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Invited Review

X-ray computed tomography of planetary materials: A primer and review of recent studies

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ABSTRACT

X-ray computed tomography (XCT) is a powerful 3D imaging technique that has been used to investigate meteorites, mission-returned samples, and other planetary materials of all scales from dust particles to large rocks. With this technique, a 3D volume representing the X-ray attenuation (which is sensitive to composition and density) of the materials within an object is produced, allowing various components and textures to be observed and quantified. As with any analytical technique, a thorough understanding of the underlying physical principles, system components, and data acquisition parameters provides a strong foundation for the optimal acquisition and interpretation of the data. Here we present a technical overview of the physics of XCT, describe the major components of a typical laboratory-based XCT instrument, and provide a guide for how to optimize data collection for planetary materials using such systems. We also discuss data processing, visualization and analysis, including a discussion of common data artifacts and how to minimize them. We review a variety of recent studies in which XCT has been used to study extraterrestrial materials and/or to address fundamental problems in planetary science. We conclude with a short discussion of anticipated future directions of XCT technology and application.

Contents

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1. Introduction

X-ray computed tomography (XCT) has exploded in popularity over the last two decades as a powerful, non-destructive method to characterize objects in three dimensions. Similar to medical CAT scanning in its basic principles and underlying physics, XCT as applied in the physical sciences utilizes higher energies, smaller X-ray focal spot sizes, and/or longer acquisition times (up to a few hours) to enable higher resolution and superior quality data not attainable in medical settings where dose limitation and subject movement are concerns. In recent years, XCT technology has evolved such that smaller systems are approaching the cost of a high-end scanning electron microscope (SEM) and, thus, more academic and research laboratories are acquiring them to complement other analytical techniques.

The application of X-ray CT for non-medical research purposes began in earnest in the early 1980s after the initial development of medical instruments in the 1960s and 1970s (Hounsfield, 1973, 1976). In the planetary sciences, XCT was applied fairly early as an imaging and qualitative investigation tool for meteorites (Arnold et al., 1983; Hirano et al., 1990; Kondo et al., 1997; Masuda et al., 1986). However, limited access to XCT facilities and expertise prevented its wide application, and it was several years before the first studies aimed at addressing particular planetary problems via the 3D quantification capabilities of XCT appeared (e.g., Gnos et al., 2002; Kuebler et al., 1999; Rubin et al., 2001; Tsuchiyama et al., 2000).

As a non-destructive technique, XCT is particularly useful for documenting and analyzing rare and/or irreplaceable specimens such as meteorites or returned samples (e.g., Apollo, Stardust, Hayabusa), where sample preservation is of particular concern (Blumenfeld et al., 2015; Flynn et al., 2000; Masuda et al., 1986; Tsuchiyama et al., 2002; Zeigler et al., 2014). Using XCT, the entirety of a sample can be imaged prior to slabbing, sectioning, or distribution to museums and researchers. This not only allows digital curation of the sample but also preserves the 3D context of any subsamples to the original sample and to each other. In addition, the XCT data can be used to characterize macroscale features such as sample heterogeneity, pore structure, and/or petrofabrics that may not be noticeable or measurable with traditional 2D microanalytical techniques (e.g., Benedix et al., 2008; Friedrich and Rivers, 2013; Hanna et al., 2015; Zolensky et al., 2014).

There are several review papers that cover different aspects of XCT as it applies to various geoscientific problems (Cnudde and Boone, 2013; Ebel and Rivers, 2007; Fusseis et al., 2014; Ketcham and Carlson, 2001; Kyle and Ketcham, 2015; Wildenschild and Sheppard, 2013). A recent review by Fusseis et al. (2014) focuses on the application of synchrotron CT to geology and rock mechanics and compiles information on the major synchrotron beamlines available for research around the world, as well as helpful information on how to apply for beam time at these facilities. Wildenschild and Sheppard (2013) focus on the application of XCT to porosity measurement and include a discussion of current and future XCT hardware technology. A more generalized review of XCT in geosciences using both X-ray tubes as well as synchrotron X-ray sources is given by Cnudde and Boone (2013). Ebel and Rivers (2007) provide an informative review of meteoritical investigations and applications, mainly using synchrotron-based XCT, including details on an XCT beam line (13-BM-D) at the Advanced Photon Source (APS) at Argonne National Laboratory. The present contribution provides an updated overview of XCT investigation of planetary materials with emphasis on more widely used and available lab-based XCT systems.

Our primary goal is to acquaint the general planetary and geochemical science communities with XCT as it applies to extraterrestrial materials, including details on data acquisition and its optimization for different curatorial and research goals. Because of the proliferation of laboratory-based polychromatic cone-beam XCT instruments (in contrast to more specialized systems with synchrotron sources or a helical acquisition geometry), we will focus on the technology, imaging geometry, and data artifacts that are characteristic of these systems, but provide additional details as well as case studies that utilize others. We first give an introduction to the underlying physical principles of XCT, the common components of a laboratory cone-beam system, and how data acquisition parameters are determined and the various trade-offs encountered. We present the numerous ways XCT data can be processed, corrected, visualized, and quantified, with particular emphasis on common data artifacts that are inherent when using polychromatic cone-beam instruments. We then present several recent case studies of how XCT data have been used to address various planetary science problems, and conclude with a short discussion of the future trajectory of XCT. Our intention is that this review serves as a useful primer for planetary scientists to optimize their own XCT data acquisition, be better prepared to interpret and analyze XCT datasets, and be inspired to use this powerful technique to address problems in their own research.

2. Principles and physics of XCT

2.1. X-ray generation

The easiest way to generate X-rays is to bombard a target material (usually a high-atomic-number metal such as tungsten) with high-energy electrons produced by a heated filament, as in a standard X-ray "tube". A continuum of X-ray energies is produced due to various interactions of the incoming free electrons with bound electrons in the target material. The most dominant interaction produces so-called bremsstrahlung radiation, in which incident electrons decelerate due to interactions with target nuclei (bremsstrahlung arises from the German word *bremsen* for brake). The energy of the resulting radiation depends on the amount of electron kinetic energy transferred by this interaction, and so the X-ray radiation emitted features a broad spectrum of energies up to the maximum energy of the incident electrons (i.e., it is polychromatic). The maximum energy is generated when an electron actually collides with the nucleus and all of its kinetic energy is converted to X-ray radiation, although the probability of such a collision is low, which is why the majority of the radiation is emitted at lower energies (Fig. 1) (Hsieh, 2009). The X-ray tube voltage setting represents the electric potential applied across the chamber that will accelerate electrons up to this maximum energy. For example, if the tube voltage is set to 200 kV, the filament electrons will be accelerated fast enough to generate X-rays up to 200 keV,