction between GRBs and protoplanetary systems.

A GRB can reveal planetary forming systems in other galaxies because there will be short duration (~ 1 hour) bursts of infrared radiation from the melting dust when chondrules form across the whole nebula. These infrared bursts can occur for up to several hundred years after the GRB when the expanding shell of radiation melts the dust in planetary forming systems. The faint infrared bursts can be detected with powerful telescopes such as the Overwhelmingly Large Telescope and the Next Generation Space Telescope if the GRB is in a nearby galaxy.

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