SYNCHROTRON RADIATION-BASED NANO-TOMOGRAPHY FOR EXTRATERRESTRIAL MATERIALS.

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Introduction: X-ray computed tomography (CT) is a non-destructive method for obtaining the 3D internal structure of an object with quantitative size information (e.g., length and volume) usually by using X-ray absorption. This method was originally developped for medical diagnostics [1] and are used in a variety of research fileds including earth and planetary science. In addition to X-ray absorption, a variety of information of X-rays such as phase diference, diffraction, fluorescence and XAFS can be used particularly if we use synchrotron radiation (SR) X-rays, which has high coherency and are easily monochromatized. Monochromatized X-rays make it possible to obtain quantitative information about absorption and phase contrasts with high S/N ratio and high spatial resolution. If we use parallel X-ray beam, the spatial resolution is limited to the wave length of visual light because the X-ray is converted to visual light to obtain projection images (micro-tomography) [2]. If we use imaging optical system with a Fresnel zone plate (FZP), nanometer-scale resolution (~30 nm) can be obtained (nano-tomography). Nano-tomography developed at SPring-8, SR facility in Japan, and its application to returned samples are introduced.

Absorption tomography and dual-energy tomography (DET): Refractive index of X-ray is expressed by n=1-δ+$i\beta$. The imaginary part, β, is the extinction coefficient, which is related to the liner attenuation coefficient (LAC), $\mu = \rho\Sigma\tau_j(E)w_j$. ρ is the material density, $\tau_j(E)$ is the mass attenuation coefficient (MAC) of element-j, which is a function of the X-ray energy, E, and w_j is the weight fraction of element-j. Thus, absorption contrast images (spatial distributions of μ) have inforamtion on the chemical compositions of objects. Elemental images can be obtained by the difference between images measured just below and above the absorption edge energy of the element (subtrtaction tomography) [3]. However, the concentration cannot be obtained without the date of ρ.

It is sometimes diffuicult to discreminate between minerals from its LAC value alone. We can discreminate many minerals by using the LAC values below and above the absorption edge energy of a specific element (dual-energy microtomography: DET) [4]. If we use the Fe K-edge energy (7.11 keV), we can discreminate Fe-poor and Fe-rich minerals as well as minerals with light and heavy elements and mineral distribution in 3D can be obtained. However, we cannot discriminate between void, organics and water because their LAC values are similar.

Phase tomography and scanning-imaging X-ray micropscopy (SIXM): The real part in the equation of n, 1-δ, is the refractive index. δ is the deviation from unity (refractive index decrement; RID) and nearly proportional to ρ. Thus, phase contrast images (spatial distributions of δ) correspond to distribution of ρ, and we can discriminate between void and organics (or water). Phase and absorption contrast images can be simultaneously obtained in 3D by using scanning-imaging X-ray microscopy (SIXM) [5]. By combining DET and SIXM, more detailed information on the 3D distribution of minerals, organic s (or water) and voids can be obtained (three-color tomography) [6].

Application to returned samples and related materials: SR-based absorption tomography has been applied to Stardust samples. Particles collected from impact tracks of comet Wild-2 dust were imaged by nano-tomography and particles selected by CT were further examined by SEM, TEM and nano-SIMS, and chondrule-like materials were found [7]. The 3D track shapes were also obtained by micro-tomography [8] and dust size and density were estimated [9]. Absorption nano-tomography was systematically used in the initial analysis of Hayabusa samples [10]. Mineral discrimination was successively made by DET and impact origin of the regolith particles were proposed from the 3D shapes [11]. By combining with FIB micro-sampling from a thin section, we can obtain 3D structures for regions of interest [12]. SIXM was applied to search fluid inclusions in carbonate grains in carbonaceous chondrites [13]. By using combined DET-SIXM, ultra-porous lithology as fossil of ice in chondrite was found in Acfer 094 meteorite [14]. We are now preparing for the initial analysis of Hayabusa2 samples collected from C-type Asteroid Ryugu, which will be returned to Earth in December 2020.

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