Published in final edited form as:

Meteorit Planet Sci. 2017 January ; 52(1): 174–190. doi:10.1111/maps.12786.

Modeling orbital gamma-ray spectroscopy experiments at carbonaceous asteroids

Lucy F. LIM^{1,*}, Richard D. STARR^{1,2}, Larry G. EVANS^{1,3}, Ann M. PARSONS¹, Michael E. ZOLENSKY⁴, William V. BOYNTON⁵

¹NASA Goddard Space Flight Center, Code 691, Greenbelt, Maryland 20771, USA

²Catholic University of America, Washington, District of Columbia 20064, USA

³Computer Sciences Corporation, Lanham-Seabrook, Maryland 20706, USA

⁴ARES, NASA Johnson Space Center, Houston, Texas 77058, USA

⁵Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721, USA

Abstract

To evaluate the feasibility of measuring differences in bulk composition among carbonaceous meteorite parent bodies from an asteroid or comet orbiter, we present the results of a performance simulation of an orbital gamma-ray spectroscopy (GRS) experiment in a Dawn-like orbit around spherical model asteroids with a range of carbonaceous compositions. The orbital altitude was held equal to the asteroid radius for 4.5 months. Both the asteroid gamma-ray spectrum and the spacecraft background flux were calculated using the MCNPX Monte-Carlo code. GRS is sensitive to depths below the optical surface (to ≈ 20 –50 cm depth depending on material density). This technique can therefore measure underlying compositions beneath a sulfur-depleted (e.g., Nittler et al. 2001) or desiccated surface layer. We find that 3σ uncertainties of under 1 wt% are achievable for H, C, O, Si, S, Fe, and Cl for five carbonaceous meteorite compositions using the heritage Mars Odyssey GRS design in a spacecraft-deck-mounted configuration at the Odyssey end-of-mission energy resolution, FWHM = 5.7 keV at 1332 keV. The calculated compositional uncertainties are smaller than the compositional differences between carbonaceous chondrite subclasses.

CARBONACEOUS METEORITES AND THEIR PARENT BODIES

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 (Wiik 1956; Jarosewich 1990) 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 (Grady et al. 2002; Pearson et al. 2006) and bulk sulfur from <1% in CKs to >5 wt% in CI chondrites (Jarosewich 1990).

*Corresponding author. lucy.f.lim@nasa.gov.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article:

We evaluated the feasibility of measuring these differences in bulk composition from an asteroid or comet orbiter by conducting a performance simulation of an orbital gamma-ray spectroscopy (GRS) experiment in a Dawn-like orbit around five spherical model asteroids with carbonaceous meteoritic compositions. As in the Dawn Vesta encounter as planned (e.g., Russell et al. 2004) the orbital altitude was held equal to the asteroid radius for 4.5 months. Because GRS is sensitive to depths below the optical surface (to $\approx 20\text{--}50$ cm depth depending on material density), it can provide bulk compositions of material hidden from other spectral techniques beneath a sulfur-depleted (e.g., Nittler et al. 2001) or desiccated surface layer.

METHODS

Monte-Carlo Model

We applied the well-established Monte-Carlo radiation transport code MCNPX (Pelowitz 2005; Waters et al. 2007) 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). Key elemental abundances are given in Table 1 and full compositions in Table S1 in supporting information.

We then modeled a spacecraft background based on a Dawn-like spacecraft model, also using MCNPX, as described below (see The Spacecraft Model section). Finally, MCNPX was used to model the interaction of the combined asteroid and spacecraft spectra with the heritage Mars Odyssey GRS instrument (Boynton et al. 2004; Detector Efficiency and Resolution section), and the resulting spectra analyzed (see Peak Fitting and Count Rate Extraction section) to calculate sensitivity to key elements of geochemical interest (Table 2).

Cosmic-Ray Flux Source Term

The integral 4π -steradian flux of GCR protons varies from 1.5 to 5.0 particles/cm²/s over the course of the 11 year solar cycle (McKinney et al. 2006). 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 yr in Mars orbit. Missions that orbit instead during solar minimum may thus see gamma-ray fluxes up to three times higher than those described here.

We normalized the GCR flux on the planet's surface as in McKinney et al. (2006), dividing the isotropic GCR flux by a factor of 4, which provides the proper weighting for a surface source flux in MCNPX. For a solar potential of 1000 (solar maximum), McKinney et al. give GCR proton and alpha 4π fluxes of 1.5 and 0.1 particles/cm²/s, respectively. Following McKinney et al. and others (e.g., Masarik and Reedy 1996) we accounted for the alpha contribution by multiplying the alpha flux by a factor of 3.8, giving us an effective isotropic GCR proton flux of $1.5 + 0.38 = 1.88$ particles/cm²/s, which corresponds to 0.47 particles/cm²/s on the asteroid surface. (We note, however, that the 25% contribution of the alpha particle component remains minor in comparison with the $\approx 300\%$ variation caused by the solar cycle.)

The Spacecraft Model

The model spacecraft was a Dawn-like solar-electric propulsion design. The spacecraft mass is dominated by aluminum (615 kg). Xenon tanks for a solar-electric system were included together with smaller hydrazine tanks for chemical attitude control. The stainless fuel tanks added a small amount of iron to the model. The tanks were modeled as full, with 538 kg Xe and 50 kg of N_2H_4 . A 19 kg carbon-fiber antenna was also included; this represented the only onboard carbon in the model.

There was no oxygen or silicon in the spacecraft model. In addition, although fairly massive, the Dawn solar panels were far from the GRS and preliminary calculations indicated that their contribution to the GRS background would be minimal, whereas including them would have increased the Monte-Carlo running time significantly.

GCR-Induced and Neutron-Induced Spacecraft Background—Background spectra were produced both by direct GCR/spacecraft interactions and by the interaction of the GCR-induced asteroid neutron emission with the spacecraft. The GCR-induced spacecraft background can be measured directly during cruise, but the neutron flux from the asteroid only produces the neutron-induced background during proximity operations.

The asteroid spectrum and both spacecraft background spectra are shown in Figs. 2 and 3. Note that at almost all energies the GCR-induced background dominates over the neutron-induced background. This is in contrast to the spacecraft background in planetary mission GRS data sets such as the low-altitude MESSENGER data (Goldsten et al. 2007; Evans et al. 2012) and in the Mars Odyssey orbital data: the neutron flux received by the spacecraft is proportional to the solid angles occupied by the planets from the point of view of the spacecraft, which were much higher than is practical for an asteroid orbiter.

Compensating for Limitations of the MCNPX Code

The spectra in this work were initially generated using version 2.6f of MCNPX with the default libraries. As the gamma-ray production cross sections are not known for their reliability, we carefully checked and corrected the photon output of the code as described below. In addition, the count rates of the gamma rays of interest in the model spectra were compared to the flight data from the Mars Odyssey GRS experiment (see Validation: Comparison of Model Results with Mars Odyssey GRS Flight Data section, Tables 7 and 8).

Identification and Removal of Spurious Lines—Although the MCNPX code is reliable in generating neutron fluxes and energy distributions, the gamma-ray spectra produced by the code suffer from certain inaccuracies. Spurious lines generated by MCNPX had to be removed from the model spacecraft spectrum—notably lines in both the GCR-induced and neutron-induced spacecraft background that were generated by MCNPX modeling of GCR interactions with aluminum. We verified that these lines were separate from the genuine signal by generating single-element spectra of GCR interactions with various elements including aluminum, oxygen, and carbon. We also verified that these lines were not evident in the cruise data from the Mars Odyssey and MESSENGER missions.

Note that we did not search the entire MCNPX-generated spectrum for spurious lines. Only the lines in our scientific regions of interest were closely examined. A full list of removed lines is given in Table S2 in supporting information.

Identification of Inaccurate Line Energies—We identified several inaccurate line energies in the MCNPX output. The 2131 keV ($n,n'\gamma$) line of sulfur is inaccurately tallied at 2136 keV. The 1951 keV line of chlorine was useful for the Mars Odyssey GRS analysis but is unfortunately not accurately represented by MCNPX. We based our Cl sensitivity estimates on the stronger 6111 keV neutron capture count rate instead.

Branching Ratios—The oxygen branching ratio used by MCNPX places too many counts in the 4438 keV line (i.e., the 4438/6129 keV ratio is too high; see Peplowski et al. 2015). Thus, we are slightly overestimating (see Table 6) the uncertainty in carbon based on the oxygen counts in this line.

Application of Doppler Broadening—Several important spectral lines produced by inelastic scattering of neutrons, such as the 2211 keV Al ($n,n'\gamma$) line, the 2231 keV S($n,n'\gamma$) line, and the 4438 keV $^{12}\text{C}(n,n'\gamma) + ^{16}\text{O}(n,n'\alpha\gamma)^{12}\text{C}$ line, are always Doppler broadened by the nuclear recoil of their production. However, the MCNPX code itself was not used to account for this physical effect—although the neutron scattering was modeled, the entire gamma-ray flux from the reaction was deposited in a single energy channel. Thus, each MCNPX simulation produced a line spectrum superimposed on a continuum (Fig. 2).

In order to accurately simulate a flight spectrum, we applied Doppler broadening to the relevant MCNPX-generated lines (Table 3). This was done prior to modeling the gamma-ray/detector interaction and applying the detector energy resolution function to the full spectrum.

Detector Efficiency and Resolution

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 experiment, the Mars Odyssey Gamma-Ray Spectrometer (Boynton et al. 2004). The large detector size and high energy resolution (0.3% at 1332 keV during its prime mission) of this instrument give it the best sensitivity of any heritage GRS instrument to carbon, sulfur, and other minor elements in carbonaceous asteroids (see Fig. 12). However, we modeled a deck-mounted instrument configuration (similar to that of the Mercury MESSENGER GRS experiment) in which the spacecraft background is much higher than in the boom-mounted Mars Odyssey flight experiment.

Attenuation in the Detector Housing—In order to represent attenuation in the detector housing (including the passive cooler), the gamma rays were simulated as passing through a 2 cm thick titanium plate prior to entry into the detector. This simplified model of the detector housing was validated by comparison with Mars Odyssey flight data.

Detector Energy Resolution—After the above corrections, the last step in preparing the simulated GRS spectrum (Fig. 2) was applying the detector energy resolution function, $\sqrt{E}$, as described below.

Modeling the Effects of Long-Term Radiation Exposure on Detector

Resolution—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 to December 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 (Table 4).

We generated asteroid and spacecraft background spectra both at the 4.1 keV resolution of the Odyssey prime mission data and at the 5.7 keV resolution of the “Epoch 3” Odyssey data, analyzed both (see the Peak Fitting and Count Rate Extraction section), and compared the results.

We note that raising the anneal temperature will increase the efficacy of the annealing process. In the Odyssey GRS design, this may be accomplished by adding a heater to the anneal door. Thus, on future missions, it is likely to be feasible to improve the energy resolution over the Odyssey end-of-mission value even after several years of space exposure.

Energy Resolution of the Kaguya GRS—The Kaguya lunar mission carried the largest planetary science HPGe GRS experiment flown to date (Hasebe et al. 2008) with a 250 cm³ HPGe detector. The preflight energy resolution was established at 3.0 keV at 1332 keV (Hasebe et al. 2008) comparable to the preflight Mars Odyssey and MESSENGER values (Table 4). However, the energy resolution appears to have deteriorated during and after the month-long journey to lunar orbit (September 14, 2007 to October 18, 2007; Kobayashi et al. 2010) with the energy resolution at 1461 keV having been measured at ≈ 6.5 keV in November 2007 and ≈ 9.5 keV by February 2008 (fig. 4c of Hasebe et al. 2010). Scaling by $\sqrt{E}$, these values would correspond to 1332 keV resolutions of 6.2 and 9.1 keV, respectively. Later in the mission, the detector was annealed at nominal temperatures of 80–90 °C for 48 h (Kobayashi et al. 2013) but the postanneal resolution for the period February 2, 2009 to May 29, 2009 was limited to 20 keV at 3.7 MeV (Yamashita et al. 2012) or 6–7 keV at 1461 keV (Kobayashi et al. 2013).

The Mars Odyssey and MESSENGER instruments were also both in flight during this time but did not experience comparable postanneal losses of energy resolution. The unusual severity of the Kaguya GRS radiation damage has been attributed to cryocooler stoppages (Hasebe et al. 2010; Kobayashi et al. 2013).

We note that in spite of the unusual radiation damage, the energy resolution of the Kaguya GRS remained significantly better than that of the various scintillator GRS experiments and thus the Kaguya data remain by a wide margin the highest-energy-resolution lunar GRS spectra to date.

Peak Fitting and Count Rate Extraction

When the model spectra were complete, peak fluxes were extracted and uncertainties estimated using the same methods that were applied to the Mars Odyssey flight data (Evans et al. 2006) (see Fig. 6).

Line count rates as retrieved by the peak fitting procedure are given in Table 5.

Line Sensitivity and Compositional Sensitivity

Inelastic-Scatter Lines—Inelastic scatter line strength is influenced by the total neutron population, which is more or less a function of average atomic number (Z). However, for chondritic materials, we find that the inelastic line strengths are essentially proportional to the abundances of their parent elements.

Neutron Capture Lines—Neutron capture lines are influenced by the population of thermal (low-energy) neutrons, which are much more likely to be captured than higher energy neutrons. As light elements thermalize neutrons most effectively, the total concentration of light elements influences the strength of all the neutron capture lines. Conversely, certain elements such as Cl and Fe are strong absorbers of thermal neutrons and thus decrease the strength of all capture lines. Hydrogen both thermalizes high-energy neutrons and absorbs thermal neutrons very effectively.

Because the thermal neutron population affects all capture lines equally, the ratio of two capture lines will be proportional to the ratio of their parent elements (see Fig. 5).

Decay of Radiogenic Elements—The natural radioisotopes of K, Th, and U produce gamma rays independent of the neutron population. The strengths of these lines are directly proportional to the concentrations of their parent nuclides.

RESULTS

The resulting sensitivity estimates are given above in Table 2. Specific results are discussed below.

Discussion of Specific Elements and Gamma-Ray Lines

Silicon: Inelastic and Capture Lines—Silicon is very useful for gamma-ray spectral interpretation because planetary gamma-ray spectra generally include strong Si lines produced both by inelastic scatter ($^{28}\text{Si}(n,n'\gamma)$ at 1779 keV) and by neutron capture ($^{28}\text{Si}(n,\gamma)^{29}\text{Si}$ at 3539 and 4934 keV). Thus, elements for which only inelastic lines can be measured (e.g., C) can be referenced to the 1779 keV line, whereas those for which only capture lines can be measured (e.g., H) can be normalized to the capture lines of Si.

Figures 4 and 5 show the count rates in these three lines as a function of model silicon abundance.

Hydrogen and the 2223 keV Region—The 2223 keV $^1\text{H}(n,\gamma)^2\text{H}$ is the only gamma ray by which hydrogen can be measured in planetary gamma-ray spectra. Fortunately, the cross

section for this reaction is very high relative to the atomic mass of hydrogen, enabling hydrogen to be measured at low concentrations even in the presence of the overlapping Doppler-broadened peaks from aluminum (primarily spacecraft background) at 2211 keV and sulfur at 2231 keV. Figure 6 illustrates the position of the 2223 keV line between these two Doppler-broadened peaks.

Figure 7 shows the relationship between 2223 keV count rates and model hydrogen abundances.

Sulfur—Sulfur sensitivity was estimated on the basis of the 5420 keV neutron capture line. Figure 8 illustrates count rate in this line as a function of model sulfur abundance.

Chlorine—Chlorine is a trace element (<0.1 wt%) in chondrites but thanks to its unusually high neutron capture cross section it can nevertheless easily be measured by an orbital gamma-ray experiment. Figure 9 illustrates count rate and sensitivity in the 6111 keV line as a function of chlorine abundance.

Carbon, Oxygen, and the 4438 keV Region—The strong 4438 keV line produced by $^{12}\text{C}(n,n'\gamma)$ and $^{16}\text{O}(n,n'\alpha\gamma)^{12}\text{C}$ is Doppler broadened by the nuclear recoil of its production. Measurement of carbon abundance based on this line is challenging but achievable (Peplowski et al. 2015). Overlapping lines from iron, silicon, and aluminum sit on the broad wings of the C+O peak (Fig. 10). The carbon count rate in the 4438 keV line may be determined by subtracting the oxygen contribution, which can be calculated based on the count rate in the 6129 keV line of $^{16}\text{O}(n,n'\gamma)$ (Table 6).

We find that an integration time of 135 days in a Dawn/LAMO-like orbit is sufficient to characterize the carbon abundances in carbon-rich meteorite compositions and to set meaningful upper limits on the abundances in carbon-poor compositions (Fig. 11; Table 2).

Validation: Comparison of Model Results with Mars Odyssey GRS Flight Data

We compared our model line count rates against the Mars Odyssey count rates (Evans et al. 2006) for the two models closest to Mars Odyssey in hydrogen content, as the hydrogen abundance has a greater effect than that of any other element on the thermal neutron population.

Our model asteroid orbiter has a less favorable geometry than the Odyssey experiment ($\Omega = 0.84$ steradians, versus 3.47 steradians of solid angle at Mars), but benefits from the absence of the Martian atmosphere, which attenuates both incoming cosmic rays and outgoing gamma rays. After accounting for the atmospheric effects (Masarik and Reedy 1996) and the differences in geometry and abundances of gamma-ray source nuclides, our CO chondrite model count rates (Table 7) are consistent with the Mars Odyssey midlatitude flight count rates to within $\pm 45\%$ over a wide range of gamma-ray energies. This is as expected given the significant differences in the neutron population caused by the much lower abundances of Cl and much higher abundances of Fe in the chondrite models as compared to Mars.

Table 8 gives a similar comparison for the next model up in hydrogen concentration, the CM chondrite model. The super-Martian hydrogen abundance drives up the thermal neutron population in the Monte-Carlo model, thus elevating all the capture lines except that of hydrogen itself relative to the scaled Mars Odyssey count rates. Meanwhile, the inelastic lines are reduced in strength compared to the CO model, most likely because of the lower Fe concentration in the CMs.

Note that count rates in the 4438 keV line in the Odyssey flight data are always dominated by emission from the Martian CO₂ atmosphere and thus not informative about the surface composition.

Carbon Sensitivity in the MESSENGER GRS Flight Experiment

Like the Mars Odyssey GRS, the MESSENGER GRS experiment (Goldsten et al. 2007; Evans et al. 2012) used a high-purity germanium detector with the high energy resolution required to resolve lines in the complex 4438 and 2223 keV regions where carbon and hydrogen can be measured (Table 4, “Flight Detector Resolution”) as demonstrated by Peplowski et al. (2015). Unfortunately, Peplowski et al. found that the carbon sensitivity of the MESSENGER experiment was limited to ± 2.7 wt% (3σ) primarily by the background signal from the large carboniferous plastic anticoincidence filter surrounding the detector (0.14 counts per minute in the 4438 keV line) and thus did not obtain a confident detection of carbon in the GRS spectrum of Mercury. Without the spacecraft background, they estimate that carbon would have been detectable at ≈ 0.5 wt%.

The large size (6.7 cm diameter $\times$ 6.7 cm height right circular cylinder) of the Mars Odyssey GRS gave it greater gamma-ray stopping power than the smaller (5 cm $\times$ 5 cm) MESSENGER GRS in the 4438 and 6129 keV lines needed for the carbon measurement (Fig. 12).

CONCLUSIONS

A major objective of any small-body orbiter mission will be to illuminate the relationship between the materials in the target object and the meteorites that have been delivered to Earth. Currently, the parent bodies of the various carbonaceous chondrite subclasses and their relationships to one another remain unknown. We find that global measurements of sulfur, carbon, hydrogen, and other elements with sufficient accuracy to establish undifferentiated composition and carbonaceous subclass can be achieved with a heritage gamma-ray instrument, and that the integration time required for a successful experiment at a feasible orbital altitude are consistent with the operational time frames of prior NASA small-body missions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments—

The authors gratefully acknowledge Bob Reedy and Ed Cloutis for providing helpful reviews of this work.

REFERENCES

- Antilla A, Keinonen J, Hautala M, and Forsblom I 1977 Use of the $^{27}\text{Al}(\text{p}, \gamma) ^{28}\text{Si}$, $E_p = 992 \text{ keV}$ resonance as a gamma-ray intensity standard. *Nuclear Instruments and Methods* 147:501–505.
- Boynton WV, Feldman WC, Mitrofanov IG, Evans LG, Reedy RC, Squyres SW, Starr R, Trombka JJ, D’Uston C, Arnold JR, Englert PAJ, Metzger AE, Wänke H, Brückner J, Drake DM, Shinohara C, Fellows C, Hamara DK, Harshman K, Kerry K, Turner C, Ward M, Barthe H, Fuller KR, Storms SA, Thornton GW, Longmire JL, Litvak ML, and Ton’chev AK 2004 The Mars Odyssey gamma-ray spectrometer instrument suite. *Space Science Reviews* 110:37–83.
- Boynton WV, Taylor GJ, Evans LG, Reedy RC, Starr R, Janes DM, Kerry KE, Drake DM, Kim KJ, Williams RMS, Crombie MK, Dohm JM, Baker V, Metzger AE, Karunatillake S, Keller JM, Newsom HE, Arnold JR, Brückner J, Englert PAJ, Gasnault O, Sprague AL, Mitrofanov I, Squyres SW, Trombka JJ, d’Uston L, Wänke H, and Hamara DK 2007 Concentration of H, Si, Cl, K, Fe, and Th in the low- and mid-latitude regions of Mars. *Journal of Geophysical Research (Planets)* 112:E12S99.
- Brown PG, Hildebrand AR, Zolensky ME, Grady M, Clayton RN, Mayeda TK, Tagliaferri E, Spalding R, MacRae ND, Hoffman EL, Mittlefehldt DW, Wacker JF, Bird JA, Campbell MD, Carpenter R, Gingerich H, Glatiotis M, Greiner E, Mazur MJ, McCausland PJ, Plotkin H, and Mazur TR 2000 The fall, recovery, orbit, and composition of the Tagish Lake meteorite: A new type of carbonaceous chondrite. *Science* 290:320–325. [PubMed: 11030647]
- Evans LG, Reedy RC, Starr RD, Kerry KE, and Boynton WV 2006 Analysis of gamma ray spectra measured by Mars Odyssey. *Journal of Geophysical Research (Planets)* 111:E03S04.
- Evans LG, Peplowski PN, Rhodes EA, Lawrence DJ, McCoy TJ, Nittler LR, Solomon SC, Sprague AL, Stockstill-Cahill KR, Starr RD, Weider SZ, Boynton WV, Hamara DK, and Goldsten JO 2012 Major-element abundances on the surface of Mercury: Results from the MESSENGER Gamma-Ray Spectrometer. *Journal of Geophysical Research (Planets)* 117:E00L07.
- Goldsten JO, Rhodes EA, Boynton WV, Feldman WC, Lawrence DJ, Trombka JJ, Smith DM, Evans LG, White J, Madden NW, Berg PC, Murphy GA, Gurnee RS, Strohehn K, Williams BD, Schaefer ED, Monaco CA, Cork CP, Eckels JD, Miller WO, Burks MT, Hagler LB, Deteresa SJ, and Witte MC 2007 The MESSENGER gamma-ray and neutron spectrometer. *Space Science Reviews* 131:339–391.
- Goodrich CA, Patchett PJ, Lugmair GW, and Drake MJ 1991 Sm-Nd and Rb-Sr isotopic systematics of ureilites. *Geochimica et Cosmochimica Acta* 55:829–848.
- Grady MM, Verchovsky AB, Franchi IA, Wright IP, and Pillinger CT 2002 Light element geochemistry of the Tagish Lake CI2 chondrite: Comparison with CI1 and CM2 meteorites. *Meteoritics & Planetary Science* 37:713–735.
- Hasebe N, Yamashita N, Okudaira O, Kobayashi S, Yamamoto H, Ishizaki T, Hirano K, Sakurai K, Miyachi T, Miyajima M, Fujii M, Kobayashi M, Takashima T, Shibamura E, Gasnault O, Maurice S, d’Uston C, Reedy R, and Grande M 2008 The high precision gamma-ray spectrometer for lunar polar orbiter SELENE. *Advances in Space Research* 42:323–330.
- Hasebe N, Shibamura E, Miyachi T, Takashima T, Kobayashi M, Okudaira O, Yamashita N, Kobayashi S, Karouji Y, Hareyama M, Kodaira S, Hayatsu K, Iwabuchi K, Nemoto S, Sakurai K, Komatsu S, Miyajima M, Ebihara M, Hihara T, Arai T, Sugihara T, Takeda H, D’Uston C, Gasnault O, Diez B, Forni O, Maurice S, and Reedy RC 2010 High performance germanium gamma-ray spectrometer on Lunar Polar Orbiter SELENE (KAGUYA). *Transactions of Space Technology Japan* 7:Pk_35–Pk_41.
- Jarosewich E 1990 Chemical analyses of meteorites—A compilation of stony and iron meteorite analyses. *Meteoritics* 25:323–337.
- Kobayashi S, Hasebe N, Shibamura E, Okudaira O, Kobayashi M, Yamashita N, Karouji Y, Hareyama M, Hayatsu K, D’Uston C, Maurice S, Gasnault O, Forni O, Diez B, Reedy RC, and Kim KJ 2010 Determining the absolute abundances of natural radioactive elements on the Lunar Surface by the Kaguya gamma-ray spectrometer. *Space Science Reviews* 154:193–218.
- Kobayashi M, Hasebe N, Miyachi T, Fujii M, Shibamura E, Okudaira O, Karouji Y, Hareyama M, Takashima T, Kobayashi S, d’Uston C, Maurice S, Yamashita N, and Reedy RC 2013 The Kaguya

gamma-ray spectrometer: Instrumentation and in-flight performances. *Journal of Instrumentation* 8:P04,010.

- Masarik J and Reedy RC 1996 Gamma ray production and transport in Mars. *Journal of Geophysical Research* 101:18,891–18,912.
- McKinney GW, Lawrence DJ, Prettyman TH, Elphic RC, Feldman WC, and Hagerty JJ 2006 MCNPX benchmark for cosmic ray interactions with the Moon. *Journal of Geophysical Research (Planets)* 111:E6004.
- Nittler LR, Starr RD, Lim L, McCoy TJ, Burbine TH, Reedy RC, Trombka JI, Gorenstein P, Squyres SW, Boynton WV, McClanahan TP, Bhangoo JS, Clark PE, Murphy ME, and Killen R 2001 X-ray fluorescence measurements of the surface elemental composition of asteroid 433 Eros. *Meteoritics & Planetary Science* 36:1673–1695.
- Nittler LR, McCoy TJ, Clark PE, Murphy ME, Trombka JI, and Jarosewich E 2004 Bulk element compositions of meteorites: A guide for interpreting remote-sensing geochemical measurements of planets and asteroids. *Antarctic Meteorite Research* 17:231–251.
- Pearson VK, Sephton MA, Franchi IA, Gibson JM, and Gilmour I 2006 Carbon and nitrogen in carbonaceous chondrites: Elemental abundances and stable isotopic compositions. *Meteoritics & Planetary Science* 41:1899–1918.
- Pelowitz DB, ed. 2005 MCNPX user's manual, version 2.5.0 Report LA-UR-05–0369. Los Alamos, New Mexico: Los Alamos National Laboratory 473 p.
- Peplowski PN, Lawrence DJ, Evans LG, Klima RL, Blewett DT, Goldsten JO, Murchie SL, McCoy TJ, Nittler LR, Solomon SC, Starr RD, and Weider SZ 2015 Constraints on the abundance of carbon in near-surface materials on Mercury: Results from the MESSENGER Gamma-Ray Spectrometer. *Planetary and Space Science* 108:98–107.
- Reedy RC 1978 Planetary gamma-ray spectroscopy. *Proceedings, 9th Lunar and Planetary Science Conference*. pp. 2961–2984.
- Russell CT, Coradini A, Christensen U, de Sanctis MC, Feldman WC, Jaumann R, Keller HU, Konopliv AS, McCord TB, McFadden LA, McSween HY, Mottola S, Neukum G, Pieters CM, Prettyman TH, Raymond CA, Smith DE, Sykes MV, Williams BG, Wise J, and Zuber MT 2004 Dawn: A journey in space and time. *Planetary and Space Science* 52:465–489.
- Spitz AH and Boynton WV 1991 Trace element analysis of ureilites—New constraints on their petrogenesis. *Geochimica et Cosmochimica Acta* 55:3417–3430.
- Wasson JT and Kallemeyn GW 1988 Compositions of chondrites. *Royal Society of London Philosophical Transactions Series A* 325:535–544.
- Waters LS, McKinney GW, Durkee JW, Fensin ML, Hendricks JS, James MR, Johns RC, and Pelowitz DB 2007 The MCNPX Monte Carlo Radiation Transport Code. In *Hadronic Shower Simulation Workshop*, American Institute of Physics Conference Series, vol. 896 pp. 81–90.
- Wiik HB 1956 The chemical composition of some stony meteorites. *Geochimica et Cosmochimica Acta* 9:279–289.
- Wiik HB 1972 The chemical composition of the Haverø meteorite and the genesis of the ureilites. *Meteoritics* 7:553–557.
- Yamashita N, Gasnault O, Forni O, d'Uston C, Reedy RC, Karouji Y, Kobayashi S, Hareyama M, Nagaoka H, Hasebe N, and Kim KJ 2012 The global distribution of calcium on the Moon: Implications for high-Ca pyroxene in the eastern mare region. *Earth and Planetary Science Letters* 353:93–98.
- Yanai K and Kojima H 1995 Catalog of the Antarctic meteorites: Collected from December 1969 to December 1994, with special reference to those represented in the collections of the National Institute of Polar Research. Tokyo: National Institute of Polar Research. 230 p.

Fig. 1.

a) Orbital gamma-ray spectroscopy experiments can measure bulk sulfur and carbon at the $\approx 1\text{--}5$ wt% levels found in carbonaceous meteorites. b) GRS is sensitive to bulk hydrogen and oxygen. Tagish Lake compositional data from Brown et al. (2000) and Grady et al. (2002); other meteorites as compiled by Nittler et al. (2004), including data from Wiik (1956), Jarosewich (1990), and Yanai and Kojima (1995). Sensitivities reflect the end-of-mission energy resolution of the Odyssey GRS, full-width-at-half-maximum (FWHM) = 5.7 keV at 1332 keV. See Table 2.

Simulated CI Chondrite Spectrum As Detected: Mars Odyssey GRS sensitivity and energy reso

Fig. 2.

a) CI chondrite gamma-ray spectrum as generated by MCNPX and detected from a Dawn-like low-altitude orbit. Doppler broadening (Table 3) has already been applied to these spectra but the detector resolution has not. b) The same spectra, but as would be detected by the Mars Odyssey detector at its prime mission energy resolution, FWHM = 4.1 keV at 1332 keV (as with all HPGc detectors, $\Delta E \propto \sqrt{E}$). See Detector Efficiency and Resolution section.

Simulated CI Chondrite Spectrum As Detected: Mars Odyssey GRS sensitivity and energy reso

Fig. 3.

Details of spectra shown in Fig. 2 illustrating the Doppler-broadened 4438 keV line. a) MCNPX-generated spectra after application of Doppler broadening but without detector sensitivity or resolution functions. This corresponds to the energy distribution of photons arriving at the detector. b) Spectra as detected by Mars Odyssey GRS, $E(\text{FWHM}) = 4.1$ keV at 1332 keV.

Fig. 4.

Retrieved count rate in the 1779 keV inelastic line of Si as a function of model asteroid composition. Error bars are derived from peak fitting and represent photon statistical errors (σ) after 30 days of integration. (In this case, the error bars are smaller than the plot symbols [diamonds]).

Fig. 5.

Ratios of neutron capture line strengths correlate with ratios of elemental abundances. a) Two neutron capture lines of Si. For individual neutron capture lines, the line strengths are not generally linear with the abundance of the emitting element. Capture line strengths depend heavily on how quickly the GCR-produced neutrons are thermalized, which is highly dependent on the light-element abundance in the regolith. However, ratios of one capture line to another are highly correlated with compositional ratios, as can be seen here (b) in the ratios of neutron capture lines produced by silicon and iron as a function of composition. The Mars Odyssey midlatitude count rate ratio (Evans et al. 2006) is also plotted for reference.

Fig. 6.

Fitting of the gamma-ray lines in the complex hydrogen region (2223 keV): model spectra versus Mars Odyssey data. a) Spacecraft-only spectrum. The large Doppler-broadened peak at 2211 keV is aluminum from the spacecraft background. b) Fit to the CI chondrite asteroid spectrum with spacecraft background. In spite of the high background, the hydrogen line at 2223 keV is sufficiently strong (1.8 cpm) to be measured to well under 1% in flux within 30 days, corresponding to $<<0.1$ wt% in abundance. Note that the high energy resolution provided by the HPGe detector (0.3%) is required to distinguish these lines. c) The same spectral region in the Mars Odyssey mid-latitude data. The count rate in this line was 1.08 counts per minute (see fig. 12 and table 1 of Evans et al. [2006] for additional details). As with Mars Odyssey, future missions may increase the hydrogen sensitivity of gamma-ray

experiments by mounting the gamma-ray sensor on a boom, thus greatly reducing the spacecraft-originating Al background at 2211 keV.

Fig. 7.

Retrieved count rate in the 2223 keV line of hydrogen versus model asteroid composition. Error bars are derived from peak fitting in Fig. 6 and represent photon statistical errors (σ) after 30 days of integration. In this case, the error bars are smaller than the plot symbols (diamonds).

Fig. 8.

Retrieved count rate in the 5420 keV line of sulfur versus model asteroid composition. Error bars are derived from peak fitting and represent photon statistical errors (σ) after 30 days of integration.

Fig. 9.

Retrieved count rate in the 6111 keV line of chlorine versus model asteroid composition.

Error bars are derived from peak fitting and represent photon statistical uncertainties (σ) after 30 days of integration.

Fig. 10.

Fitting of the gamma-ray lines in the complex $^{12}\text{C}(n,n'\gamma)$ and $^{16}\text{O}(n,n'\alpha\gamma)^{12}\text{C}$ region (4438 keV) of the (a) CO chondrite and (b) Tagish Lake model spectra. The large Doppler-broadened peak is the combined $^{12}\text{C} + ^{16}\text{O}$ signal. Peak identifications are as follows: 4403/4405 keV, $^{56}\text{Fe}(n,\gamma)$ (nominal energy 4406.1 keV); 4423 keV, escape peak of $^{28}\text{Si}(n,\gamma)$ at 4934 keV; 4438 keV, $^{12}\text{C}(n,n'\gamma) + ^{16}\text{O}(n,n'\alpha\gamma)^{12}\text{C}$; 4498/4500 keV, multiple sources including $^{28}\text{Si}(n,n'\gamma)$ and $^{27}\text{Al}(p,c)^{28}\text{Si}$ (nominal energy 4496.8 keV). See Evans et al. (2006), Reedy (1978), and Antilla et al. (1977).

Fig. 11.

Retrieved count rates attributable to carbon in the 4438 keV line versus model asteroid composition. Error bars are derived from peak fitting and represent photon statistical errors (σ) after 30 days of integration. The C contribution to the 4438 keV peak is higher in count rate than the 5420 keV S peak (Fig. 8) but the C uncertainties are much higher both because of the Doppler broadening and because each of the many additional lines that must be analyzed contributes to the error budget.

Fig. 12.

Detection efficiencies of two successful heritage HPGe (high-resolution) gamma-ray instruments: the 6.7×6.7 cm cylindrical Mars Odyssey Gamma-Ray Spectrometer and the 5 cm MESSENGER Gamma-Ray Spectrometer (Goldsten et al. 2007). 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.

Table 1.

Compositional models based on carbonaceous meteorites.

Z	Element	Abundance (wt%)				
		CI	Tagish Lake	CM	CO	Novo Urei
1	H	2.02	1.5	1.4	0.07	0
6	C	3.45	3.6 ^a	2.2	0.45	2.23
8	O	46.1	45.2	43.2	37.0	38.7
14	Si	10.64	11.4	12.7	15.9	18.57
16	S	5.41	3.8	2.7	2.0	0.58
17	Cl	0.07	0.056	0.043	0.024	0.00765
19	K	0.055	0.065	0.037	0.0345	0.03
26	Fe	18.2	19.3	21.3	24.8	15.64

^aCarbon wt% from table 2 of Brown et al. (2000). Higher bulk carbon abundances for this meteorite are reported in the text of Brown et al. (2000) and in other papers (e.g., Grady et al. 2002; Pearson et al. 2006).

Meteorite models were based on published analyses or averages as follows: CI, Tagish Lake, CM—Brown et al. (2000); CO—subclass average from Wasson and Kallemeyn (1988); Novo Urei—major elements from Wiik (1972); REE and trace elements from Goodrich et al. (1991) and Spitz and Boynton (1991).

Table 2.

Summary orbital GRS single-line sensitivities after 4.5 months (135 days) integration time

Gamma ray	Accumulated gamma-ray count uncertainty (3σ) after 135 days int. time		Idealized compositional uncertainty (wt%; 3σ)	
	At energy resolution of:	Element wt% in model ^d	At energy resolution of:	
	4.1 keV		4.1 keV	5.7 keV
Neutron capture gamma rays (n, γ)				
H 2223 keV ^b				
CI	$\pm 0.80\%$	2.02 wt%	± 0.016 wt%	± 0.024 wt%
Tagish Lake	$\pm 1.01\%$	1.50 wt%	± 0.015 wt%	± 0.017 wt%
CM	$\pm 1.12\%$	1.40 wt%	± 0.016 wt%	± 0.019 wt%
CO	$\pm 30.1\%$	0.07 wt%	± 0.021 wt%	± 0.040 wt%
Novo Urei	...	0 wt%	...	...
Si 4934 keV				
CI	$\pm 4.6\%$	10.64 wt%	± 0.49 wt%	± 0.62 wt%
Tagish Lake	$\pm 4.3\%$	11.40 wt%	± 0.49 wt%	± 0.61 wt%
CM	$\pm 4.3\%$	12.70 wt%	± 0.54 wt%	± 0.65 wt%
CO	$\pm 5.4\%$	15.90 wt%	± 0.86 wt%	± 1.04 wt%
Novo Urei	$\pm 4.3\%$	18.57 wt%	± 0.80 wt%	± 0.97 wt%
S 5420 keV				
CI	$\pm 4.3\%$	5.41 wt%	± 0.23 wt%	± 0.29 wt%
Tagish Lake	$\pm 6.1\%$	3.80 wt%	± 0.23 wt%	± 0.31 wt%
CM	$\pm 8.9\%$	2.70 wt%	± 0.24 wt%	± 0.36 wt%
CO	$\pm 23\%$	2.00 wt%	± 0.46 wt%	± 0.76 wt%
Novo Urei ^c	$\pm 99.6\%$	0.58 wt%	± 0.58 wt%	...
Cl 6111 keV				
CI	$\pm 7.8\%$	0.070 wt%	± 0.0054 wt%	± 0.0066 wt%
Tagish Lake	$\pm 9.4\%$	0.056 wt%	± 0.0053 wt%	± 0.0065 wt%
CM	$\pm 11.9\%$	0.043 wt%	± 0.0051 wt%	± 0.0061 wt%
CO	$\pm 34\%$	0.024 wt%	± 0.0083 wt%	± 0.0098 wt%
Novo Urei	$\pm 53\%$	0.008 wt%	± 0.0041 wt%	± 0.0064 wt%
Fe 7632 keV				

Accumulated gamma-ray count uncertainty (3σ) after 135 days int. time			Idealized compositional uncertainty (wt%; 3σ)		
At energy resolution of:			At energy resolution of:		
Gamma ray	4.1 keV	5.7 keV	Element wt% in model ^d	4.1 keV	5.7 keV
CI	±1.3%	±1.8%	18.20 wt%	±0.23 wt%	±0.33 wt%
Tagish Lake	±1.2%	±1.4%	19.30 wt%	±0.24 wt%	±0.27 wt%
CM	±1.2%	±1.6%	21.30 wt%	±0.26 wt%	±0.34 wt%
CO	±1.6%	±1.8%	24.80 wt%	±0.41 wt%	±0.46 wt%
Novo Urei	±1.9%	±2.1%	15.64 wt%	±0.30 wt%	±0.34 wt%
Inelastic scatter gamma rays (n,n'γ)					
Si 1779 keV ^d					
CI	±2.6%	±2.9%	10.64 wt%	±0.28 wt%	±0.31 wt%
Tagish Lake	±2.3%	±2.6%	11.40 wt%	±0.27 wt%	±0.30 wt%
CM	±2.1%	±2.4%	12.70 wt%	±0.27 wt%	±0.30 wt%
CO	±1.2%	±1.3%	15.90 wt%	±0.19 wt%	±0.21 wt%
Novo Urei	±1.1%	±1.2%	18.57 wt%	±0.20 wt%	±0.22 wt%
C 4438 keV ^e					
CI	±14.3%	±18.2%	3.45 wt%	±0.49 wt%	±0.63 wt%
Tagish Lake	±14.2%	±16.0%	3.60 wt%	±0.51 wt%	±0.58 wt%
CM	±19.2%	±19.8%	2.20 wt%	±0.42 wt%	±0.44 wt%
CO	±33%	±49%	0.45 wt%	±0.15 wt%	±0.22 wt%
Novo Urei	±20%	±22%	2.23 wt%	±0.45 wt%	±0.48 wt%
O 6129 keV					
CI	±1.80%	±1.95%	46.1 wt%	±0.83 wt%	±0.90 wt%
Tagish Lake	±1.75%	±1.91%	45.2 wt%	±0.79 wt%	±0.86 wt%
CM	±1.82%	±1.98%	43.2 wt%	±0.79 wt%	±0.86 wt%
CO	±1.78%	±1.92%	37.0 wt%	±0.66 wt%	±0.71 wt%
Novo Urei	±1.65%	±1.80%	38.7 wt%	±0.64 wt%	±0.70 wt%
Radiogenic gamma rays					
K 1461 keV					
CI	±1.15%	±1.28%	0.056 wt%	±0.00064 wt%	±0.00072 wt%
Tagish Lake	±1.04%	±1.15%	0.065 wt%	±0.00068 wt%	±0.00075 wt%
CM	±1.35%	±1.50%	0.037 wt%	±0.00050 wt%	±0.00056 wt%

Accumulated gamma-ray count uncertainty (3σ) after 135 days int. time		Idealized compositional uncertainty (wt%, 3σ)	
At energy resolution of:		At energy resolution of:	
Gamma ray	4.1 keV	5.7 keV	5.7 keV
CO	$\pm 1.15\%$	$\pm 1.24\%$	± 0.00050 wt%
Novo Urei	$\pm 1.28\%$	$\pm 1.39\%$	± 0.00042 wt%

“Idealized Compositional Uncertainty” represents the best possible uncertainty in derived elemental abundance from a single gamma-ray line based solely on counting statistics. It is the product of the model wt% with the line uncertainties and thus assumes a perfect knowledge of a linear relationship between the gamma ray’s count rate and the abundance of its source element. This limiting uncertainty can vary with composition. For each gamma ray, the composition for which this element’s uncertainty is the highest has been marked in bold.

^aSee Table 1 for sources of meteorite compositional data.

^bIn addition to total line strength uncertainties, H 2223 keV uncertainties incorporate (in a root-sum-squared sense) uncertainties in the subtracted line background from hydrazine fuel in the spacecraft model as determined by analysis of a spacecraft-only spectrum. This background contributes ~0.03 counts per minute to the total line strength.

^cMarginal detection at 4.1 keV resolution; no detection at 5.7 keV resolution.

^dSi 1779 keV uncertainties include uncertainties in the subtracted (≈ 0.25 counts per minute) line background from Al in the spacecraft model.

^eC 4438 keV values are statistics in the difference between the Doppler-broadened 4438 keV fitted peak and the predicted counts in this line due to (1) spacecraft background emission from carbon and (2) asteroidal oxygen emission in the 4438 keV line, which is determined from the O 6129 keV line and thus incorporates uncertainties propagated from the 6129 keV line. See Table 6.

Table 3.

Doppler-broadened gamma-ray lines in regions of interest.

Line energy (keV)	Doppler-broadened FWHM (keV)	Reaction
2211	14.5	$^{27}\text{Al}(\text{n},\text{n}'\gamma)^{27}\text{Al}$
2236	22.9	$^{32}\text{S}(\text{n},\text{n}'\gamma)^{32}\text{S}^a$
4438	81.3	$^{12}\text{C}(\text{n},\text{n}'\gamma)^{12}\text{C} + ^{16}\text{O}(\text{n},\text{n}'\alpha\gamma)^{12}\text{C}$

^aThe actual energy of this line is 2231 keV but it is produced by MCNPX in the model spectrum at 2236 keV.

Table 4.
Energy resolution of heritage high-purity germanium detectors in deep space over time.

Gamma-ray FWHM at a reference energy of 1332 keV (all values postanneal) Energy resolution in high-purity germanium detectors varies according to: $\Delta E \propto \sqrt{E}$					
	Time after launch	Mars Odyssey GRS Typical anneal 73 °C	MESSENGER GRS ^d Anneal temp. 85 °C		
		Dates	E	Dates	E
Prelaunch		Before April 2001	2.8 keV	<August 2004	3.49 keV
Cruise	≈0.3 years	June–July 2001	3.8 keV	November 2004	3.7 keV ^b
Mars Odyssey Prime Mission	1.2 years	June 2002	4.1 keV		
Mars Odyssey Ext. Mission Epoch 2	4–5 years	April 2005–March 2006	5.06 keV ^b		
Mars Odyssey Ext. Mission Epoch 3	5–6.5 years	May 2006–December 2007	5.79 keV ^b		
Mercury MESSENGER Prime Mission	6.6 years			March 2011	4.8 keV ^b

^aGoldsten et al. (2007) and Evans et al. (2012).
^bMeasurement taken at 1369 keV.

Table 5.

Model results: Modeled gamma-ray line count rates and retrieved count rates in counts per minute (CPM).

Gamma line/model		Retrieved count rate (CPM)				% retrieved ^b	
		Line CPM	At 4.1 keV resolution ^a		At 5.7 keV resolution ^a		
Si 1779 keV ^c							
CI	0.726	0.736	±0.0069	0.723	±0.0085	101.3%	99.6%
Tagish Lake	0.788	0.794	±0.0070	0.783	±0.0077	100.8%	99.3%
CM	0.846	0.854	±0.0071	0.839	±0.0078	101.0%	99.2%
CO	1.358	1.372	±0.0080	1.346	±0.0085	101.0%	99.1%
Novo Urei	1.570	1.585	±0.0082	1.559	±0.0089	101.0%	99.3%
H 2223 keV							
CI	1.839	1.783	±0.0087	1.795	±0.0133	97.0%	97.6%
Tagish Lake	1.350	1.303	±0.0078	1.359	±0.0087	96.5%	100.7%
CM	1.208	1.159	±0.0075	1.209	±0.0092	95.9%	100.1%
CO	0.099	0.069	±0.0058	0.099	±0.0072	69.6%	100.3%
Novo Urei ^d	0.067	0.029	±0.0052	0.080	±0.0064	42.9%	120.2%
Si 4423 keV							
CI	0.038	0.046	±0.0028	0.056	±0.0056	120.7%	146.0%
Tagish Lake	0.039	0.042	±0.0040	0.047	±0.0056	107.6%	120.1%
CM	0.041	0.044	±0.0040	0.048	±0.0055	106.4%	116.3%
CO	0.028	0.031	±0.0039	0.039	±0.0054	113.0%	138.5%
Novo Urei	0.039	0.042	±0.0040	0.047	±0.0055	107.0%	119.5%
Si 4934 keV							
CI	0.088	0.100	±0.0040	0.088	±0.0036	113.1%	99.9%
Tagish Lake	0.092	0.107	±0.0033	0.096	±0.0036	116.3%	104.9%
CM	0.096	0.109	±0.0033	0.100	±0.0036	113.7%	104.3%
CO	0.067	0.081	±0.0031	0.075	±0.0035	120.7%	111.6%
Novo Urei	0.091	0.106	±0.0032	0.097	±0.0036	116.2%	106.3%
S 5420 keV							
CI	0.105	0.096	±0.0029	0.099	±0.0037	92.2%	94.7%

Gamma line/model	Line CPM	Retrieved count rate (CPM)		% retrieved ^b	
		At 4.1 keV resolution ^a	At 5.7 keV resolution ^a	At 4.1 keV	At 5.7 keV
Tagish Lake	0.072	0.064	±0.0028	±0.0036	89.2% 86.9%
CM	0.048	0.042	±0.0027	±0.0035	88.2% 77.7%
CO	0.020	0.015	±0.0025	±0.0033	73.9% 60.8%
Novo Urei	0.008	0.003	±0.0024	...	43.7% ...
Cl 6111 keV ^e					
Cl	0.042	0.043	±0.0024	±0.0029	101.7% 104.1%
Tagish Lake	0.032	0.036	±0.0024	±0.0029	112.4% 110.2%
CM	0.024	0.028	±0.0024	±0.0028	117.7% 119.0%
CO	0.007	0.009	±0.0021	±0.0027	127.8% 136.6%
Novo Urei	0.003	0.006	±0.0022	±0.0027	188.8% 147.5%
O 6130 keV					
Cl	0.266	0.262	±0.0033	±0.0037	98.4% 100.8%
Tagish Lake	0.271	0.277	±0.0034	±0.0037	102.1% 102.0%
CM	0.258	0.262	±0.0034	±0.0037	101.4% 101.4%
CO	0.264	0.259	±0.0033	±0.0036	97.9% 101.4%
Novo Urei	0.289	0.294	±0.0034	±0.0037	101.7% 101.5%
Fe 7631 keV					
Cl	0.359	0.359	±0.0033	±0.0046	100.0% 100.3%
Tagish Lake	0.377	0.377	±0.0033	±0.0037	100.1% 99.1%
CM	0.392	0.393	±0.0034	±0.0044	100.1% 99.0%
CO	0.233	0.235	±0.0027	±0.0030	101.0% 100.1%
Novo Urei	0.181	0.182	±0.0025	±0.0028	100.9% 100.1%
Fe 7645 keV					
Cl	0.313	0.315	±0.0031	±0.0044	100.4% 100.2%
Tagish Lake	0.328	0.328	±0.0031	±0.0035	100.1% 99.8%
CM	0.341	0.342	±0.0032	±0.0043	100.2% 100.1%
CO	0.200	0.202	±0.0026	±0.0029	100.8% 100.6%
Novo Urei	0.155	0.158	±0.0023	±0.0026	101.9% 101.8%

^aEnergy resolution (FWHM) at the reference energy, 1332 keV; $\Delta E \propto \sqrt{E}$.

NASA Author Manuscript

NASA Author Manuscript

NASA Author Manuscript

^bRetrieved using peak fitting techniques of Evans et al. (2006).

^cIncludes spacecraft background counts from A1.

^dThe Novo Urei model includes no hydrogen. All counts at 2223 keV are attributable to hydrazine in the spacecraft model.

^eSum of 6108 and 6109 keV channels in the MCNPX output.

All count rates refer to the combined spacecraft background + asteroid spectra. Count rate uncertainties are statistical uncertainties after 30 days of accumulation.

Table 6.
Carbon sensitivity estimation and error budget for a CI chondritic asteroid composition.

	Counts per minute ($\pm 3\sigma$ after 135 days)
Total 4438 keV count rate, retrieved from model spectrum = $C_{\text{Total}}(4438)$:	0.431 ± 0.016
Spacecraft 4438 keV count rate, retrieved from model background ^a = $C_{\text{Spacecraft}}(4438)$:	0.038 ± 0.011
Asteroid-originating 4438 keV count rate = $C_{\text{Total}} - C_{\text{Spacecraft}} \equiv C_{\text{Asteroid}}(4438)$:	0.393 ± 0.020
Asteroid-originating 6129 keV ^{16}O (n,n' γ) count rate, retrieved = $C_{\text{O}}(6129)$	0.266 ± 0.004
MCNPX oxygen (single-element spectrum) line ratio, $C_{\text{O}}(4438)/C_{\text{O}}(6129) = 0.95^b$	
Calculated O_{4438} count rate = $(C_{\text{O}}(6129)) * (C_{\text{O}}(4438)/C_{\text{O}}(6129)) = C_{\text{O}}(4438 \text{ keV})$:	0.253 ± 0.004
Asteroid carbon (4438 keV) = $C_{\text{Asteroid}}(4438) - C_{\text{O}}(4438 \text{ keV})$:	0.140 ± 0.020

^aIn reality, only the GCR component of the spacecraft background can be measured by direct spectral fitting. For one technique to determine the neutron/spacecraft component of the background, see (Peplowski et al. 2015). Note also that the neutron/spacecraft component is much smaller in a one-radius asteroid orbit than it was for MESSENGER or Mars Odyssey because of the lower solid angle (Ω) occupied by the asteroid (Fig. 3).

^bThis ratio is significantly higher than that determined by Peplowski et al. (2015) via integration over the neutron cross sections, even accounting for the differences in detector efficiency between the two instruments. Thus, MCNPX is overestimating the background due to oxygen in this line and thus also overestimating the associated uncertainties. However, as is evident from the table, this is not the dominant component of the error budget.

Table 7.

Mars Odyssey GRS data versus CO chondrite model gamma-ray line count rates, in counts per minute (CPM).

Gamma-ray CO model energy (keV)	CPM ^a	Mars ice-free model wt% ^b	CO model wt%	Ody. GRS count rate (CPM) ^c	Geometric factor ^d	Mars atmos. factor ^e	Ody. CPM scaled to CO ^f	Ratio: CO model to scaled Ody. GRS data
Neutron capture gamma rays								
H 2224	0.099	0.32	0.07	1.077	0.242	2.69	0.154	0.64
Si 3539	0.072	21.33	15.90	0.228	0.242	2.15	0.089	0.81
Si 4423	0.028	21.33	15.90	0.121	0.242	1.84	0.040	0.70
Si 4934	0.067	21.33	15.90	0.223	0.242	1.84	0.074	0.91
S 5420	0.020	2.20	2.00	0.038	0.242	1.76	0.015	1.36
Cl 6111	0.007	0.54	0.024	0.323	0.242	1.66	0.006	1.21
Fe 7631	0.233	14.60	24.80	0.336	0.242	1.49	0.206	1.13
Fe 7646	0.200	14.60	24.80	0.306	0.242	1.49	0.188	1.07
Inelastic scatter gamma rays								
Si 1779.90	1.358	21.33	15.90	1.773	0.242	2.97	0.952	1.43
O 6127.00	0.264	45.30	37.00	0.952	0.242	1.66	0.312	0.85
							Median:	1.07
							σ :	0.27

^aCO chondrite-based asteroid model line count rates from Table 5.

^bAverage composition of ice-free latitudes from Boynton et al. (2007).

^cOdyssey midlatitude count rates from Evans et al. (2006).

^dRatio of asteroid solid angle $\Omega = 0.84$ sr to Mars Odyssey solid angle $\Omega = 3.47$ sr.

^eIncludes cosmic-ray production and atmospheric absorption effects (Masarik and Reedy 1996).

^fScaled for atmosphere, composition, and solid angle.

Table 8. Mars Odyssey GRS data versus CM chondrite model gamma-ray line count rates, in counts per minute (CPM).

Gamma-ray energy (keV)	CM model CPM ^a	Mars ice-free model wt% ^b	CM model wt %	Odyssey GRS count rate (CPM) ^c	Geometric factor ^d	Mars atmos. factor ^e	Odyssey CPM scaled to CM ^f	Ratio: CM model to scaled Ody. GRS data
Neutron capture gamma rays								
H 2224	1.208	0.32	1.40	1.077	0.242	2.69	3.071	0.39
Si 3539	0.114	21.33	12.70	0.228	0.242	2.15	0.071	1.60
Si 4423	0.041	21.33	12.70	0.121	0.242	1.84	0.032	1.28
Si 4934	0.096	21.33	12.70	0.223	0.242	1.84	0.059	1.63
S 5420	0.048	2.20	2.70	0.038	0.242	1.76	0.020	2.42
Cl 6111	0.024	0.54	0.043	0.323	0.242	1.66	0.010	2.32
Fe 7631	0.392	14.60	21.30	0.336	0.242	1.49	0.177	2.21
Fe 7646	0.341	14.60	21.30	0.306	0.242	1.49	0.161	2.11
Inelastic scatter gamma rays								
Si 1779.9	0.846	21.33	12.70	1.773	0.242	2.97	0.760	1.11
O 6127.0	0.258	45.30	43.20	0.952	0.242	1.66	0.364	0.71
							Median:	1.63
							σ :	0.70

^aCM chondrite-based asteroid model line count rates from Table 5.
^bAverage composition of ice-free latitudes from Boynton et al. (2007).
^cOdyssey midlatitude count rates from Evans et al. (2006).
^dRatio of asteroid solid angle $\Omega = 0.84$ sr to Mars Odyssey solid angle.
^eIncludes cosmic-ray production and atmospheric absorption effects.
^fScaled for atmosphere, composition, and solid angle.