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Lunar Surface Radioactivity: Preliminary Results of the Apollo 15 and Apollo 16 Gamma-Ray Spectrometer Experiments

Abstract. *Gamma-ray spectrometers on the Apollo 15 and Apollo 16 missions have been used to map the moon's radioactivity over 20 percent of its surface. The highest levels of natural radioactivity are found in Mare Imbrium and Oceanus Procellarum with contrastingly lower enhancements in the eastern maria. The ratio of potassium to uranium is higher on the far side than on the near side, although it is everywhere lower than commonly found on the earth.*

The Apollo 15 and Apollo 16 missions carried a group of orbiting geochemistry experiments, including an alpha-particle spectrometer (*1*), an x-ray spectrometer (*2, 3*), and a gamma-ray spectrometer (*4*). These instruments, located in the scientific instrument module bay of the service module, were operated in orbit during the lunar stay of each mission. This report is an account of the preliminary findings of the gamma-ray spectrometer experiment. A gamma-ray spectrometer was previously operated in lunar orbit aboard Luna 10 (*5*).

This experiment was designed to measure the concentrations of the most important natural gamma-ray emitters, Th, U, and K, in the surface layers of the region overflown. The instrument is also capable of measuring the concentrations of other elements which give rise to characteristic gamma-ray lines under cosmic-ray bombardment. The Apollo instrument consisted of a scintillation detector and a 511-channel pulse-height analyzer. The sensing element of the detector was a cylindrical scintillation crystal (7.0 by 7.0 cm) of NaI(Tl), coupled to a photomultiplier tube 7.6 cm in diameter. In order that the instrument reject signals produced by charged particles, the NaI(Tl) crystal assembly was surrounded by a plastic scintillator coupled to a photomultiplier tube 3.8 cm in diameter. The entire instrument was contained within a cylindrical thermal shield and mounted on a boom which was extended 7.6 m during prime periods of operation to remove the detector from the vicinity of gamma radiation produced in the spacecraft. The details of the instrumentation have been discussed elsewhere (*4*).

Prime data for this experiment could be collected only after the separation of the lunar module from the orbiting spacecraft, because of the presence of a radioisotope thermoelectric generator used to power surface experiments. During the Apollo 15 mission, 74 hours of lunar data were collected with the gamma-ray boom fully extended. Because of the comparatively high latitude of the landing site, the orbit of the spacecraft was inclined about 30°, which, in combination with the monthly rotation of the moon, allowed a considerable fraction of the lunar surface to be investigated. This instrument drifted in gain rather rapidly at first. We compensated for the total decrease in gain of 32 percent while in lunar orbit by commanding an increase in the high voltage supplied to the larger photomultiplier tube. The energy resolution (full width at half maximum) for the ^{137}Cs line at 0.662 Mev was 8.6 percent. The Apollo 16 mission covered a different region of the moon, with more intensive coverage of a smaller area. Useful lunar data were collected for 71 hours. The drift in gain was only 9 percent in lunar orbit; the energy resolution was also notably better, about 7.4 percent.

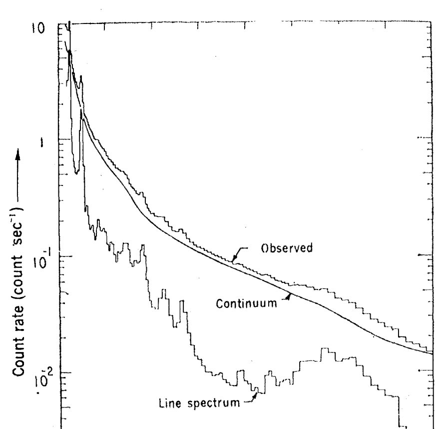

Fig. 1. Apollo 16 pulse-height spectrum, 270-minute accumulation, over 1° to 73°W. (Upper curve) Transmitted data; (middle curve) featureless continuum; (lower curve) net line spectrum.

The total areal coverage achieved on both missions was about 20 percent of the entire lunar surface at altitudes of 100 to 120 km. Regions at the east and west limbs were flown over on both missions, and data for these regions provide a cross-check of results.

A typical Apollo 16 pulse-height spectrum is shown in Fig. 1. The upper curve shows the transmitted spectrum; most of the events of the upper curve are part of a smooth continuum (middle curve) containing little useful chemical information. In the lowest spectrum of Fig. 1 our best present estimate for that continuum has been removed, and the line structure shows more clearly. The net line pulse-height spectrum must be unfolded (*6*) to obtain the incident photon spectrum from which concentrations can be calculated.

Quantitative values for the concentrations of the nine elements detected to date will not be reported here since the full matrix inversion analyses required are not yet complete. However, some major results are already available. 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 2.61-Mev line due to Th, the regional *differences* in count rate are overwhelmingly attributable to the varying intensities of the lines of the radioactive elements Th, U, and K. This is a fortunate circumstance, since the statistical precision of the total count rate in this region (fixed in practice at 0.55 to 2.75 Mev) is excellent, and we can thus obtain the best possible areal resolution. At a nominal altitude of 100 km, the theoretical resolution of the system is of the order of 70 km or 2.5°, for cases of distinctive contrast (*6*). This resolution appears to be confirmed by the data. In the procedure adopted here, an analysis of the relative counting rates at 0.55 to 2.75 Mev within the crossover area provided the factor for normalizing the Apollo 16 results to those of Apollo 15. The Apollo 16 average counting rate in this region is 4.6 percent greater than that from Apollo 15, in close agreement with the ratio of the particle radiation fluxes observed on the two missions when charged particles were not rejected. The data from both missions have been corrected to an altitude of 100 km; the solid angle subtended by the moon at the detector is an accurate enough normalization over the narrow range of altitudes at which data were taken. Adequate information is not yet available to permit a lesser correction for local topography. The data were also corrected for the live time of the instrument; no other corrections have been applied.

The main results of this portion of the analysis are presented on a 5° scale in Fig. 2, A and B, for the near and far sides, respectively; 60 hours of Apollo 15 data and 45 hours of Apollo 16 data were available for this compilation. For the areas covered by both Apollo 15 and Apollo 16, the data represent a time-weighted average.

The range of the corrected counting rates is from about 73 to 94 count sec^{-1}, or about 25 percent. The standard deviation for a typical counting time of 300 seconds per 5° square is about 0.5 count sec^{-1} on the basis of counting statistics alone; it is about 1 count sec^{-1} for the shortest counting times used. The reproducibility of successive passes, and in regions overflown on both missions, is good.

The observations warrant some definite conclusions even at the present stage of data analysis:

1) On both missions, all 5° regions within and bounding the overflown western maria show higher levels of radioactivity than any 5° region elsewhere. The contrast between these regions and the rest of the observed moon is striking, particularly in comparison with the eastern maria. We believe it can be reasonably inferred that the western mare regions not flown over are also, at least in the main, highly radioactive, and that other regions of the moon are generally less so. With reference to the abundances of the radioactive elements, the boundaries between Oceanus Procellarum and named mare regions contiguous to Oceanus Procellarum, such as Mare Nubium, do not correspond to boundaries of composition, thus settling an old question (*7*). These observations, when combined with the data on the radioactive content of samples from the Apollo 12

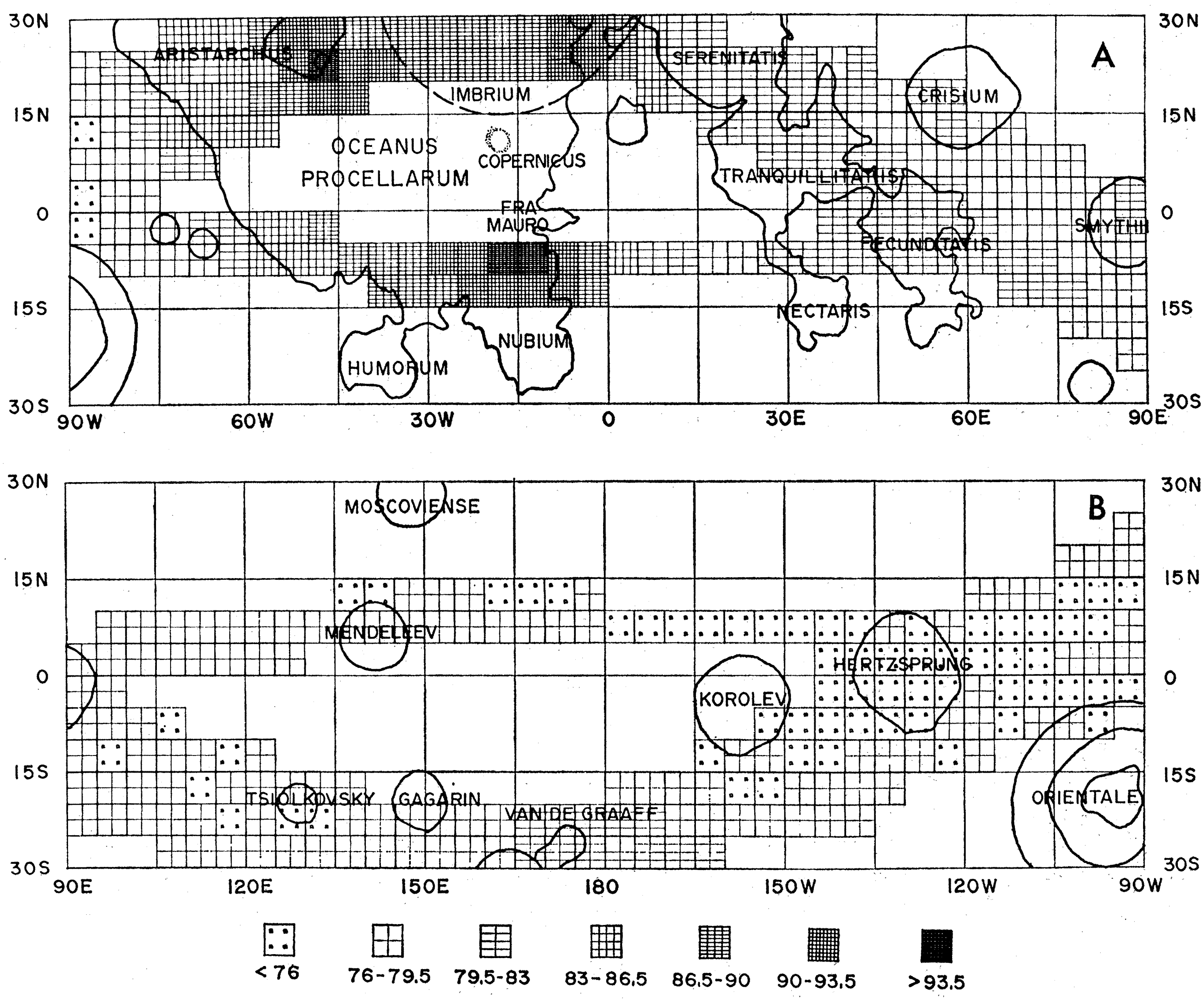

Fig. 2. Distribution of lunar radioactivity in the energy region from 0.55 to 2.75 Mev over the Apollo 15 and Apollo 16 ground tracks: (A) near side; (B) far side. The data are presented on a 5° × 5° scale over a base map freely adapted from one furnished by F. El Baz. The intensity key is in counts per second.

and Apollo 14 sites (*8*), imply a geochemical relationship for the entire Mare Imbrium–Oceanus Procellarum region.

2) There is detailed structure within the region of high radioactivity. The highest concentrations observed are in the Aristarchus area, in high ground west of the Apollo 15 landing site and south of Archimedes, and in the area south of the crater Fra Mauro. The Fra Mauro area overflown is about 7° south of the Apollo 14 landing site, soil from which showed comparable levels of radioactivity. The data from this area indicate that the Fra Mauro area is, surficially at least, related to the western maria rather than to the adjacent highlands, as has sometimes been inferred from the albedo and topography.

3) The eastern maria show evidence of locally enhanced, although lower radioactivity than the western maria. Higher intensities relative to the surrounding highlands occur in Mare Tranquillitatis, Mare Fecunditatis, Mare Crisium, and Mare Smythii. Such a local contrast has not been observed in Mare Serenitatis, but the accessibility of Mare Serenitatis to ejecta from Mare Imbrium tends to "wash out" any inherent difference. On the basis of a numerical analysis, Mare Crisium shows more contrast in radioactivity relative to its surroundings than the other eastern maria overflown.

4) The highland regions show low radioactivity, except on the borders of the western maria where lateral mixing from major impact ejecta seems to have occurred. On the far side, the highlands to the east (180° to 90°E) are perceptibly more radioactive than those of the west (90° to 180°W) particularly over the northerly track of Apollo 16. The same is true for the limb areas (compare the highland area from 60° to 105°E with the area from 90° to 120°W). There is a small maximum on the far side near Van de Graaff (where a major magnetic anomaly also occurs); no increase is seen at 8° to 10°N. Some of the small differences in count rate between the highland and eastern mare regions may be due to other elements such as Fe.

5) The results of the gamma-ray and x-ray experiments complement each other. Adler *et al.* (*2*) found that the ratio of Al to Si was low in the mare regions and high in the highlands. The Mg/Si ratio generally correlates inversely with the Al/Si ratio. The simplest interpretation of both the x-ray and gamma-ray data invokes three major components of the lunar regolith, whose compositions are derived from studies of the lunar soil and rocks. The KREEP component (potassium, rare earth elements, phosphorus) (*9*), high in radioactive and other trace elements and low in Al, originated in and is mainly confined to the western maria and their neighborhood. The mare basalt component, lower in Al and rather low in radioactivity, is significant in the western maria, dominant in the eastern maria, and low in the highland areas (*10*). The third component, commonly called anorthositic gabbro, is dominant in the highlands (*11*). This component is high in Al and Ca and low in radioactivity.

6) The values obtained for the radioactive elements in preliminary analysis are consistent with those observed at those landing sites which were overflown or might be expected to be similar to areas overflown. Thus, the average value for Th in the western maria was found to be around 5 parts per million (ppm), comparable to that observed at the Apollo 12 site, with the highest Th level somewhat above 8 ppm. The concentration in the 5° region which includes Descartes is close to 2 ppm, in agreement with the analysis of Apollo 16 fines (*12*). Over longitudes from 5° to 60°E, corresponding to the region of the eastern maria, the measured Th concentration is in the range of 1.5 to 2 ppm as compared with 2.1 ppm at the Apollo 11 mare site. The highlands on the far side show Th concentrations close to 1 ppm except near the Van de Graaff intensity high where the concentration approaches 2 ppm. The present uncertainty in these values is estimated as ± 30 percent.

7) From an analysis of peak shapes at 1.46 and 2.61 Mev and of spectra unfolded to date, it is clear that the K/Th and K/U ratios (the former have been determined with greater precision) are low for all major units of the moon as compared to the mean values of 2700 and 10^4, respectively, found for terrestrial rock types (*13*). The ratios are higher for the western maria than for the eastern maria, as found in soil samples from the landing sites. Although we cannot yet fix values with confidence, distinctively higher values are found in the farside regions than in and near the maria.

8) Of the other elements whose concentrations can be determined, Fe is one of the most interesting. Its concentrations are high, as expected in mare regions. In the farside highlands the Fe concentration is lower but still significant, comparable to the concentrations observed at the Surveyor 7 or at the Apollo 16 landing site.

The uniquely high concentrations of KREEP in the western maria may be evaluated in terms of the following: (i) the composition of a postulated single major impacting body which formed this unit; (ii) the size of an impacting body, irrespective of composition, which may have ejected, as well as melted, magmatically fractionated material from a greater depth than any other lunar impact; (iii) a lateral as well as vertical nonhomogeneity of the primitive lunar surface; or (iv) a combination of possibilities ii and iii. That the high concentration of radioactivity both within the boundaries of the western maria unit and for distances up to 300 km beyond them could be entirely due to the chemical composition of an incoming body seems most unlikely (unless the body was very large and slow moving).

The locations of the three regions of highest radioactivity do not suggest to us a common maximum at some intermediate latitude (for example, Copernicus or Kepler). The broad distribution of ejecta around the western maria, the noncentral location of Mare Imbrium, and the observation of three maxima in the concentration of natural radioactivity, only one of which is in Mare Imbrium, could imply that the Imbrium impact was not the only major impact event which preceded the formation of Oceanus Procellarum and its contiguous maria.

An alternative, suggested by the extent and magnitude of the radioactivity in the highlands that surround the western maria, is that the KREEP was emplaced by magmatic fractionation from the interior over a broad area including these adjoining highlands prior to the excavation of Mare Imbrium and the subsequent filling of the Imbrium-Procellarum region. This model would be consistent with a measured KREEP age of 4.4×10^9 years (*9*), as well as with the observation that the three locations of highest KREEP concentration within the western maria can be associated with nonmare type regions, two with possible Imbrium ejecta and the third with the Aristarchus plateau.

If most of the highland radioactivity in the region of 60° to 80°W arose by emplacement rather than from ejecta from the mare basin, there is no need to invoke multiple major impacts as part of the process of formation of the Mare Imbrium–Oceanus Procellarum complex. The irregular western boundary of Oceanus Procellarum is evidence that its configuration is the result of topography rather than excavation. Whether the highland radioactivity is the result of emplacement or ejecta, what seems clear from these observations is that the radioactive material was a major component of the excavated basin as well as of the subsequent lava flows which filled the basin and the surrounding regions of lower elevation.

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Cannabis and Temporal Disintegration in Experienced and Naive Subjects

Abstract. *The effects of 3.3 and 6.6 milligrams of Δ^9-tetrahydrocannabinol and of placebo on performance of three cognitive tasks were compared for naive subjects and experienced cannabis smokers. No differences in performance or reported subjective effects were found between these two groups. A significant decrement was found following dosage at both levels, replicating earlier findings of temporal disintegration during cannabis intoxication.*

Behavioral tolerance to the effects of cannabis intoxication has frequently been claimed by experienced users of the drug (*1*, *2*) and has recently received some support from experimental data. Prolonged administration of Δ^9-tetrahydrocannabinol (Δ^9-THC) to pigeons has resulted in evidence of behavioral tolerance (*3*). Weil *et al.* (*4*) found a difference in the performance of experienced and naive subjects after smoking cannabis on two of the three performance tasks employed. They did not, however, control for practice effects for the experienced users, so the lack of performance impairment for these subjects cannot be considered definitive evidence for behavioral tolerance. Two further studies using human subjects have investigated the experience variable (*5*, *6*). Both of these studies compared casual users with heavy users of cannabis and found trends toward less impairment of heavy users' performance, although only one of the eight tasks used in the two studies showed a significant difference between the two groups.

In the present study, performance of naive and experienced subjects was compared on three cognitive tasks, previously shown to be impaired after oral ingestion of cannabis (*7*). While a significant dose-related impairment occurred in two of these tasks, indicative of temporal disintegration, no significant differences in performance between the two groups were found. There was also no difference in reports by experienced and naive subjects of subjective effects experienced during intoxication.

The basic task investigated was the Goal Directed Serial Alternation task (GDSA), a task which required the subject to simultaneously hold in mind and coordinate information as well as perform mental operations relevant to pursuing a goal. The subject was assigned a starting number in the range 106 to 114 and asked to subtract 7 and then add either 1, 2, or 3 and to continue such alternate subtraction and addition until the initially assigned goal number was reached. Two other simpler tasks were employed to measure short- and long-term memory during cannabis intoxication. These were the Serial Subtraction of Seven task (SSS) which required subjects to repeatedly subtract 7 from an assigned starting number, in the range 96 to 104, until zero was reached, and finally, the Digit Span (DS), both backward and forward. There was a significant dose-related decrement in performance after smoking cannabis for both experienced and naive subjects on both the GDSA and the SSS, and no impairment in the performance of either group on the DS both backward and forward.

Eighteen male volunteers were screened by a psychiatric interview and a psychological test before taking part in the study. Nine of these had no experience with cannabis and nine had histories of smoking cannabis socially, ranging from 18 months to 10 years (median, 3 years). Frequency and regularity of use fluctuated considerably and varied within the group from about once a month to three times a week (median, once a week). The two groups of naive and experienced subjects were matched with regard to age and education.

The placebo material was prepared by extracting leaf in a Soxhlet apparatus with hexane for 3 hours. This gave material with smell and taste very similar to those of the active leaf. This placebo material was generally accepted as a low dose of cannabis during the experimental session. Cigarettes containing 500 mg of active leaf material, 250 mg of active leaf material, or placebo material alone were prepared with a hand rolling machine. The active leaf was sandwiched between placebo material so that no active leaf was lost during lighting or left in the unsmoked butt. The total leaf content of all cigarettes was 700 mg. The ciga-