Chang'E-1 gamma ray spectrometer and preliminary radioactive results on the lunar surface

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\textbf{A B S T R A C T}

The Chang'E-1(CE-1) spacecraft took a gamma-ray spectrometer (hereafter, CGRS) to detect the element distributions on the lunar surface in a circular, 200 km altitude, polar orbit with approximately 2 h periodicity. CGRS consists of two large CsI(Tl) crystals as the main and anticoincidence detectors. The large CsI crystal of CGRS has a higher detector effective area than other lunar gamma ray spectrometers. For its 1-year mission, gamma ray spectra including many peaks of major elements and trace elements on the lunar surface have been measured by CGRS. Global measurement within 0.55–0.75 MeV is given here to describe the distribution of radioactive composition (e.g., uranium and thorium) on the lunar surface. Although CGRS has a lower energy resolution that cannot separate the uranium peak from others in this energy region, 609 keV uranium gamma ray line dominates the shape of the spectrum in this energy region. Therefore, the radioactive map can indirectly describe the uranium distribution on the lunar surface. The radioactive map shows that the higher radiation is concentrated in the Procellarum KREEP Terrene (PKT) on the nearside with an oval shape. The secondary high-radiation is located in South Pole-Aitken (SPA) basin. Lunar highlands have lower concentration. The relationship between radiation and topography displays different linear correlations for lunar highlands and SPA basin, which imply the different processes for these two regions.

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1. Introduction

KREEP materials are thought to be last crystallized and sank into the layer between the lunar crust and the mantle. Radioactive elements (uranium, thorium, and potassium, hereafter, U, Th, and K), enriched in KREEP materials, are known as incompatible elements because of their large ionic radii. Their presence at the lunar surface is the end product of a series of processes, such as accumulation, collision, and modification. Therefore, the distribution of radioactivity (U, Th, and K) on the lunar surface not only helps us to address lunar formation and evolution but also gives us more key information to study lunar interior structure, concerning compositions in its crust and mantle. In addition, since moon had a process of interior slowly heating up from the decay of radioactive elements, which caused the partially melted lunar mantle and gave rise to a thin veneer of flood basaltic lava flows (Shearer et al., 2006), the distribution of radioactivity is also very important to constrain our understanding of Moon's thermal history.

Gamma ray spectrometer, as a payload of Chang'E-1 mission, was aimed to provide maps of the abundances of major elements, O, Si, Mg, Al, Ca, Ti, Na, and Fe, and of the natural radioactive elements, U, Th, and K (Zheng et al., 2008; Chang et al., 2009) in the subsurface of the entire Moon. CE-1 spacecraft was launched successfully from XiChang Satellite Launch Center on 24 October, 2007, and achieved its working orbit on 27 November. After several orbit-adjustments, it achieved its final mapping orbit, a circular, 200 km altitude, and polar orbit with approximately 2 h periodicity (Zheng et al., 2008).

In this paper, we will describe the inner structure and scientific specification of CGRS and analyze the measured gamma-ray peaks for their corresponding elements. Next, we provide details of CE-1 global radioactive compositional (U+Th, within energy range of 0.55–0.75 MeV) distribution on the lunar surface, then give the comparison with that of Lunar Prospector. Finally, the relationship between radioactive concentration and CE-1 topography is discussed.

2. Gamma-ray spectrometer

The gamma-ray spectrometer on board CE-1 mission was mounted inside the spacecraft. It consists of an 11.8 cm × 7.8 cm CsI crystal with added thallium as the main detector. The main detector is sensitive to gamma rays in the energy region between...
300 keV and 9 MeV with the energy resolution of \( \sim 9\% \) full width at half maximum (fwhm) at 662 keV. Surrounding the main crystal is a 17.8 cm diameter by 10.8 cm long, well-shaped CsI anticoincidence shield (ACS), which is used in anticoincidence with the main crystal to exclude cosmic-ray events and radiation coming from the materials of the spacecraft body. The ACS is viewed by two 3 in. photomultiplier tubes (PMTs) as well as the main crystal viewed by a 5 in. PMT. The inner structure is shown in Fig. 1 while the structural materials surrounding the crystals and PMTs are mainly aluminum. In order to achieve the best energy resolution, experiments were conducted repeatedly to select the best combination of crystal and PMTs because of the sensitivity of temperature causing signal gain of PMT. The results show that the signal gain of PMT is not particularly sensitive to temperature but is sensitive to voltage variations (Chang et al., 2009). Therefore, keeping stable high voltage is very important for effective measurement in the lifetime of CGRS. Seven levels of high voltage are used and could be controlled easily by command. Two types of gamma rays spectra are recorded simultaneously: 512-channel gamma-ray spectrum every 3s and 256-channel from ACS each second. Since CE-1 spacecraft kept the nominal 200 km altitude, the spatial resolution for omni-directional CGRS is about 300 km (about 1–1.5 times the altitude (Maurice et al., 2004; Lawrence et al., 2003)).

Energy resolution is an important parameter of gamma ray spectrometer in identifying the gamma ray lines from the lunar surface in the energy range from 0.1 to 12 MeV. Poor energy resolution leads to a large systematic error and needs a complicated analysis (Prettyman et al., 2006; Hasebe et al., 2009). The energy resolution of CGRS is \( \sim 9\% \) fwhm at 662 keV, which is higher than that of Lunar Prospector (\( \sim 10.5\% \) at 622 keV (Lawrence et al., 1998)), but little lower than Apollo GRSs (\( \sim 8.6\% \) for Apollo 15 and \( \sim 7.4\% \) for Apollo 16 at 622 keV (Metzger et al., 1973)). But while comparing with that of Kaguya, the energy resolution of CGRS becomes relatively lower because the Kaguya gamma ray spectrometer (KGRS) uses high purity Ge crystal as its detector (The energy resolution of KGRS is \( \sim 0.4\% \) fwhm at 662 keV, which is about 20 times superior to CGRS and Lunar Prospector gamma ray spectrometer (LP-GRS) (Hasebe et al., 2009, 2010a)). However, high purity Ge crystal used in KGRS needs a cooling system and is degraded by possible serious radiation damage in its 1-year orbital mission (Chang et al., 2009; Hasebe et al., 2010b). In addition, scintillators used by CGRS are suitable for a 1-year space mission because of its robustness and low power consumption. The detection efficiency of CGRS, taking 2.5–2.7 MeV window as an example, is about 0.294 counts per incident gamma ray compared with that of 0.322 counts per incident gamma ray for BGO used by LP-GRS (Lawrence et al., 2000). The detection efficiency of CsI crystal is lower than that of BGO with the same size, but the detector effective area of CGRS (efficiency times the area) at 2.5–2.7 MeV window is larger than that of LP-GRS because of its large cross sectional area (109.36 cm\(^2\)). The detector effective area of CGRS is about 32.15 cm\(^2\) while that of LP-GRS is about 17.4 cm\(^2\) (the effective detector area of LP-GRS at the lunar equator is 54 cm\(^2\) (Lawrence et al., 2000)). Comparing to that of Apollo 15 and 16, LP-GRS, CGRS and KGRS used anticoincidence shield technology (plastic, CsI(Tl), and BGO, respectively) to exclude cosmic-ray events and noise signal from spacecraft body, which greatly improves the signal to noise ratio and enhances the sensitivity of gamma ray detection (Feldman et al., 1999; Ma et al., 2008; Hasebe et al., 2009).

3. Observations

Overall the mission, CE-1 spacecraft kept a polar-orbital with a period of 127 min at a nominal altitude of \( \sim 200 \) km. The main detector sampled a spectrum in each 3 s interval. In-flight gamma ray spectra were calibrated and the results displayed that CGRS had a rather good energy resolution in 100 keV–9 MeV. CE-1 dataset was stored on the spacecraft and downlinked in packets to the Earth (received by both Miyun and Kunming receivers at the same time) each time when the spacecraft saw the Earth each time. All the received 0 level data were processed to time series data by several primary processes, including telemetry sync, eliminating noisy data, RS-coding, frame analysis, etc. Gamma ray scientific data were obtained from both receivers and the better one was selected for that at the same time.

Gamma ray spectral data covering from November 27, 2007, to July 25, 2008, containing a total of 2,467,169 separate 3s spectra were collected in CE-1 1-year mission. Accumulation time distribution in hours on each binned pixel area with 150 km (see Fig. 2), suggests that accumulation interval is relatively long in high latitude as well as short at lower latitude because of circular, polar orbit. The shortest accumulation time in binned pixel, about half an hour, is considered as long enough to distinguish elements in the spectrum and sufficiently good to allow preliminary mapping.

4. Gamma-ray spectrum

Before analyzing the spectra from CGRS, a series of corrections were made to the time series data for dead time, gain, galactic
cosmic ray, and solid angle variations. Energy spectrum measured during the first eight hours of November 28, 2007, is shown in Fig. 3 to illustrate the quality of the data. The figure is plotted with count accumulation of gamma rays per second as the vertical axis and energy of gamma ray as the horizontal axis. From this figure, it can be seen that CGRS measures the data with excellent quality and has high energy resolution. Sharp peaks are displayed, clearly corresponding to the elements on the lunar surface, such as K, Th, O, Ti, and Fe.

To identify peaks in gamma ray spectrum, global data were summed together to reduce statistical influence in each spectrum. The spectrum in Fig. 4 was created by averaging all the 3s-spectra in the energy range from 0.3 to 9 MeV. Simply, peaks at 1.46, 2.64, and 6.1 MeV appeared clearly corresponding to the radioactive elements K, Th, and O. To estimate the background, numerical methods of statistics-sensitive nonlinear iterative peak-clipping and inverse count accumulation process (Morhac et al., 1997; Zhu et al., 2009) were used, respectively. Average spectrum of backgrounds (see Fig. 4) estimated by both methods was selected to remove the contributions from cosmic ray, Compton continuum, and the spacecraft itself. The subtracted spectrum is as shown in Fig. 5.

In Fig. 5, the outstanding peak at 511 keV is the electron–positron annihilation emission. Since the energy resolution is ~9% at 662 keV (Chang et al., 2009), the peak in the energy range 0.6–0.7 MeV is mainly dominated by element U at 609 keV and perhaps partly contributed by Th lines at both 583 and 727 keV (Reedy, 1978). The peak near 1.4 MeV includes $^{24}$Mg(n,γ) of 1.369 MeV and $^{40}$K of 1.461 MeV. The peak near 1.8 MeV is the $^{28}$Si(n,γ) peak. The contribution of $^{26}$Mg(n,γ) and $^{27}$Al(n,2pγ) to the peak at 1.81 MeV is relatively small and can be ignored (its flux is 0.0152 photons/cm$^2$ min while that of $^{28}$Si(n,γ) is 3.233 photons/cm$^2$ min, see Reedy (1978)). $^{27}$Al peak is found near 2.21 MeV and dominates the shape from 2.0 to 3.0 MeV, which makes peak analyses of other elements near those energies difficult. This larger Al peak at 2.21 MeV may mainly come from the detector whose major material is aluminum. The large sharp peak near 6.0 MeV may be mainly caused by the residual fuels box near the detector, which has a mass of oxygen and nitrogen. Since the location of residual fuel box is very close to the detector, strong effect from the fuel makes a sharp increase of this peak. Lunar Prospector BGO GRS also shows an increase in peak near 6.0 MeV, which is thought to be due to the complication of other nearby, poorly resolved peaks, or imperfect background subtraction.
subtraction (Starr et al., 2000). Small peak increase near 6.0 MeV was also found in the NaI gamma ray spectrum of Apollo (Bielefeld et al., 1976). However, the increase of 6.0 MeV peak for CGRS has a very different character from that of lunar GRS as the increase at the lower edge of the peak near 6.0 MeV looks suddenly steeper. The problem is still under discussion. The acceptable explanation is that there are some problems in the electronics of the detector. The flux of oxygen gamma ray lines near 6.13 MeV is mainly from the inelastic scattering of fast neutrons, which are the direct product of the interaction of the galactic cosmic ray protons with the Moon (Lawrence et al., 2004). But since the location of residual fuel box is very close to the detector, the 6.13 MeV oxygen gamma ray line is dominated by that near 6.0 MeV, which make the calculation of oxygen concentration on the lunar surface more complex. Furthermore, because of the constant concentration of oxygen, the 6.13 MeV peak is a good indicator of the galactic cosmic ray flux. Another oxygen peak at 7.12 MeV protrudes, probably including the O peak at 6.92 MeV, even taking contribution from its neighbors of Ti at 6.76 and 6.42 MeV. However, the steep continuum from 6.2 to 6.8 MeV together with the lower energy resolution in this range makes the analysis of Ti more difficult.

5. Preliminary results of radioactive composition

In this section, the main goal is to determine the radioactive concentration on the lunar surface from CGRS. Previous radioactive maps from Apollo’s 18% coverage of the lunar surface (Metzger et al., 1973, 1977) and Lunar Prospector’s global coverage for different average altitudes of 30 and 100 km (Lawrence et al., 1998, 1999, 2000, 2003, 2004; Prettyman et al., 2002, 2006) have significantly improved our understanding of the lunar formation and evolution, including the perspective of geochemical province (Jolliff et al., 2000; Gasnault et al., 2008; d’Uston et al., 2010), the composition in the lunar crust (Warren, 2000, 2001; Jolliff et al., 2000; Haskin et al., 2000; Wieczorek and Phillips, 2000), the ratio of volatile-to-refractory materials (K/Th ratio) (Gillis et al., 2004; Prettyman et al., 2007; Taylor et al., 2006), characterization of mare basalts (Jolliff et al., 2001; Flor et al., 2002; Gasnault et al., 2001, 2002), etc. Recent Kaguya results with different periods (Hasebe et al., 2010a; Kobayashi et al., 2010; Yamashita et al., 2009, 2010) also give us new insights about Th, K, and U distributions on the lunar surface, especially some new features in some small areas, because of its higher energy and inherent spatial resolution.

For the gamma ray spectrum in the energy region above the positron line at 0.51 MeV (which is attributable to many sources and contains little chemical information), up to and including the highest-energy line due to radioactivity, namely, the 2.64 MeV line due to Th, the regional differences in counting rate are overwhelmingly attributable to the varying intensities of the lines of the radioactive elements Th, U, and K. Therefore, any energy band below 2.7 MeV will map natural radioactivity on the lunar surface because those gamma rays scatter often in the Moon and make a large continuum that dominates changes below 2.7 MeV. Like Apollo GRS mapped radioactivity with the energy range 0.55–2.75 MeV (Metzger et al., 1973, 1977, 1993), the energy range of 0.55–0.75 MeV is selected here for CGRS to re-calculate the radioactive distribution on the lunar surface. Within this energy range, the U peak from 609 keV line of $^{208}$Bi is the most intensive and the second one is 583 keV line of $^{208}$Th in the Th decay chain. Another 727 keV line from $^{212}$Bi also contributes to the complex peak in this energy region (Reedy, 1978). Therefore, the radioactive map (U+Th) within this energy band can describe, indirectly, uranium distribution on the lunar surface. In addition, in this energy range, the statistical precision of the total counting rate is rather excellent and the energy resolution is higher than that in other ranges. Any shift in spectrum, if it happened, is rather little compared with that in the higher energy range.

Global radioactive distribution from CGRS is shown in Fig. 6. In this map, 3σ-counts are binned into equal areas, about 150 km × 150 km firstly. Then counting rates within the energy range 0.55–0.75 MeV are calculated for each spectrum. As seen, the enhanced radioactivity is confined to the mare regions with an oval shape on the nearside that corresponding to KREEP Procellarum Terrane (PKT) (Jolliff et al., 2000). Counting rate in this area is larger than 40 counts per second (cps) and no other area has such high value. Therefore, this region appears to be a unique feature on the lunar surface. A secondary high radioactivity is concentrated in the South Pole-Aitken basin on the lunar farside, corresponding to the South Pole-Aitken Terrane (SPAT). Most areas in SPA basin have counting rates that lie between 39 and 40 cps, while areas outside SPA region have

![Fig. 6. Distribution of lunar radioactivity (counts/s) in the energy region from 0.55 to 0.75 MeV for CGRS with more than 2000 h accumulation. The data are presented on a 150 km × 150 km scale.](image_url)
values less than 39 cps. Lunar highlands, corresponding to the Feldspathic Highlands Terrane (FHT), have lower radioactive concentration that is different from both PKT and SPAT. Most parts of this region have radioactive counting rate less than 39 cps.

The highest radioactive region is found in the area extending from the Carpathian Mountains (15°N, 30°W) to the west of Fra Mauro (5°S, 10°W), near the Apollo 14 landing site, especially in the south part of this area (0°, 15°W). Higher topography (see Fig. 7) and lower FeO concentration (not shown here) in this region suggest that the radioactive components in this area may be the ejecta from the Imbrium impact (Lawrence et al., 1999, 2000).

High radioactive element abundances are also found surrounding the rim of Imbrium basin (33.7°S, 16.5°W). All these areas are thought to be related to the Imbrium event that excavated materials from lunar lower crust or upper mantle (Haskin, 1998). If the radioactive compositions are indeed the ejecta from Imbrium basin, it is certain that radioactive elements were asymmetrical distribution in the process of its early evolution. However, lower radioactive concentrations in other larger basins, which were also created by impacts that penetrate the lunar crust (Wieczorek and Phillips, 1999), imply that only the crust near the Imbrium basin is significantly enriched in radioactive materials. Radioactive elements that attached in KREEP material are believed to crystallize between the lunar crust and the mantle at the last period of cooling of the Magma Ocean. Although what caused the asymmetric distribution of radioactive composition is unknown, the magma ocean almost certainly played an important role in the compositional differentiation. In turn, the regional concentration of radioactive elements, at the same time, affected the course of magmatism beneath the Procellarum KREEP Terrane, yet another contribution of Magma Ocean to lunar geochemical evolution (Taylor, 2009). The low-radiation (~41 cps) and high-FeO in the inner of Imbrium basin imply that this area was filled by mare basalts. But different albedo indicates part of this area covered by mare basalts was within a different period. The counting rate of the northwest part at Sinus Iridum (44°N, 32°W) is about 42 cps, which is apparently lower than that of the southern part 42.5 cps. The lowest FeO distributed around Sinus Iridum northwest residual rims compared with higher FeO within Sinus area indicates that the old Iridum crater was formed with a large impact to excavate lower crustal or upper mantle materials. The impact event exposed low-FeO and high-radiation materials masked the ejecta from Imbrium basin. The inner high-FeO in the Iridium crater can be explained by flows of basalt melt, maybe caused by Imbrium impact. The northeast region of Imbrium basin, where the Plato crater (53°N, 9°W) is located, has a lower radioactive concentration. High resolution Clementine UV–vis image shows the rim of the Plato crater has a steep ‘reddish’ continuum, indicating that the rim may be covered by a glassy, perhaps pyroclastic material. In addition, numerous rilles and volcanic vents surrounding Plato indicate that plain-type volcanism occurred in this area, which supports the possibility that the glassy materials are pyroclastic deposits. Therefore, the lower radioactive composition surrounding Plato may be explained by pyroclastic material covering the original basin rim material and concealing its inherent radioactive concentration (Gillis et al., 1999). The other explanation is this area was flooded or embayed by later low-KREEP mare fill, because there are no KREEP-rich materials below the surface there (Elphic et al., 2000).

The southeast part of Imbrium, extending along the Apennine mountains, has the radioactive counting rate larger than 42 cps. This high-radioactive concentration comprises mainly material mapped as part of the Apennine Bench formation. However, the counting rate in Apennine Bench (~41 cps) is significantly different from that at the Apennine Mountains. The same difference can also be found for FeO. From radiation, FeO, and albedo in this region, the result can be concluded that the Apennine Bench is composed of KREEP basalt (Hawke and Head, 1978; Spudis, 1978). Either a different dilution factor prevailed if this region represents Imbrium basin ejecta or a different source was primarily responsible for the Apennine Bench. A contrasting smoothing topography, as seen from Fig. 7, reflects extrusive volcanic activity favors the latter possibility (Metzger et al., 1979; Lawrence et al., 2000).

A notable high-radiation location is found at (25°N, 48°W), west of Imbrium basin, corresponding to the Aristarchus crater (counting rate ~43 cps). Previous work (Lawrence et al., 1999) shows that the Aristarchus region has higher Th abundances and the deconvolved map displays this region is divided by a lane associated with the Agricolar Straits (in the northwest of the Aristarchus crater) into two high-Th places (Lawrence et al., 2007). But the records of both impact and volcanic processes in this region imply that it is difficult to determine whether the high radiations are strictly associated with radiation-rich ejecta from the Aristarchus crater. It was thought that the Aristarchus crater excavated materials from below the mare. Low FeO among this region suggests the excavated materials were possibly alkali anorthosite or granite. Mixing trends among the ejected material

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**Fig. 7.** CE-1 global topography. The spatial resolution of this map is 0.125° x 0.125°. The relief range is from −9.6 to 9.9 km while taking 1738.74 km as the referenced radius.
with mare basalt also suggest that monzogabbro was concentrated in this region (Jolliff et al., 2008).

Compared with that in PKT, radiation in SPA basin has a relatively lower concentration. The entire basin has an average counting rate of 39–40 as well as that the highlands outside SPA region have values less than 39 cps. The moderately high-radioactive component is concentrated in the northwest portion of SPA basin extending roughly from (30°S, 180°E) to (75°S, 160°E) with counting rate ~40. The ellipse characteristics (Garrick, 2004; Garrick and Zuber, 2005, 2009) of the radiation, iron, and topography suggest the SPA basin was created by an oblique impact. Asymmetrical excavation and uplift caused by oblique impact imply that the radiation in the surface of SPA basin was from the lunar crust or mantle at the time of basin formation. The moderately high-radioactive component is thought to be of local, rather than from Imbrium event (Haskin et al., 1996, 1997a, 1997b, 1998) or Serenitatis ejecta (Wieczorek and Zuber, 2001) in which thorium is used for the original analysis. This local radiation that enriched in KREEP materials being from the lower crustal or even mantle material are also supported by the observed mafic composition anomalies from Clementine UV-vis analysis (Pieters et al., 1997; Lucey et al., 1998).

6. Comparison with that of Lunar Prospector

Comparison between CE-1 radioactive map and that of Lunar Prospector can reveal the correctness and the quality of CGRS results. Lunar Prospector mission acquired gamma ray at two different altitudes (30- and 100-km) with various spatial resolutions (e.g., 150 km for the 100 km altitude) (Lawrence et al., 1999, 2000). Data (Th, U maps) used here for comparison were derived from the high-altitude portion of Lunar Prospector mission (maps are available through the NASA Planetary Data System). Lunar Prospector Th map was made using the well-resolved 2.61 MeV gamma ray (Lawrence et al., 2000; Prettyman et al., 2002). Because the 583 keV Th line used in this paper is also produced by radioactive decay of 208Tl in the Th decay chain, the global 2.61 MeV Th map from Lunar Prospector is assumed, which can be used to represent that for 583 keV Th. The map bin size of LP-GRS 100-km Th and U maps is 150 km × 150 km (5’ × 5’ equal-area pixel). For comparison, CGRS radioactive data are also binned on the same size pixels. Since the ratio of U and Th concentrations in representative samples of lunar rocks and regolith keeps constant at 0.27 (Korotev, 1998), in order to properly carry out the comparison, we create a mixing map including LP-GRS 100-km altitude U and Th (2.61 MeV) data points with ratio 1:1.

Fig. 8 shows the relation (black solid points) between CE-1 radioactive map and mixing map from Lunar Prospector. As seen, both maps correlate well and thus the CE-1 radioactive map appears to have good precision that can be used for further analysis. Least square fitting method was used to describe this correlation. The black dashed line represents the best-fit linear regression to these 1790 data points and the correlation coefficient (R) equals 0.95. Points with lower counting rate corresponding to lunar highlands have a good relation with that of Lunar Prospector. The main difference between two datasets, as seen from this figure, appears in the pixels with the high concentration corresponding to the Imbrium basin area. Pixels in this area are thought to have lower concentration than expected. The discrepancy at high concentration is due to the fact that the FWHM spatial resolution of the two datasets is different. The 100-km altitude LP-GRS dataset has a spatial resolution of 150 km, while the CGRS dataset has a spatial resolution of 300 km. For measurements with a larger FWHM spatial resolution, small-area features with large elemental concentration will be muted compared to measurements with a smaller FWHM spatial resolution (Lawrence et al., 2003).

To illustrate this more clearly, the comparison with the 30-km altitude LP-GRS Th data is also displayed in this figure (gray points). The data points for Lunar Prospector are created by timing the 30-km altitude Th map (2’ × 2’ equal-area pixels) (Prettyman et al., 2002) with the concentration ratio 1:1. The 2’ × 2’ data points for Lunar Prospector are created by timing the 30-km altitude Th map (Lawrence et al., 2000) with 1.37. The dashed line is the best fit regression for 5’ × 5’ data points, with R²=0.91.

7. Relationship between radioactivity and topography

The comparison of radioactivity with topography can throw light on lunar surface evolution because lunar surface keeps a record of its process mainly by impacts, which may expose the radioactive materials outside and then change the surface shape. Lawrence et al. (2000) find that lower thorium on the lunar surface has an inverse correlation with topography but higher thorium keeps an approximate linear relationship with topography at lower values. Here, the relations between radioactivity and topography, as shown in Fig. 9, are extremely similar to the results of Lawrence et al. (2000). That is, the relations are mainly segregated by topography into two components: a general inverse correlation between topography and radioactivity for lower radioactive compositional distribution; and an approximate linear relationship with topography at higher radioactivity at lower topographic area. But different from that of Lawrence et al. (2000), the inverse correlation is scattered at lower SPA basin and...
higher topographic land area; linear relationship increases at the Imbrium region. Haskin (1998), using eject deposit modeling, suggests that the distribution of Th in the highlands surface along the ground tracks of the gamma ray spectrometers is consistent with the distribution expected for Imbrium ejecta deposits. Although lunar high-lands undergo subsequent impacts from small comets and asteroids, there were no larger basins formed with hundreds of kilometers in diameter. It means that there is no basin formed by larger impactor penetrating the lunar crust and excavating the materials outside. Since the thickness of crust in highlands is larger than that in SPA and PKT regions (Wieczorek and Zuber, 2001), it is hard to excavate the radioactive-rich materials from the lower crust or the upper mantle. Therefore, radioactive compositions keep their original distributions on the highlands. The lower abundance with higher topographic data may be caused by the ejecta from the nearby basin. The ejecta masked the pre-existing radioactive compositions on the surface, making the abundance to be descended. In addition, because the impactors are dispersive on the lunar surface with different size, the relationship between radioactive compositional abundance and topographic data is scattered.

Radioactive composition in the SPA basin is thought being of local and produced by an oblique impact with north–south alignment (Garrick and Zuber, 2009). North–south asymmetry in depth of excavation supported by north–south structural and geologic asymmetries, such as sharper and higher topography, iron contours in the north, suggests that radiation-rich materials excavated from lunar crust or mantle in the north portion are more than that in the south portion. This may be the reason for the higher radioactivity distributed in the region with lower topography in SPA basin.

High-radioactive abundance in the Procellarum KREEP Terranes, as mentioned above, is related to the Imbrium event. If there are no mare basalts and volcanic flows covering, the abundance in the center of Imbrium basin should be higher than its surrounding as well as the topography should be lower than its surrounding. High-FeO mare basalts and volcanic lava flows masking the surface resulted in the lower radiation in the basin. Abundance outside Imbrium basin being lower than that in the basin is related to the ejecta where the longer distance from Imbrium center has the thinner deposits, that is lower abundance. Although radiation within the Imbrium basin having lower topography was coved by mare basalts and volcanic lava flow, that in the highlands in Procellarum KREEP Terranes has little influence since the basalts melt and volcanic flows cannot cover the places with higher topography. Therefore, in this region, areas with higher topography still keep higher radioactive abundance.

8. Conclusions

In this paper, an overview of gamma-ray spectrometer on board CE-1 spacecraft is described and its spectrum is analyzed for elements measured from the lunar surface. CGRS has a relatively higher energy resolution (~9% fwhm at 662 keV) and measures data with higher quality for its 1-year mission. Energy band (0.55 MeV < E < 0.75 MeV) method was used to calculate the distribution of radioactive elements. Since the U gamma ray line dominates the shape of the spectrum in this energy region, this radioactive map can indirectly describe the U distribution on the lunar surface. The results show that high-radioactive composition is concentrated in the PKT on the nearside. SPA basin has moderate concentration and the highlands have low concentration in radioactive elements. All these results were consistent with those of previous results (Lawrence et al., 1999, 2000; Prettyman et al., 2002, 2006; Jolliff et al., 2000). The comparison between CE-1 radioactive map and that of Lunar Prospector (mixing map of U and Th with ratio 1:1) shows that both data correlate well and can be used for further analysis.

The relation between radioactive composition and topographic data on the lunar surface shows similar characteristics with that of Lunar Prospector (Lawrence et al., 2000). The inverse correlation in highlands of PKT and much of SPA basin suggests radioactive-rich materials increasing in abundance at lower depths. But this correlation is scattered at the lower SPA basin. The linear relation in highlands of PKT may give us more evidence to explain why the emplacement of radioactive composition in the highlands of PKT is related with the Imbrium impact.

In addition, global counting rates of thorium and potassium (Zhu et al., submitted) are derived and the results will be provided in future. Absolute abundances of thorium and potassium are now calculated and analyses are under way. To analyze the lunar inner structure, such as thickness and layer model of the lunar crust, relationship between global radioactive distribution and lunar crust model is derived and the results will be described elsewhere.

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