Reports

Detection of Radon Emanation from the Crater Aristarchus by the Apollo 15 Alpha Particle Spectrometer

Abstract. *The alpha particle spectrometer aboard the Apollo 15 command/service module was designed to detect alpha particles from radon decay and to locate regions with unusual activity on the moon. A significant increase in radon-222 activity was detected from a region containing the crater Aristarchus. The result is interpreted as probably indicating internal activity at the site. By analogy with terrestrial processes, increased radon emanation may be associated with the emission of other volatiles.*

The Apollo 15 and Apollo 16 missions to the moon had, for the first time in the Apollo series, scientific instrumentation in the command/service module dedicated to orbital investigations of the lunar surface. Among the instruments were three spectrometers which shared the common objective of mapping the spatial distribution of atomic and nuclear radiation from lunar orbit and relating the spectral quality of the fluxes to the chemical composition and physical conditions at the lunar surface. We report here some results from one of these instruments, the alpha particle spectrometer (*1*). This instrument was capable of detecting alpha particles from the lunar surface and resolving their energy and spatial distributions.

The purpose was to detect the characteristic alpha particles from the decay of radon gas, a daughter product of uranium and thorium, and to identify regions with unusual activity. Kraner *et al.* (*2*) suggested that the gaseous nature of radon will permit it to diffuse through the regolith and emanate to the lunar atmosphere. As a result there will be a finite number of radon atoms above the surface, trapped by the moon's gravity. In this condition the radon atoms are free to follow ballistic trajectories until they decay. When they decay, characteristic alpha particles are emitted and heavy recoil atoms are deposited on the lunar surface. The surface deposit is itself unstable against radioactive decay and will be a further source of characteristic alpha particles. The alpha particle spectrometer maps the rate of emanation of radon from the moon. A region of the moon characterized by a locally higher rate of radon emanation that cannot be explained by a local increase in the concentrations of uranium and thorium is a candidate for being a site of internal activity.

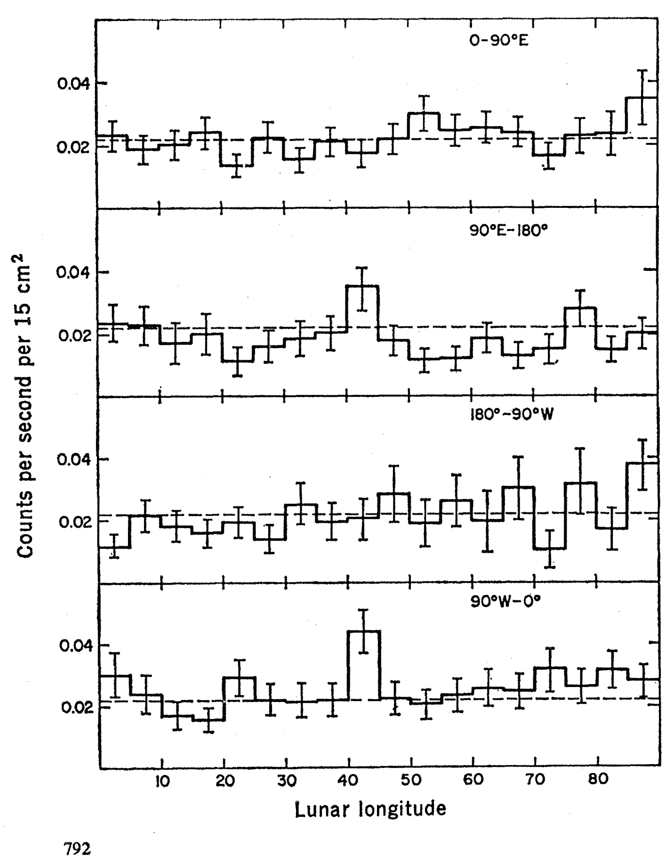

Fig. 1. Count rate of alpha particles in an energy range corresponding to the decay of ^{222}Rn and her daughters (excluding ^{210}Po), as a function of lunar longitude. The data are from Apollo 15 orbits 34 to 46. The dashed line represents the lunar average for these orbits. The error bars indicate the counting statistics. One count per second per 15 cm^2 is equivalent to 0.23 dis cm^{-2} sec^{-1} of ^{222}Rn.

There are three distinct signals of interest. First are alpha particles emitted by the uranium daughter product ^{222}Rn (half-life 3.8 days) and her daughter products. The ratio of the intensity in the ^{222}Rn line to the intensities in the daughter product lines (except that of ^{210}Po) is expected to have an equilibrium value of two. Approximately one-half of the heavy recoils from the decay of gravitationally bound ^{222}Rn atoms are directed downward and are deposited on the surface; the rest have sufficient energy to escape the moon's gravity. Polonium-210 gives a second type of signal because its production is held up by the 21-year half-life of ^{210}Pb. Thus, the instantaneous activity ratio of ^{222}Rn to ^{210}Po will depend on the history of radon emanation over a period of time comparable to 21 years. The third type of signal expected is due to alpha emission from the thorium daughter ^{220}Rn (half-life 55 seconds) and her daughters. Radon-220 has considerably less time to diffuse through the regolith than ^{222}Rn. Thus, its average concentration above the surface will be much smaller.

Thus far in the analysis of Apollo data, we have seen examples of the first and second type of signals from the moon. We report here the observations of ^{222}Rn alpha particles significantly in excess of the lunar average from the vicinity of the crater Aristarchus. We have also detected ^{210}Po from other areas of the lunar surface in amounts exceeding the quantity that would be in equilibrium with ^{222}Rn. This is evidence for transient lunar radon emanation (*3*). The alpha particle spectrometer operated in lunar orbit for most of a 224-hour period commencing at 14:45 G.M.T., 29 July 1971. Most of the data were obtained at an altitude of 110 km with the instrument directed toward the local nadir. For several 15-minute periods the instrument viewed deep space for background evaluation.

The individually telemetered counts may be sorted or accumulated in an arbitrary manner according to either energy or lunar position. The energy channels for radon-associated alpha particles are determined from the ^{208}Po calibration sources plus a ^{210}Po line which has both an instrumental and a lunar component.

Figure 1 shows the count rate as a function of longitude in 5° intervals for the energy channels associated with ^{222}Rn and her two prompt daughters. The count rate includes combined data from 13 orbits of Apollo 15. The average count rate is indicated by the dashed line. The statistics vary considerably as a function of longitude. This was caused by several operational constraints which resulted in nonuniform coverage of the ground track. It is particularly noticeable near 90°W where a transition from real-time to stored data occurs. The highest count rate occurs in the longitude bin from 45°W to 50°W. In Fig. 2 a portion of the same data is superimposed on a photograph of the moon. The region containing the highest count rate is approximately centered on the crater Aristarchus but also includes Schröter's Valley and nearby regions. Dividing these data into finer longitude intervals does not improve the degree of localization, possibly because of limitations in the counting statistics. We observe a total of 36 counts at Aristarchus for ^{222}Rn and her two prompt daughters, compared to an expected background of 18 counts. This rate is 4.3 standard deviations (S.D.) above the mean value for the moon. The excess over background is $(10.1 \pm 3.3) \times 10^{-3}$ disintegration (dis) per square centimeter per second compared to an expected background in the bin that is equivalent to $(9.9 \pm 2.35) \times 10^{-3}$ dis cm^{-2} sec^{-1}. Radon-222 itself accounts for about one-half of the excess. Aside from the feature at Aristarchus, the data are consistent with a normal distribution. On the basis of Poisson counting statistics, the probability of observing a statistical fluctuation this large or larger at the Aristarchus region is only 10^{-4}. Furthermore, the counts from Aristarchus are correctly distributed among all the detectors and among all the orbits over this region. Thus, the excess from Aristarchus at the alpha-particle energies associated with ^{222}Rn appears to be a real effect. No significant excess (more than 3 S.D.) occurs in this region at other alpha-particle energies, such as those associated with ^{220}Rn or ^{210}Po, or at other energies where we expect the background not related to radon to be predominant. The failure to see an excess at other energies indicates that the ^{222}Rn excess is not easily explained as resulting from systematic errors. If it resulted in some unknown manner from a background effect that is systematically greater at that locale, the excess would probably be detectable at other energies.

The background level shown in Fig. 1 consists in part of a diffuse radon contribution and in part of effects not related to radon, but caused by cosmic rays. We have used two methods to estimate the diffuse radon contribution. The first method consists of estimating the net lunar contribution in the ^{222}Rn energy channels by equating it to the difference between the count rates obtained with the lunar and deep-space orientation of the detectors. In the second method we examine the total energy spectrum with the detectors in a lunar orientation. The presence of ^{222}Rn will lead to an increase in certain

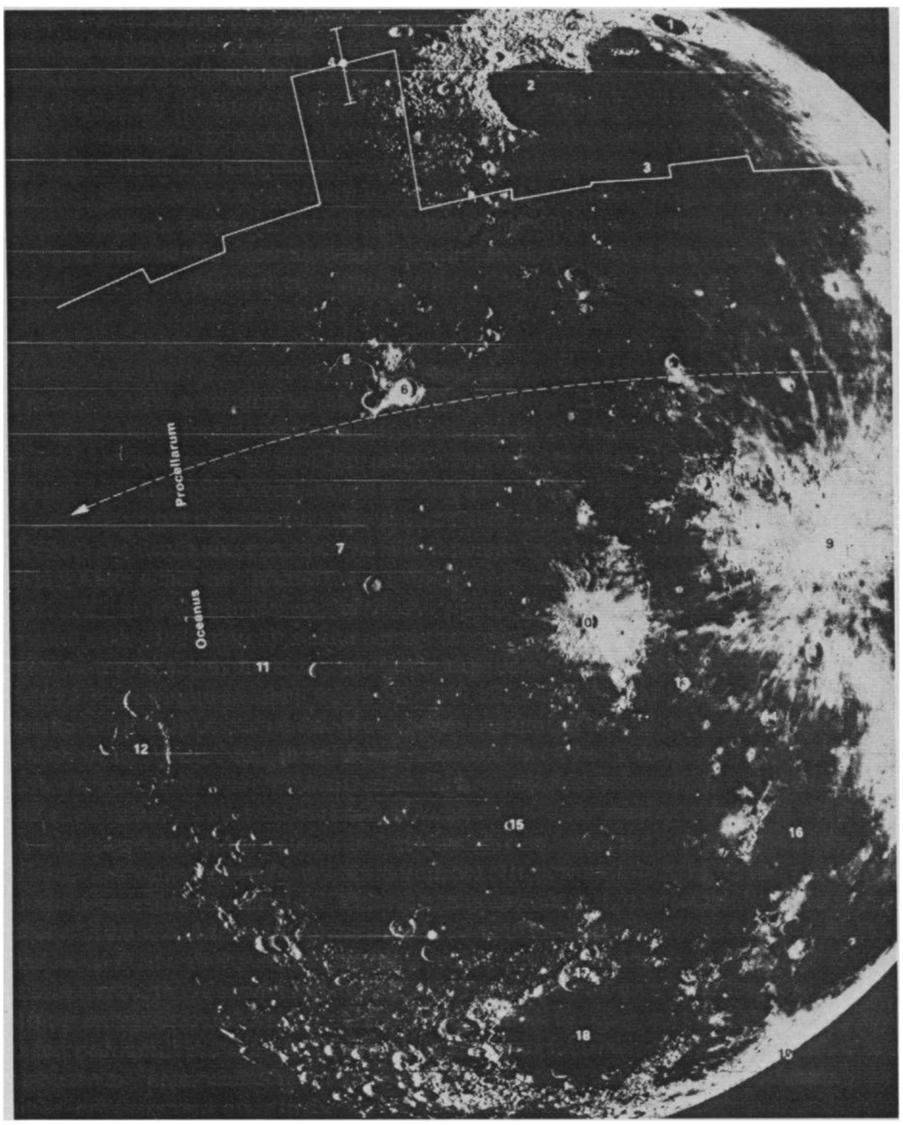

Fig. 2. A portion of the data shown in Fig. 1 superimposed on a photograph of the moon. The dashed line represents the average ground track during Apollo 15 orbits 34 to 46. It is also the baseline for the data. Key to the numbers: 1, Plato; 2, Sinus Iridum; 3, Mare Imbrium; 4, Sinus Roris; 5, Schröter's Valley; 6, Aristarchus; 7, Marius Hills; 8, Marius; 9, Copernicus; 10, Kepler; 11, Reiner Gamma; 12, Hevelius; 13, Kunowsky; 14, Lansberg; 15, Flamsteed; 16, Mare Cognitum; 17, Gassendi; 18, Mare Humorum; 19, Tycho.

energy channels of the spectrum. The count rates induced by cosmic rays are expected to be fairly uniform in energy, at least over a few million electron volts. Applying these two methods to a substantial region of the moon (40°E to 180°), we estimate the average ^{222}Rn contribution to be $(1.32 \pm 0.50) \times 10^{-3}$ and $(0.92 \pm 0.25) \times 10^{-3}$ dis cm^{-2} sec^{-1}, respectively. For present purposes it is sufficient to regard these values as an upper limit. Thus, the excess ^{222}Rn at Aristarchus is at least a factor of 4 higher than the lunar average.

Because of the localization of the observed feature, one must consider the extent to which gravitationally bound ^{222}Rn atoms are expected to remain localized about their point of emanation and compare the expected size of the distribution to the size of the Aristarchus feature. The average displacement of a radon atom during its lifetime depends on its velocity, the number of ballistic trajectories completed before decay, and the accommodation time on the surface between trajectories. A gross qualitative estimate of the mean diameter of the distribution is equal to two times the square root of the number of trajectories multiplied by the average displacement per trajectory. During the Apollo 15 orbits in which Aristarchus was observed by the alpha particle spectrometer, it was not illuminated by the sun. Thus, the temperature of the surface was probably about 100°K. At a temperature of 100°K and an assumed accommodation time of zero, the mean diameter is about 10^3 km. The size of the Aristarchus feature that can be seen above the background is at most 150 km in extent. This is considerably smaller than 10^3 km, but perhaps not unacceptably so because the accommodation time may be nonzero and because of the possibility that areas distant from the center of the source have low surface brightness and are obscured by the background. The absence of a statistically significant signal from ^{220}Rn over Aristarchus is not surprising in light of the fact that its half-life is a factor of 5000 smaller than that of ^{222}Rn. It has much less time to emanate from the regolith. The ^{220}Rn activity need only be a factor of 3 smaller than that of ^{222}Rn to be undetectable above background.

The increase of ^{222}Rn activity in the Aristarchus region must be explained in terms of either an increase in the local uranium concentration or an increase in the emanation rate, or perhaps both. First, consider the case where there is no emanation anywhere on the moon and the observed alpha particles are strictly due to decays near the surface. Only alpha particles whose energy is not reduced below about 5 Mev by absorption would be counted. Thus, only the first few micrometers of surface material could contribute. This would require an increase in the uranium concentration at Aristarchus of 200 parts per million, a value which is unacceptably high. It is much greater than the largest uranium concentrations found in returned samples and much greater than the uranium concentrations that would explain the count rates seen by the Apollo 15 gamma ray spectrometer, which explored the same ground track as this instrument (*4*). Also, one would expect an increase in thorium to accompany an increase in uranium. In that case there would be an increase at the energies of alpha particles from ^{220}Rn and her daughter products about as great as the ^{222}Rn effect. But in fact no increase in counts is seen at energies other than those corresponding to ^{222}Rn. Hence, we conclude that an increased concentration without emanation cannot explain the excess.

Now consider another situation, in which there is a uniform emanation rate over the whole lunar surface. We have established that the ^{222}Rn activity at Aristarchus is at least a factor of 4 larger than the lunar average. The regions adjacent to Aristarchus along the Apollo 15 ground track, the western maria, have a counting rate that is close to the lunar average (Fig. 1). The Apollo 15 gamma ray spectrometer indicates at most a 50 percent increase in uranium concentration in the Aristarchus region compared to the adjacent regions. Thus, the local increase in uranium concentration is not sufficient to explain the local factor of 4 increase in ^{222}Rn activity. Therefore, we conclude that the increase of ^{222}Rn activity in the region of Aristarchus must be caused primarily by a local increase in the rate of emanation.

The higher emanation rate at Aristarchus is not likely to be related to the impact process which formed Aristarchus because of the large difference between the age of the crater and the half-life of ^{222}Rn. The higher emanating power could be due to either a special condition of the regolith in which it is unusually porous locally or a mechanism that results from internal activity. It is clear from this measurement and a variety of others before Apollo 15 (*5*) that the average lunar rate of radon emanation is considerably smaller (two or more orders of magnitude) than terrestrial rates, whereas the concentrations of uranium and thorium appear to be comparable. This discrepancy between the earth and the moon cannot easily be explained by differences in passive mechanical conditions of the soil, such as grain size or volume of voids, because terrestrial variations in these factors do not affect the radon emanation so strongly. The large rate of terrestrial radon emanation is caused by an interaction between the soil and the air, a process which does not occur on the moon. The general flow of gases from the earth to the atmosphere is a primary influence in the exhalation of radon. Factors associated with terrestrial internal activity—such as gas release, volcanic activity, and seismic events—generally increase the radon emanation rates. By analogy, the locally larger emanation rates from Aristarchus may be a result of internal activity factors involving other volatiles rather than a passive condition of the regolith. Aristarchus has long been studied as a site of anomalous, transient optical events (*6*). Although no such events were reported at the time of Apollo 15, it is not unreasonable to conjecture that the observed radon emanation from Aristarchus at the time of Apollo 15 is associated with the same internal processes that will on occasion emit volatiles in sufficient quantity to produce observable optical events.

PAUL GORENSTEIN
PAUL BJORKHOLM
American Science and Engineering, Cambridge, Massachusetts 02139

References and Notes

1. P. Gorenstein and P. Bjorkholm, in *Apollo 15 Preliminary Science Report* (NASA SP-289, National Aeronautics and Space Administration, Washington, D.C., 1972), pp. 18-1 to 18-7.
2. H. W. Kraner, G. L. Schroeder, G. Davidson, J. W. Carpenter, *Science* **152**, 1235 (1966).
3. P. Bjorkholm, L. Goluh, P. Gorenstein, in preparation.
4. J. R. Arnold, J. I. Trombka, L. W. Peterson, R. C. Reedy, A. E. Metzger, paper presented at the meeting of the Committee on Space Research (COSPAR), Madrid, 1972.
5. R. S. Yeh and J. A. VanAllen, *Science* **166**, 370 (196 A. L. Turkevich, J. H. Patterson, E. J. Franzgrote, K. P. Sowinski, T. E. Economu, *ibid.* **167**, 1722 (1970); R. M. Lindstron, J. C. Evans, R. C. Finkel, J. R. Arnold, *Earth Planet. Sci. Lett.* **11**, 254 (1971).
6. For a review, see B. M. Middlehurst, *Rev. Geophys.* **5**, 173 (1967).
7. Supported by NASA contract NAS9-9982.

16 August 1972; revised 18 December 1972