

## Uranium on the Moon: Global distribution and U/Th ratio

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[1] The Kaguya Gamma-Ray Spectrometer uniquely identified uranium gamma-ray lines from the Moon with a superior energy resolution of  $\sim 1\%$ . A global lunar map of uranium distribution is derived for the first time. It was found that uranium abundances vary up to 2 ppm with an average of  $\sim 0.3$  ppm, while the average thorium abundance was  $\sim 1.2$  ppm. From these analyses, significant variation in U/Th ratio was found in the farside of the Moon that had not been reported by previous observations or in lunar materials. Our observations suggest that the lunar highland is not as uniform as has been long considered. **Citation:** Yamashita, N., et al. (2010), Uranium on the Moon: Global distribution and U/Th ratio, *Geophys. Res. Lett.*, 37, L10201, doi:10.1029/2010GL043061.

### 1. Introduction

[2] Potassium, thorium, and uranium are incompatible elements that may be concentrated in the residual magma during the cooling process of the Moon, behaving as trace elements [Shearer and Papike, 1999]. They are naturally radioactive elements that could also have acted as a heat source of the igneous activity of the Moon [Jolliff et al., 2000; Wieczorek and Phillips, 2000]. Uranium and thorium are representative example of refractory elements on the Moon, whose abundances are important for examining the questions related to the origin of the Moon [Taylor et al., 2006]. However, the global uranium abundance on the Moon has not previously been determined separately from thorium.

[3] Measurements of uranium require a high energy resolution and high sensitivity detector because intensities of uranium gamma-ray lines are much weaker compared to thorium, and the lines suffer from severe interferences from lines in energy spectra which are only a few keV apart [Reedy, 1978]. Conventional gamma-ray detectors used in previous lunar missions [Harrington et al., 1974; Feldman et al., 1999] had energy resolutions of  $\sim 100$  keV at 1 MeV and could not resolve uranium gamma-ray lines uniquely. The Gamma-Ray Spectrometer (GRS) of Japanese lunar mission SELENE

employed a Ge detector that has enough energy resolution,  $\sim 1\%$  in full width at half maximum at 1.8 MeV on average throughout the observation, to uniquely identify uranium lines. For comparison, the Mars Odyssey GRS, which also employs a Ge detector for Mars exploration, had a resolution of 0.24% for the epoch 1 (W. Boynton, personal communication, 2010), which slowly deteriorated with time [Evans et al., 2006]. This work reports the global distribution map of uranium on the Moon for the first time together with that of thorium.

### 2. Observation and Analysis

[4] The SELENE spacecrafts [Kato et al., 2008] were launched on September 14, 2007, and the main orbiter Kaguya was inserted to the lunar polar and circular orbit at 100 km altitude on October 18, 2007. The high precision GRS on Kaguya employs a large Ge detector and a massive BGO detector for anticoincidence and measures 0.2 MeV – 12 MeV gamma rays to determine the elemental composition of the lunar surface. Its specifications and preliminary observations are described by Hasebe et al. [2008, 2009] and Yamashita et al. [2009].

[5] Lunar gamma rays were observed by the GRS from December 14, 2007 to December 10, 2008 with a total effective observation time of 2674 hours. The energy resolution of gamma-ray lines at 1461 keV was less than  $\sim 10$  keV throughout this period, which was  $\sim 10$  times better than that of Apollo [Harrington et al., 1974], Lunar Prospector [Feldman et al., 1999], or Chang'e-1 GRS [Sun and Dai, 2005]. Energy spectrum obtained by the Kaguya GRS for the entire Moon is shown in Figure 1 with that by Lunar Prospector GRS [Lawrence et al., 2004] for comparison. The gamma-ray energy spectra contain a large continuum and a few hundred peaks within the observed energy region. Therefore it is critical to have a high energy resolution to uniquely identify a gamma-ray peak corresponding to the abundance of a source nuclide. In the following discussion, peaks are fitted to a analytic shape of a Gaussian with a low-energy tail to correctly derive effective signal intensities of gamma-ray lines in spectra. Background gamma rays were measured in two special operations of the orbiter in July and December, 2008 when the Kaguya GRS was pointed away from the Moon [Kobayashi et al., 2010], and subtracted from science data.

[6] Gamma-ray line intensities obtained by the Kaguya GRS were corrected for dead time and altitude variation of the satellite. Unlike Lunar Prospector GRS, attitude correction was not necessary since Kaguya was a three-axis-controlled satellite and the GRS always faced the nadir. Gain shift, mostly caused by temperature variation, was confirmed to be negligible during the period since the GRS has a Stirling refrig-

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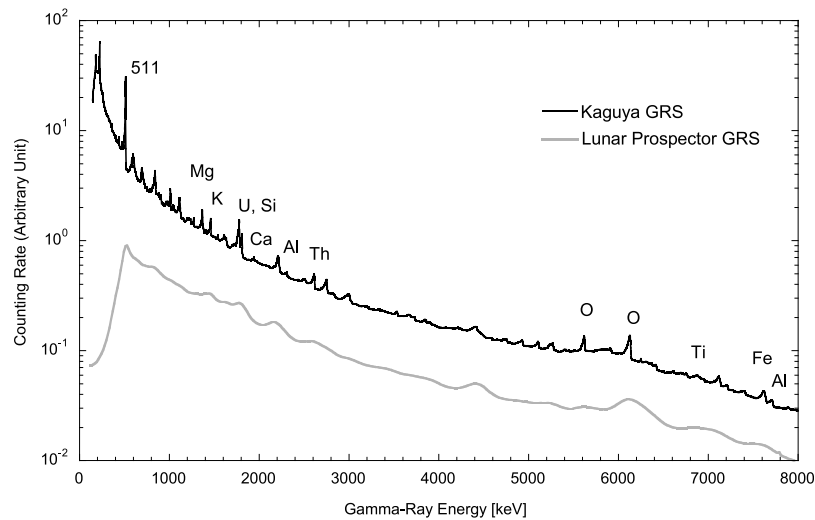


**Figure 1.** Energy spectrum of gamma rays observed by Kaguya GRS from December 2007 to December 2008 integrated for the entire Moon with the effective accumulation time of 111 days and that by Lunar Prospector GRS from January 1998 to October 1998 with 231 days for comparison. Some of the major peaks are labeled with elemental symbols or energy. Note that the vertical axis is in an arbitrary unit to avoid overlapping.

erator [Hasebe *et al.*, 2009] to actively cool the Ge crystal between 74 and 80 K [Yamashita *et al.*, 2009]. The intensities were calibrated to abundances by calculating emission rates of line gamma rays, transport of gamma rays through the lunar surface, solid angles from the lunar surface to the detector, and detection efficiencies of the spectrometer [Kobayashi *et al.*, 2010]. Note that we have not calibrated or normalized our results with ground truth because of issues such as large differences in spatial resolution and the fact that the emission rates of line gamma rays from radioactive nuclides are well known and fluxes of those gamma rays can be easily calculated [Reedy *et al.*, 1973].

[7] Uranium and thorium are naturally radioactive elements that spontaneously emit gamma-ray lines with energies characteristic to the elements with well known decay constants. The uranium line with the highest probability appears at 609 keV. However, it is too close to a background Ge peak at 596 keV with a high energy tail spreading up to ~630 keV (so-called “sawtooth” peak) [Brückner *et al.*, 1987]. The existence of such a high intensity interference made it difficult to determine the spectrum baseline below the uranium peak. Therefore, we analyzed the 1764.5 keV gamma ray in this work to derive  $^{238}\text{U}$  abundances. That gamma ray is emitted as a result of  $\beta$  decay of  $^{214}\text{Bi}$  in the decay chain originated by the decay of  $^{238}\text{U}$  [Reedy, 1978]. To measure thorium, the strong 2614.5 keV line was used, which is emitted after  $\beta$  decay of  $^{208}\text{Tl}$  in the decay chain of  $^{232}\text{Th}$  [Reedy, 1978]. The 1764.5 keV line interferes a combination of peaks including those from neutron-induced reactions with  $^{28}\text{Si}$  and  $^{27}\text{Al}$  at 1779.0 and 1808.7 keV, all of which have been successfully removed by peak-fitting analysis [Diez, 2009] as shown in Figure 2.

### 3. Results and Discussion

#### 3.1. Elemental Maps

[8] The first map of the surficial distribution of uranium on the Moon with our peak-fitting analysis is shown in Figure 3, and that of thorium in Figure 4. The color coded maps were

drawn based on  $9^\circ$  latitude x  $9^\circ$  longitude pixel data and smoothed by continuous curvature splines algorithms with the tension parameter of 0.1 [Wessel and Smith, 1991; Smith and Wessel, 1990].

[9] As can be seen from the figures, the nearside tends to record higher abundances than the farside, especially over the Procellarum KREEP terrain (PKT) [Jolliff *et al.*, 2000; Gillis *et al.*, 2004]. Highest counts occur around and southeast of

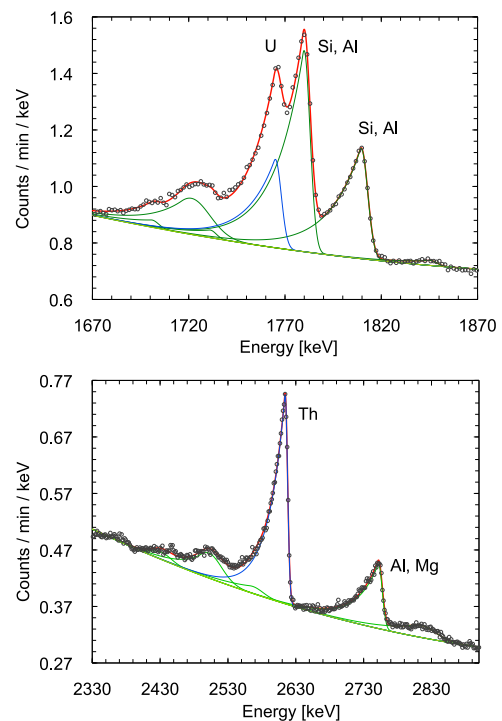


**Figure 2.** Examples of peak fitting analyses of gamma-ray lines in the energy spectra of Kaguya GRS from U at 1764.5 keV on the top and Th from 2614.5 keV on the bottom. Lines of interest are shown in blue.

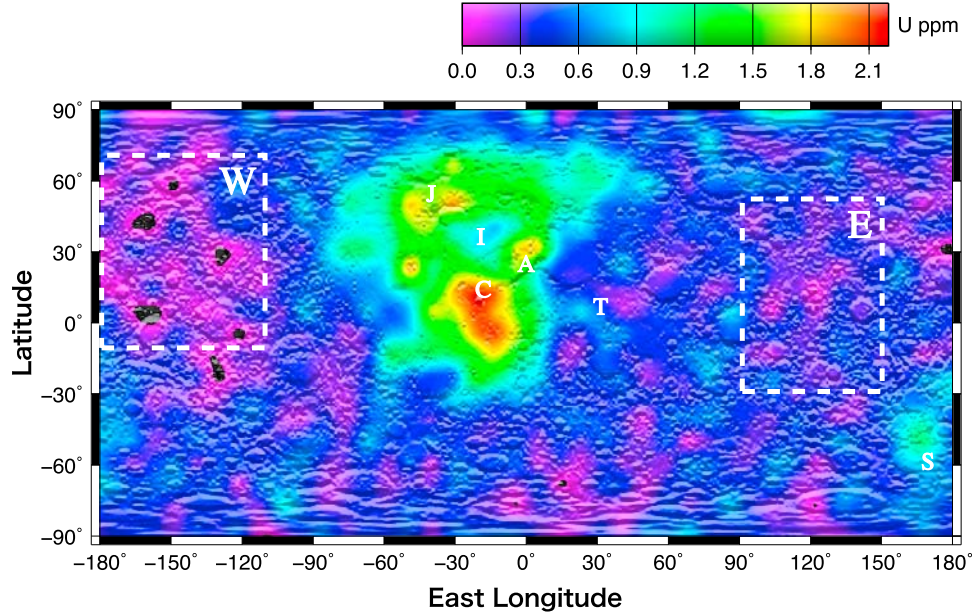


**Figure 3.** Distribution map of U on the lunar surface measured by Kaguya GRS. The abundances were determined by peak-fitting analysis of  $^{238}\text{U}$  1764.5 keV peaks. Labels on the map indicate the following lunar topographies: A, the Apennine Bench; C, Copernicus; I, Mare Imbrium; J, Montes Jura; S, South Pole-Aitken Terrane; and T, Mare Tranquillitatis. Dotted squares labeled as E and W indicate specific highland regions defined as East and West Highlands, respectively (see text). The shaded relief in Figure 3 and 4 was drawn using topographic data by Kaguya Laser Altimeter [Araki *et al.*, 2009].

Copernicus with equivalent abundances up to 2.1 ppm for uranium and 7.3 ppm for thorium. Montes Jura and the Apennine Bench are also confirmed to have higher incompatible elements while the center of Mare Imbrium is relatively depleted. Uranium and thorium abundances in Maria Serenitatis, Tranquillitatis, and Nectaris in the nearside are intermediate between the depleted highlands and enriched PKT regions. The South Pole-Aitken terrain [Jolliff *et al.*, 2000] also has higher abundances of these two elements

than the surrounding regions. The lowest abundance occurs in the farside feldspathic highland region.

### 3.2. Relative Distributions of U and Th

[10] The uranium map generally shows the same trend as the thorium maps, reinforcing the results obtained from lunar materials [Korotev, 1998]. The average uranium to thorium abundance ratio over the lunar surface was evaluated by plotting uranium abundances as a function of thorium abun-

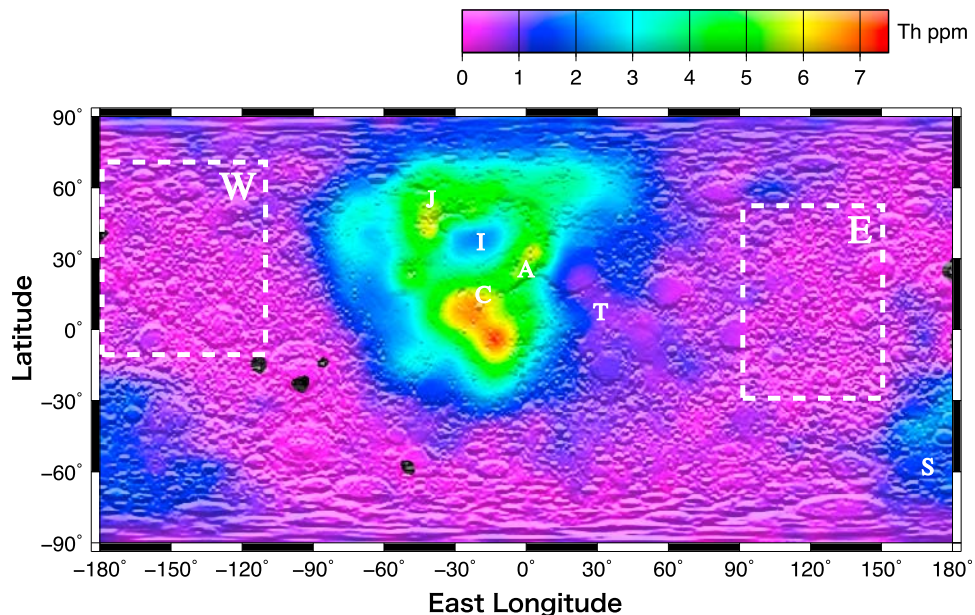


**Figure 4.** Distribution map of Th on the lunar surface measured by Kaguya GRS. The abundances were determined by peak-fitting analysis of  $^{232}\text{Th}$  2614.5 keV peaks. Labels on the map are the same as those in Figure 3 (see also text).

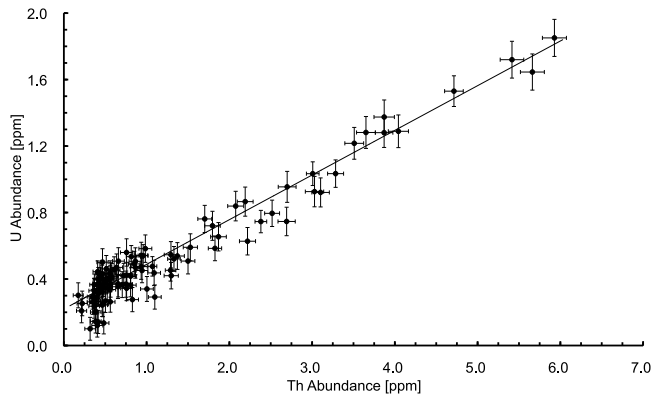


**Figure 5.** Variation in abundances of U and Th observed by Kaguya GRS. Each point represents abundances with pixel size equivalent to  $600 \times 600 \text{ km}^2$  on the lunar surface. The regression line is weighted by standard deviation and has a slope of  $0.269 \pm 0.007$  and an intercept of  $0.220 \pm 0.023$ , respectively.

dances, as shown in Figure 5. The two elements vary together linearly, as evident in the coefficient of determination ( $R^2$ ) of 0.97. Such a correlation is consistent with the results from lunar materials including Apollo and Luna returned samples and lunar meteorites [Gillis *et al.*, 2004; Korotev, 1998]. The slope of the regression, the average uranium to thorium ratio, was obtained to be  $0.269 \pm 0.007$ . This is in good agreement with that determined from various lunar material of 0.27 [Korotev, 1998] or 0.28 [Lucey *et al.*, 2006]. Lunar materials including meteorites and returned samples provide precise elemental abundances, which do not necessarily represent the whole globe. Remote sensing, on the other hand, survey the whole lunar surface but has a coarse spatial resolution of 130 km at 1.5 MeV in our case [Kobayashi *et al.*, 2010]. The agreement of the two observation techniques indicates that igneous processes did not significantly fractionate uranium from thorium at the global scale.

[11] Moreover, the observed U/Th ratio has a similar value to that of CI chondrites, 0.283 [Anders and Grevesse, 1989], and the silicate Earth, 0.276 [Taylor and McLennan, 1985], which will be an important constrain to model the origin of the Moon.

[12] However, uranium is not uniformly distributed in the highlands. Figure 3 reveals a depletion of uranium in the northern part of the western farside compared to the eastern farside. The thorium abundance shown in Figure 4 does not show such variation in those regions. To improve statistics, we defined two large regions in the farside of the Moon that are anticipated to have constant abundances of incompatible elements based on previous studies: 1) “East Highland” between  $-30^\circ$  and  $55^\circ$  in latitude and  $90^\circ$  and  $150^\circ$  in longitude, and 2) “West Highland” between  $-10^\circ$  and  $70^\circ$  in latitude and  $-180^\circ$  and  $-110^\circ$  in longitude (see the dotted squares in Figures 3 and 4). Such large accumulation areas help delineate average mass fractions of the elements with higher precision by improving counting statistics, especially for regions that contain negative values (Figure 3), which are attributed to the very low abundances and consequent large uncertainties. As expected, the thorium abundances in East and West Highlands were consistent with each other within

the Poisson statistical errors, with values of  $0.36 \pm 0.02 \text{ ppm}$  and  $0.33 \pm 0.02 \text{ ppm}$  respectively. However, the uranium abundance changes from  $0.34 \pm 0.01 \text{ ppm}$  in East Highland to  $0.21 \pm 0.01 \text{ ppm}$  in West Highland. (Note that uranium abundances possibly include a systematic error that corresponds to the relatively high y-intercept in Figure 5. One possibility to evaluate the systematic error would be to compare uranium- and thorium-poor regions with feldspathic lunar meteorites [Korotev *et al.*, 2003], which leads to a correction factor of  $-0.11 \text{ ppm}$  for uranium while thorium contents are consistent in both data sets.)

[13] That the average uranium abundances of the two large regions differ by some 60% while the thorium abundances vary only 10% suggests meaningful variations in U/Th ratio in the farside of the Moon, where the crust is considered to be quite ancient and laterally homogeneous. Uranium and thorium are so similar in terms of volatility and incompatibility that it is unlikely for uranium to fractionate from thorium in the absence of water during igneous processes. Such variation in uranium and thorium casts light on the possibility of heterogeneous formation of the farside crust, unless there is a mechanism for spreading thorium or removing uranium afterwards. Theoretical interpretation of the change in U/Th ratio in the farside is needed to reveal the mechanism of crust formation.

[14] It should be noted that the above results were derived by the peak fitting method, only applicable to high energy resolution spectra with sufficient statistics. It means that the analysis is free from ambiguity regarding peak identification or ground truth information obtained by returned samples. Previous missions, like Lunar Prospector GRS, incorporate a spectral mixing model and library of elemental spectral components that may be a source of systematic errors [Prettyman *et al.*, 2006]. Peak fitting method gives unique and far more reliable results for many elements. Therefore the Kaguya GRS provides the first uranium distribution map that is not only precise, but also reliable, which will likely improve the understanding of the lunar evolution. At the same time, the confidence in thorium maps was also improved compared with the previous results.

#### 4. Conclusions

[15] The first reliable uranium distribution map on the Moon was generated independently of the thorium map using the Kaguya Gamma-Ray Spectrometer data acquired from December 14, 2007 to December 10, 2008. The Kaguya GRS has the highest energy resolution to date. Consequently, uranium and thorium were uniquely identified by fitting their peaks at 1764.5 keV and 2614.5 keV, respectively, and their abundances were mapped using  $9^\circ$  pixel data. In general, the uranium abundances correlate well with Th, which is consistent with the results from lunar samples and meteorites. In detail though, the U/Th ratio was variable between east and west highlands in the farside, which is strongly suggestive of heterogeneities that may shed insight into the evolution of the lunar crust. The global knowledge of radioactive elements such as uranium and thorium should facilitate verification of crust formation models, locating the oldest crust, and assessment of bulk abundances of refractory and heat-producing elements to reveal the cause of dichotomy in the lunar crust.

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