MUON RADIOGRAPHY AS A PROBE OF THE INTERIOR STRUCTURE OF SMALL SOLAR SYSTEM BODIES.

R. S. Miller[1] and D. J. Lawrence[2], [1]University of Alabama in Huntsville (richard.s.miller@uah.edu), [2]Johns Hopkins University Applied Physics Laboratory (david.j.lawrence@jhuapl.edu).

Introduction: We are developing a new approach to the study of Small Solar System Bodies (SSSBs): cosmic-ray induced muon radiography. This technique will enable remote determination of the density and three-dimensional structure of SSSBs using the muons generated naturally by cosmic-ray interactions in these planetary bodies.

The fundamental feasibility for the muon radiography approach has been established by leveraging experience in space- and ground-based cosmic-ray physics, planetary science, and radiographic analysis techniques,. In addition, we have defined top-level requirements specifications and performance measures for a dedicated mission concept utilizing this new exploration capability. Once fully implemented this concept will:

- Remotely measure density and structure variations for meter- to kilometer-scale asteroids and/or comets.
- Uniquely enhance our understanding of the early solar system by providing new measurements of density, macroporosity, and other structural features of SSSBs.
- Provide critical inputs to computational models of Near Earth Objects (NEOs) for impact avoidance strategies.
- Support efforts related to asteroid retrieval, mining, and in situ resource utilization.

Background and Motivation: SSSBs such as asteroids are remnants of the early solar system. Our understanding of these objects has changed significantly over the past few decades with investigations of asteroid surfaces dominating these new insights. Studies of surface composition, crater morphologies, and other physical properties by flyby and rendezvous missions have contributed to a deeper understand our solar system's formation and evolution. However, in contrast to these surface studies there has been no direct measurement of their internal structure (Figure 1), which remains largely unknown.

For over 50 years a variety of theoretical (e.g. [1, 2]) and dynamical studies have suggested that some asteroids and comets might be "rubble piles", the by-product of high velocity collisions, instead of solid objects. Indirect observational evidence supporting this process of formation by gravitational re-accumulation comes primarily from optical and radar imaging and includes [3] low bulk-densities, rotational measurements, and the presence of large craters.

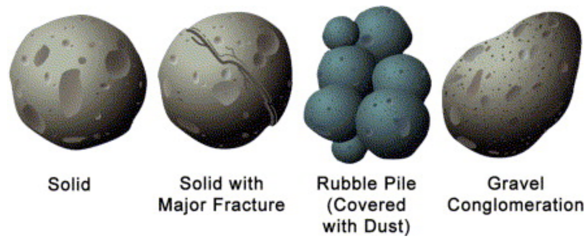

Figure 1. Possible asteroid internal structures [4].

These indirect measures are intriguing but not definitive, leaving critical knowledge gaps that affect solar system science, remote characterization, and impact avoidance protocols. A mission utilizing muon radiography will directly probe the *interior* of these objects.

Muon Radiography: The fundamentals of muon radiography are well-understood and have been validated in terrestrial applications. For example, it was recognized as early as the 1950s that muon radiography could be used as the basis for unique imaging experiments such as the search for hidden chambers within Egypt's pyramids [5]. More recently this technique has been used to search for special nuclear mate-

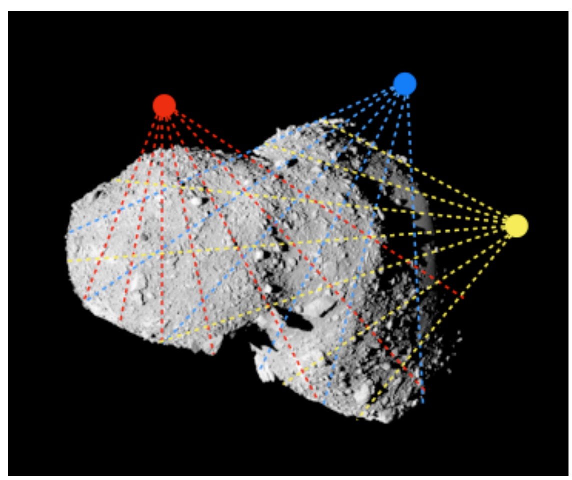

Figure 2. Conceptual diagram of muon radiography technique. Muons traverse paths (lines) through asteroid and may be detected by a muon telescope (circles). Radiographic reconstruction techniques enable a determination of interior structure.

rials [6] and to determine the density distribution within terrestrial volcanos [7].

Conceptually, muon radiography is analogous to the X-ray computed tomography (CT Scan) used in medical imaging. Here muons are differentially absorbed as they propagate through a heterogeneous body. The probability of this absorption depends directly on the thickness and density distribution within the target object. Advanced radiographic analyses use the measured transmission data to produce 3-dimensional structure and density determinations independent of any assumed object models.

The principal measurement of the radiography technique is muon transmission. Continuous cosmic ray bombardment of the SSSB generates muons from the decay of secondary mesons created by the interactions with matter. Muons transmitted through the target body may be detected by an orbiting muon telescope (Figure 2) to produce a database of muon trajectories that serve as inputs to a radiographic structure analysis to produce a 3-dimensional map of interior structure. An enabling feature of this approach is the extended range of muons through dense media. At the multi-GeV energies of interest here path lengths varying from meters to kilometers are achievable, dependent only on the particle's energy and the composition along the muon's path through the target body.

Simulations: To evaluate feasibility and study the performance of the muon radiography concept an integrated set of simulation and analysis tools has been developed. The simulation is made up of four key elements: an SSSB structure and composition model, cosmic-ray induced muon flux generation [8], muon transport simulation, and finally detection. This suite of tools has been used to create virtual muon datasets that enable for a variety of scenarios and facilitate implementation tradeoffs, the establishment of top-level mission requirements specifications, and estimation of performance measures. These datasets are an approximation to the fundamental data product that would be acquired in a real-world implementation.

Structure Reconstruction. Radon transform techniques form the basis of the density reconstruction. Muons that survive transport through the target body are used to produce a set of radiographic intensity projections at a range of angles (θ, φ). These radiographic projections, or slices, are the inputs to a full 3D reconstruction. One reconstruction example, a sphere (ρ=1.8 g/cm^3) with an interior void, is shown in Figure 3. The structure determination capabilities of muon radiography are evident.

Summary: The feasibility of cosmic-ray induced muon radiography as a probe of SSSBs has been studied. Top-level performance metrics, tradeoffs, and requirements specifications have been derived using a suite of simulation and data analysis tools that enable 3D density reconstruction. We will report these detailed measures, limitations of the approach, and how such an approach could be implmented.

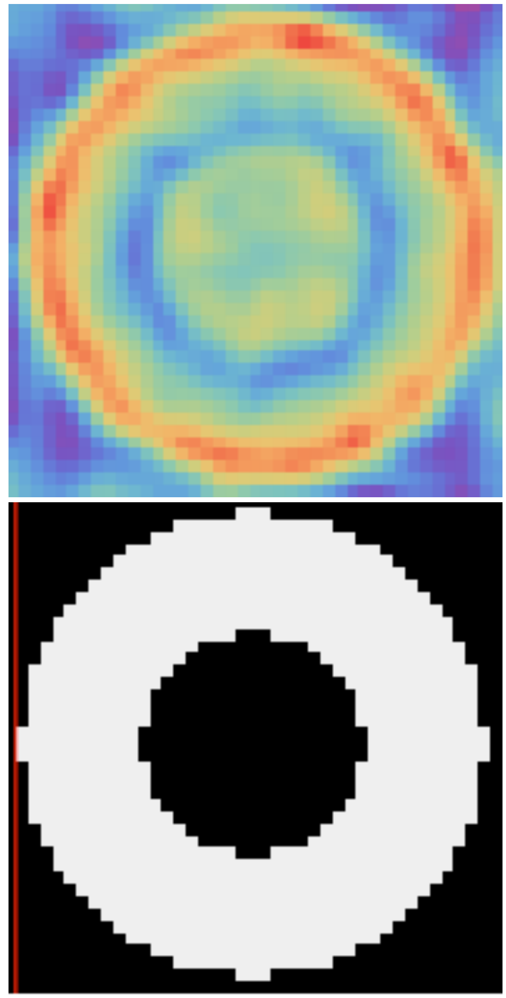

Figure 3. Example radiographic reconstruction using muons. Actual structure (bottom) is a sphere (ρ=1.8 g/cm^3) with interior void. Volumetric reconstruction using muon simulations (top). Object diameter is 100 m and color scale represents detected muon intensity.

References: [1] Jeffreys, H. (1947) MNRAS, 107, 260. [2] Opik (1947), Irish Astronomical Journal, 1, 25. [3] Batatin, A.C. (2008) Mem. S.A. It. Suppl., 12, 150. [4] Walkers, J., et al. (2006) Adv. Space Sci 37, 142. [5] Alvarez, L.W., et al. (1970) Science 167, 832. [6] Morris, C.L., et al. (2008) Science and Global Security 16, 37. [7] Hiroyuki, K.M., et al. (2010) J. Geophys. Res. 115, B12331. [8] Miller, R.S. and Cohen, T. (2006) Astroparticle Physics 25, 368.