Measuring Bulk Carbon, Hydrogen, and Sulfur from Orbit: Modeling Gamma-Ray Spectroscopy of Carbonaceous Asteroids. Lucy F. Lim[1], Richard D. Starr[1,2], Larry G. Evans[1,3], Ann M. Parsons[1], Michael E. Zolensky[5], William V. Boynton[6], [1]NASA Goddard Space Flight Center, (lucy.f.lim@nasa.gov), [2]Catholic University of America, [3]Computer Sciences Corporation, [4]NASA/JSC, [5]University of Arizona

Carbonaceous meteorites differ substantially from one another in degree of hydration and in their bulk abundances of carbon, sulfur, and various other elements. Levels of hydration in carbonaceous chondrites range from >17 wt% in the CI chondrites [1, 2] to essentially zero in the CK and reduced CV subclasses. Bulk carbon (Fig. 1) can range from <0.5% in the CK chondrites to > 4% in Tagish Lake [3, 4] and bulk sulfur from <1% in CKs to >5 wt% in CI chondrites [2].

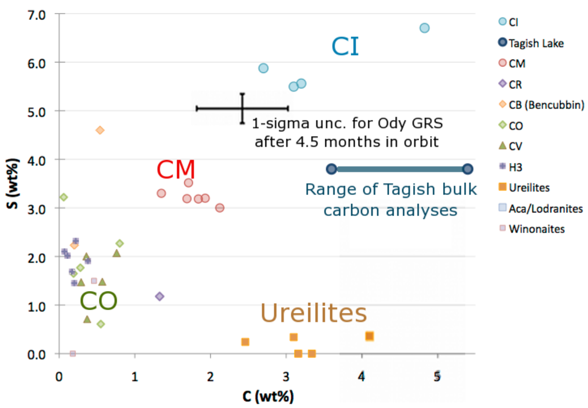

Figure 1: Orbital GRS experiments can measure bulk sulfur and carbon at the levels found in carbonaceous meteorites. Meteorite composition data from [1, 2, 4, 5]. Sensitivities reflect the end-of-mission energy resolution of the Odyssey GRS, FWHM=5.7 keV at 1332 keV.

In order to find out whether these differences in bulk composition could be measured by an asteroid or comet orbiter, we have modeled the performance of an orbital gamma-ray spectrometer (GRS) experiment in a Dawn-like orbit around various model asteroids: e.g., the orbital altitude was equal to the asteroid radius for 4.5 months. Because the GRS is sensitive to depths below the optical surface (to ≈20–50 cm depth depending on material density), this technique can potentially see beneath a sulfur-depleted [6] or dessicated surface layer to provide a better estimate of bulk composition.

Monte-Carlo Model: We applied the MCNPX Monte-Carlo radiation transport code [7] to simulate natural galactic cosmic-ray (GCR)- induced gamma-ray production in the surfaces of five model asteroids with compositions based on each of four types of carbonaceous chondrites and on a ureilite (a carbonaceous achondrite). We then modeled a spacecraft background based on a Dawn-like spacecraft model, also using MCNPX: background spectra were produced both by direct GCR/spacecraft interactions and by the interaction of the GCR-induced asteroid neutron emission with the spacecraft. Finally, the same Monte-Carlo code was used to model the interaction between the summed source and background spectra and the gamma-ray detector, which we based on the most sensitive heritage flight GRS, the Mars Odyssey Gamma-Ray Spectrometer [8]. The large detector size and high energy resolution (0.3% at 1332 keV during its prime mission) of this instrument made it the most likely of any heritage GRS instrument to be able to detect carbon, sulfur, and other minor elements in carbonaceous asteroids (Fig. 2). However, we modeled a MESSENGER-like deck-mounted instrument configuration in which the spacecraft background is much higher than in the boom-mounted Mars Odyssey flight experiment.

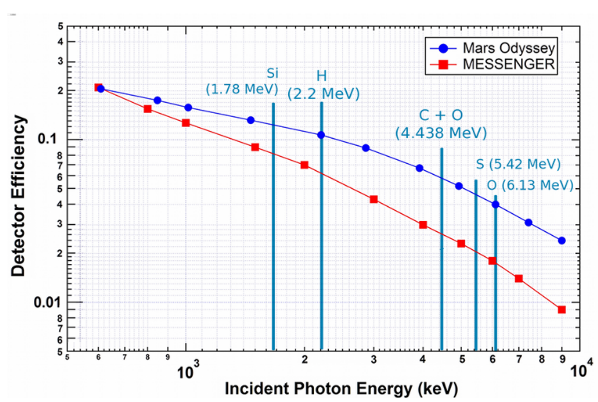

Figure 2: Detection efficiencies of two successful heritage HPGe (high-resolution) gamma-ray instruments: the 6.7-cm Mars Odyssey Gamma-Ray Spectrometer and the 5-cm MESSENGER Gamma-Ray Spectrometer [9]. The larger size of the Odyssey GRS enables high sensitivity to high-energy gamma-ray lines, including the 4.4 MeV line of carbon and the 6.13 MeV line of oxygen. Both of these lines are needed to determine carbon abundance.

Doppler broadening and the detector resolution were applied to the spectra based on either the 4.1 keV prime mission or the 5.7 keV end-of-mission in-flight energy resolution of the Odyssey GRS, and peak fluxes then extracted and uncertainties estimated using the same methods that were applied to the flight data [10]. (Fig. 3)

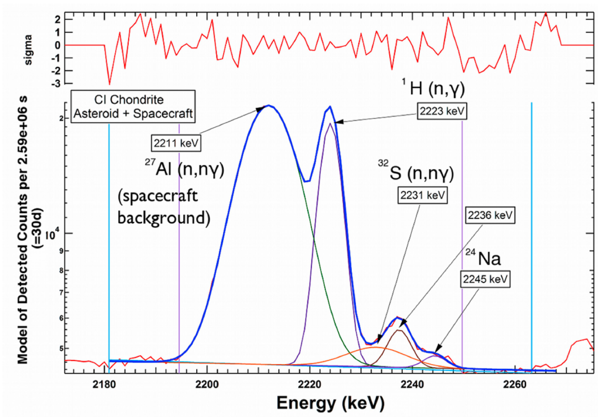

Figure 3: Fitting of the gamma-ray lines in the complex hydrogen region (2223 keV) of the CI chondrite model spectrum. The large Doppler-broadened peak is aluminum from the spacecraft background. Nevertheless, the hydrogen line is strong enough (1.7 cpm) to be measured to well under 1% in flux within 30 days, corresponding to $\ll$0.1 wt% in abundance. Note that the high energy resolution provided by the HPGe detector (0.3%) is required to distinguish these lines; scintillation detectors such as the Dawn GRaND (>3% resolution for the CZT sensors, 10% for the BGO detector [11]) provide at least 10x less energy resolution.

Cosmic ray flux: The flux of galactic cosmic rays (GCRs) typically varies by more than a factor of 3 over the course of the 11-year solar cycle [12]. To be conservative, we normalized our model GCR flux to high solar potential (low GCR flux), comparable to that seen by the Mars Odyssey GRS during its first 3 years in Mars orbit. Missions that orbit during solar minimum may thus see gamma-ray fluxes up to three times higher than those described here.

Comparison with Mars Odyssey GRS flight data: Our model asteroid orbiter has a less favorable geometry than the Odyssey experiment (0.84 sr, vs. 3.47 sr solid angle at Mars), but benefits from the absence of the Martian atmosphere, which attenuates both incoming GCRs and outgoing gamma rays. After accounting for the atmospheric effects [13] and the differences in geometry and composition, our CO chondrite model count rates are consistent with the Mars Odyssey midlatitude flight count rates to within ±40% over a wide range of gamma-ray energies, which is as expected given the composition-related differences in neutron energy distribution.

Radiation, Detector Resolution, and Science Performance: During the Odyssey mission, the GRS detector was successfully annealed multiple times to repair degradation in energy resolution due to space radiation exposure. The post-anneal energy resolution was slowly degraded by accumulated radiation damage, from 4.1 keV in June 2002 to 5.7 keV over May 2006-Dec. 2007 (FWHM at 1332 keV). We therefore investigated the sensitivity effects of this loss of resolution by analyzing Odyssey GRS data from late in the mission and by broadening our MCNPX model asteroid spectra to 5.7 keV. We find that our meteorite-based asteroid models can still be distinguished from each other within a 4.5-month mission at the degraded resolution (Table 1).

Table 1: Orbital GRS Sensitivities after 4.5 Months

Element	Energy (MeV)	1σ at 4.1 keV Resolution	1σ at 5.7 keV Resolution
H	2.223	± 0.010 wt%	± 0.02 wt%
O	6.13	± 0.32 wt%	± 0.4 wt%
S	5.42	± 0.15 wt%	± 0.3 wt%
Cl	1.95	± 0.003 wt%	± 0.0045 wt%
C	4.44	± 0.6 wt%	± 0.6 wt%*

*The C+O line at 4438 keV is Doppler broadened by nuclear recoil to 69 keV (well beyond the detector resolution) so the count rate uncertainties in that line are not affected by the degradation in detector resolution, although other lines in the complex region are.

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