ORBITAL HIGH PURITY GERMANIUM (HPGe) COMPOSITION MEASUREMENTS OF CARBONACEOUS ASTEROIDS.

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Introduction High Purity Germanium (HPGe) gamma ray spectrometers [1,2] have very successfully mapped the surface and near-subsurface bulk elemental compositions of Mars and Mercury. The powerful technique represented by these heritage instruments can also be applied to determine the surface and near-subsurface bulk elemental compositions of carbonaceous asteroids and other small bodies.

Unlike visible/near infrared (VNIR) or X-ray spectroscopy, detected gamma rays and neutrons are produced at ~30-50 cm (depending on regolith density) below the surface of a planetary body, thus allowing orbital measurements significantly deeper than the optically active layer. On Mars this was critical to the discovery from orbit by The Mars Odyssey Gamma Ray Spectrometer (GRS) of extensive high-latitude subsurface ice deposits underneath a centimeters-thick desiccated surface layer. Similarly, on asteroids the optically active layers may be devolatilized or otherwise altered by thermal or other space weathering processes.

Gamma ray measurements are thus complementary to VNIR and X-ray observations and can be made using remote sensing instruments from a Dawn-like low altitude (altitude ~ radius) orbit above an asteroid. Various gamma ray detector technologies are available. Here we focus on the capabilities of the HPGe detectors due to their unparalleled energy resolution and sensitivity. High heritage designs exist based on the successful Mars Odyssey [1] and MESSENGER [2] instruments.

Reuse of the Mars Odyssey GRS Design: The Mars Odyssey GRS was launched in 2001 and performed excellently in orbit for seven years, after which the Odyssey orbit was altered in such a way that the GRS could no longer operate. The detector was successfully annealed multiple times to effectively maintain the 4.1 keV FWHM energy resolution at 1332 keV that it achieved during cruise. Although the Odyssey GRS was launched in 2001, its design and flight spare hardware have been carefully curated at the University of Arizona. With almost all of the design drawings still currently available, a rebuild of the Odyssey GRS is entirely practical. A build-to-print philosophy is realistic in this case because the original engineering team that designed, built, and tested the GRS is still intact at the University of Arizona. A complete flight spare GRS has also been kept in a class 10,000 clean room since launch and, along with accompanying ground support equipment, is available for use in validating the rebuilt electronics. The flight spare passive cooler is also available for reuse. We will present further evidence that the reuse of the Odyssey GRS for a new asteroid mission is practical and low-risk. Figure 1 is an illustration of the Mars Odyssey GRS sensor head.

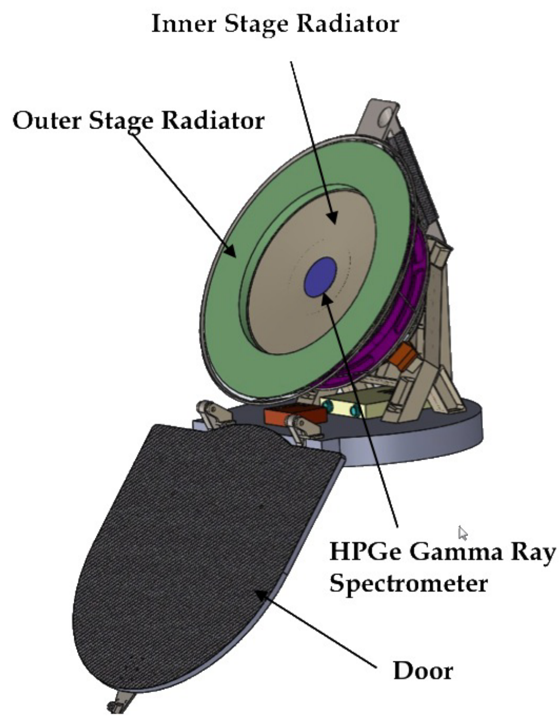

Figure 1. Mars Odyssey GRS Sensor Head

Basis of the Technique: Gamma ray spectrometers measure subsurface composition from orbit by measuring the energies and intensities of the gamma rays emitted by the asteroid as a result of its bombardment by Galactic Cosmic Rays (GCR). GCR protons interact with the asteroid surface materials to produce high-energy neutrons within the topmost few meters. These neutrons subsequently interact with the atomic nuclei of the asteroid materials to produce characteristic gamma rays at energies specific to the nuclei involved. A Gamma Ray Spectrometer (GRS) must measure the energy of these 0.2 – 10 MeV gamma rays with excellent precision to identify all of the elements present.

The abundance of each element is determined by the count rates in specific energy peaks in the GRS spectra.

Gamma ray spectroscopy can determine the complete subsurface elemental composition of an asteroid including elements such as H, C, O, Na, Al, Si, P, S, Cl, K, Ca, Fe, Th, and U. (Mg and Ti also produce useful gamma rays, but because the Odyssey GRS contains substantial amounts of these elements in its structure, the Odyssey GRS has high background counts in these lines. Chondritic Ti is low in any case.)

Measurements of H, Cl, C, S, Si and O will be particularly valuable for determination of the volatile and organic content of these asteroids and coarse mapping of their subsurface distribution.

Due to its low band gap energy (0.7 eV), the resulting low energy required for per electron-hole pair (3.0 eV), good stopping power and its extreme material purity, HPGe semiconductor gamma ray spectrometers provide the best available energy resolution for measurements in the 0.2 – 10 MeV energy range (Figure 2). The low bandgap energy, however, requires detector operation at cryogenic (75 – 90 K) temperatures so that noise from current due to thermal excitation of charge carriers doesn't swamp the signal.

The GRS to be presented is a HPGe gamma ray spectrometer that is a direct copy of the Mars Odyssey (MO) GRS, the largest and most sensitive HPGe detector ever flown on a planetary mission. The Mars Odyssey GRS is a cylindrical, coaxial (6.7 cm diameter, 6.7 cm long) HPGe detector operated at 85 K. This operating temperature is reached via a high-heritage (Mars Odyssey, WIND/TGRS) passive cooler that is designed to radiate heat into cold space to achieve cryogenic temperatures without any moving parts or power requirements. This two-stage radiative passive cooler surrounds the HPGe detector and is shown in an illustration of the GRS sensor head in Figure 1.

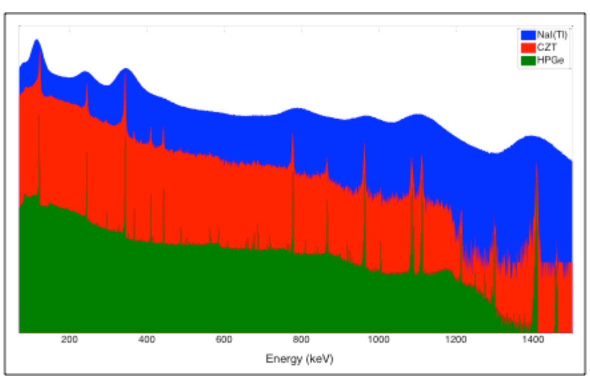

Figure 2. *The spectral performance of HPGe detectors (green) is shown to be superior to CZT (red) and very significantly improved over NaI(Tl) (blue) scintillators. The narrowness of the spectral peaks is the key feature shown in this comparison of detector response to a ^{152}Eu source. Note that the spectra are vertically offset to make these performance differences more clear.*

Monte Carlo Computer Simulations: We have estimated the science performance of a MO GRS-like HPGe experiment in orbit around asteroids with model compositions corresponding to those of carbonaceous chondritic meteorites at levels of hydration ranging from CI-like (~17 wt% structural water) to CO-like (<2 wt% structural water).

The Monte Carlo N-Particle eXtended (MCNPX) radiation transport code [3-5] was used to simulate the GRS gamma ray measurements with high fidelity. The observing geometry was a Dawn-like orbit in which the orbital altitude was equivalent to the asteroid radius. In addition to the gamma ray flux from the asteroid itself, the simulation also included spacecraft background due both to direct GCR/spacecraft interactions and to asteroidal neutron flux interacting with the spacecraft. The spacecraft was modeled as a Dawn-like aluminum bus with xenon and hydrazine tanks. The MO GRS is modeled as fixed at 1 m from the nadir spacecraft deck.

The MCNPX asteroid spectra were summed with the MCNPX background simulated gamma ray spectra and applied to the MO GRS detector model. Finally, a realistic energy resolution was applied based on the Mars Odyssey in-flight energy resolution (4.1 keV FWHM at 1332 keV). Doppler broadening of lines was also applied where appropriate.

Carbonaceous Asteroid Modeling Results: The low-albedo asteroids (*e.g.* C-complex, D, and P spectral types) that dominate the outer Main Asteroid Belt, Hildas, and Trojan clouds are thought to be related to carbonaceous meteorites (carbonaceous chondrites and ureilites). However, carbonaceous meteorites include several very different rock types and it remains unclear which subclasses represent which asteroids or asteroid (or cometary) populations. Because the variation in abundances of hydrogen, oxygen, and other light elements among carbonaceous meteorites influences the neutron population that is the parent population of the gamma-ray spectrum, it cannot be assumed that line strengths vary linearly with composition. Thus, several Monte-Carlo simulations were conducted.

We find that asteroids can be identified as having CI-like vs. CO-like compositions in H/Si, O/Si, S/Si, and C/Si with MO GRS within 4.5 months in a Dawn-like low altitude mapping orbit. In addition, the Fe/Si and S/Si sensitivity are sufficient to distinguish CO and other low-hydrogen carbonaceous chondritic compositions from achondritic carbon-rich (ureilitic) compositions. Finally, since gamma ray spectrometers are especially sensitive to the elements chlorine and potassium, hypotheses that suggest salt lag deposits on asteroids can readily be tested [6].

Comparison of simulation results with in-flight MO GRS count rates: The relationship between the new MCNPX simulations and the in-flight MO GRS count rates will be discussed in detail. Gamma-ray count rates in Mars orbit benefited from a more favorable spacecraft/planet geometry (higher solid angle) than is likely to be achievable at an asteroid, but suffered from substantial attenuation in the Martian atmosphere. Atmospheric attenuation in Mars orbit ranges from a factor of ~3.5 at 7 MeV to over a factor of 10 at 847 keV. Moreover, Odyssey spectra were not analyzed for carbon or oxygen because of the challenge of separating atmospheric from surface signal. In addition, the high levels of hydrogen in Orgueil-like and Murchison-like (CI and CM) carbonaceous chondrites thermalize a large number of neutrons, thus enhancing the fluxes of various neutron capture lines. In particular, the neutron capture lines of carbon at 4945 keV and of sulfur at 5420 keV become more useful at high hydrogen concentrations.

Conclusions: An orbital MO GRS would be an excellent probe of the elemental composition of carbonaceous asteroids. Leveraging NASA's investment in this high heritage, high performing instrument would yield unprecedented asteroid gamma ray spectra that would be instrumental in understanding the subsurface volatiles composition and securing the connection between different asteroid types and the large variety of meteorites that have been collected on Earth.

References: [1] Boynton, W. V. et al. (2004) *Space Science Reviews, 110*, 37–83.; [2] Goldsten, J. O. et al. (2007) *Space Science Reviews, 131*, 339–91.; [3] Pelowitz, D. B. ed. (2005), "MCNPX User's Manual, Version 2.5.0", *Los Alamos Natl. Lab., Los Alamos, N. M., Rep. LA-UR-94–1817*, 473.; [4] McKinney, G. W. et al. (2006), *J. Geophys. Res., 111.;* [5] Evans, L. G. et al. (2012), *J. Geophys. Res. Planets, 117.;* [6] Yang, B. et al. (2013), *Icarus, 223,* 359–66.