Chondrules in the Short-Period Comet 81P/Wild 2

The formation of the early solar system is recorded in primitive solid materials such as meteorites and interplanetary dust particles. In 2006, the Stardust spacecraft (Fig. 1(a)) returned to Earth with many small rock particles that have been successfully recovered from a short-period comet 81P/Wild 2 (Fig. 1(b)) [1]. The particles from the comet were captured in a very low density material, aerogel. The particles are very primitive dust having been present in the outer regions of the early solar system, because short-period comets originally formed as Kuiper-belt objects that currently locate at 30-50AU from the Sun (Fig. 2). In fact, the comet 81P/Wild 2, now orbiting between Mars and Jupiter, had been circulating on a wider orbit reaching the Kuiper belt [1]. On the other hand, asteroids, much closer (3-5AU) to the Sun (Fig. 2), are

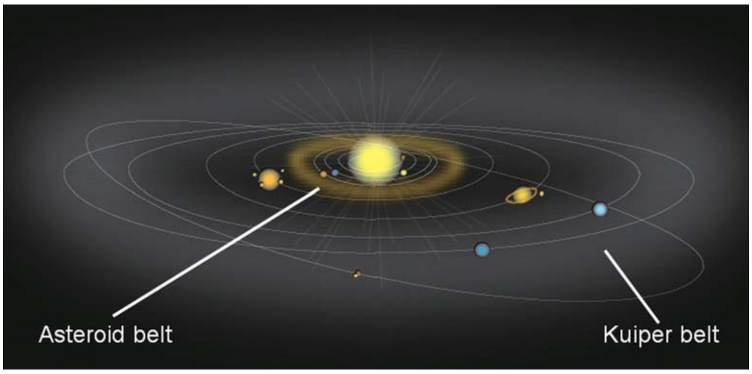

Fig. 2. Illustration of solar system showing location of asteroid belt and Kuiper belt. Short-period comets formed as small planetary bodies in the Kuiper belt.

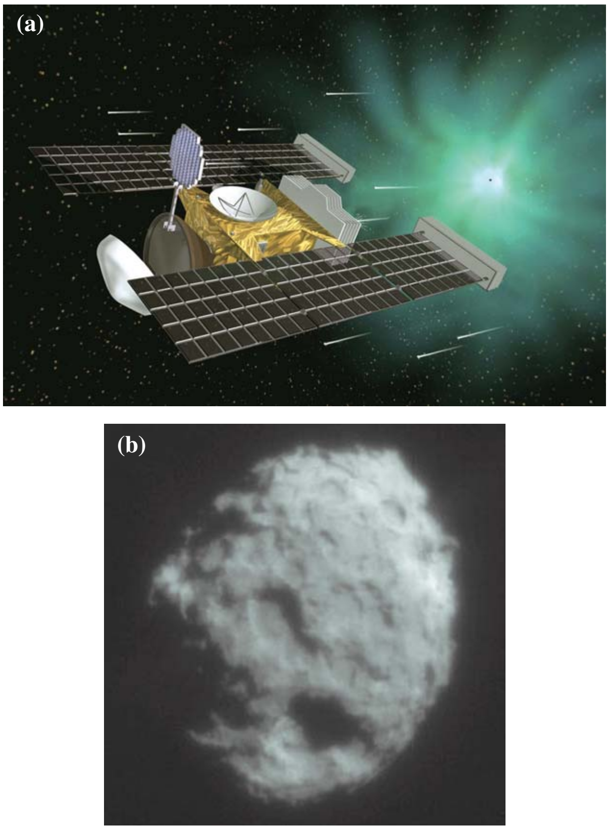

Fig. 1. **(a)** Illustration showing the Stardust spacecraft approaching short-period comet 81P/Wild 2. Small particles from the comet are captured by an aerogel grid poking out of the spacecraft. **(b)** Photograph of comet 81P/Wild 2 taken by an on-board navigation camera. This image was taken within a distance of 500 kilometers from the comet's nucleus. The diameter of the nucleus is approximately 5.5 km.

parent bodies of the primitive class of meteorites, chondrites, and they formed by the accretion of solid particles in the inner regions of the early solar nebula. Through studies of chondrites, the formation of small planetary bodies in the inner solar system is understood, but the formation of those in the outer solar system remains poorly understood. Therefore, cometary materials are the best sample for the elucidation of the evolution of outer solar system.

Chondrules are a major component of chondrites and were formed around 4.565 Gyr by the solidification of totally or partially melted Mg, Fe, Si, and O-rich silicates typically smaller than 1 mm in diameter. Abundant chondrules in chondrites, up to 80 vol% of the rocks, indicate that high-temperature heating events, that melted solid dust particles at temperatures of ~1500 °C or higher, commonly took place in the inner solar nebula. However, it is unknown whether chondrules were present in the outer regions of the early solar system.

The authors and co-investigators listed in [2,3] performed multidisciplinary analyses of small particles from the comet. The particles were first analyzed by X-ray diffraction at beamline **BL37XU** using a thin 6-keV beam to characterize bulk mineralogy. Then the particles were again exposed to a 9-keV X-ray at beamline **BL47XU** for microtomography analysis to characterize internal structures at submicron spatial resolution. Up to now, six samples were found to have bulk mineralogy rich in well-crystalline olivine, low-Ca pyroxene, and FeNi metal and to show a porphyritic internal structure suggestive of high-temperature partial melting during formation (Fig. 3(a)).

To observation of a polished surface of the six samples using a field emission scanning electron

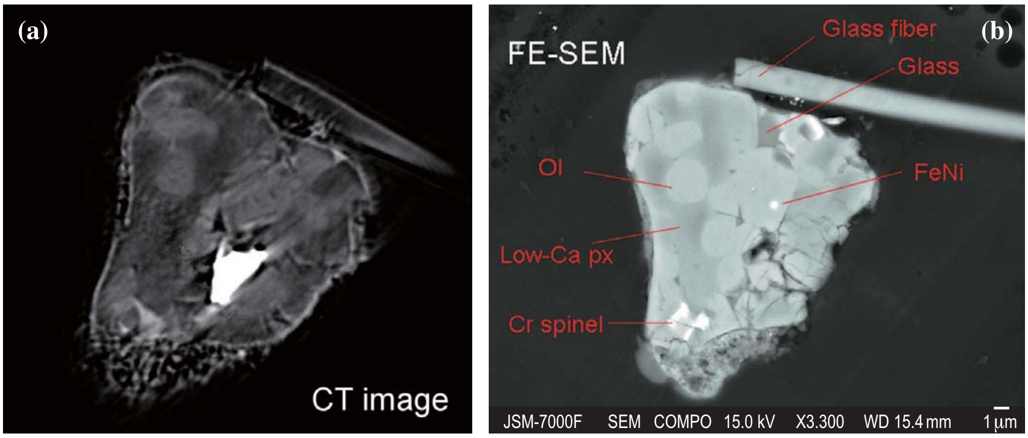

Fig. 3. **(a)** CT image of a particle C2054,0,35,6,0 (Torajiro) from comet 81P/Wild 2. This cross section is chosen to best reproduce the real image of the polished surface shown in **(b)**. **(b)** FE-SEM image of polished surface of Torajiro, showing porphyritic texture that are very similar to chondrules in chondritic meteorites from asteroids.

microscope (FE-SEM) revealed that they really show igneous texture (Fig. 3(b)) and have mineral compositions and concentrations of major and most minor elements that are very similar to those of chondrules in primitive meteorites derived from asteroids. Oxygen isotope ratios show a wide range from –50 to +5 ‰ in $\delta^{18}O_{SMOW}$, nearly along the slope = 1 mass independent fractionation line that characterizes chondrules in carbonaceous chondrites that comprise the outer asteroid belt (Fig. 4). Furthermore, highly heterogeneous oxygen isotope ratios within a single particle suggest that they formed by remelting of prexisting solid precursors. Therefore, these particles are pieces of chondrules formed through the least degree of melting, crystallization, and elemental and isotope equilibration at high temperatures. The presence of chondrules in a short-period comet from the Kuiper belt indicates that chondrules migrated from hot inner nebula regions to cold outer regions and spread widely over the early solar nebula. Our study concludes that a large-scale outward transportation of solid particles took place in the early solar system, reinforcing modifications to current models for solar system formation.

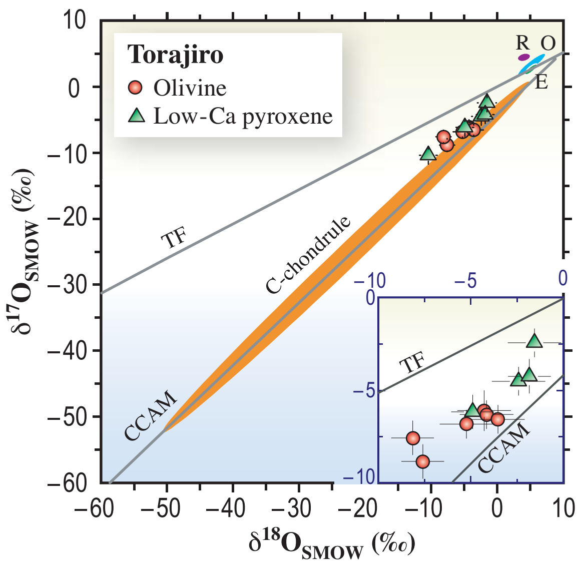

Fig. 4. Oxygen isotope ratios of olivine and low-Ca pyroxene crystals in Torajiro. The ratios are heterogeneous within the particle, suggesting that the particle formed through partial melting.

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