RADON EMANATION FROM THE MOON, SPATIAL AND TEMPORAL VARIABILITY*

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Abstract. Observations of the lunar surface with the orbiting Apollo Alpha Particle Spectrometer during the Apollo 15 and Apollo 16 missions have shown spatial and temporal variations in radon emission. There are a number of well localized features in the spatial distribution of lunar $^{222}$Rn and her daughter $^{210}$Po which apparently correlate with sites of reported transient visual events. There are sources at Aristarchus, Grimaldi and possibly Tsioirkovsky. Activity of $^{210}$Po shows enhancement at most maria edges at rates far in excess of $^{222}$Rn activity. This demonstrates unequivocally the presence of time varying radon activity at the maria edges, taking place at the present time. The increased radon emission is probably caused by sporadic internal activity. In analogy to terrestrial processes, radon may be merely a trace component accompanying the release of larger quantities of more common gases to the lunar surface.

1. Introduction

Measurements and maps of radon emission from the lunar surface have been obtained from the observations of the Alpha-particle spectrometers that were aboard the SIM bay of Apollo 15 and Apollo 16. The instrument has been described previously (Gorenstein and Bjorkholm, 1972). A number of striking features have been found in the spatial distribution of lunar radon, and we also have a positive indication of temporal variability. Some of these features will be described briefly in this paper. On the whole we feel the results of our observations require that the radon emanation be primarily the result of an internal process. In particular there is a clear association between our strongest radon signals and regions of the Moon that had been singled out previously by others as possible sites of volcanic activity.

One of the objectives of the Alpha-particle spectrometer measurements along with those of the gamma-ray and X-ray spectrometers was to map the chemical composition in the vicinity of the Apollo orbit. Radon is produced in the natural decay series of uranium and thorium so that the local radon activity might be expected to depend on the local concentrations of these elements. In addition there are various physical factors which could influence the local rate of emanation such as: porosity of the soil, gas venting, volcanic activity, and seismic activity. All of these are important on the Earth and could be important on the Moon. It is possible to imagine meteorite impacts or other large scale surficial mechanical disturbances on the Moon to be important means of liberating radon from the lunar surface, but without explanation we will say that the mechanical disturbances seem to be too small to explain signals as large as the ones we detect.


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Fig. 1. Schematic representation of $^{238}$U decay chain, showing radon diffusion to surface and decays of alpha emitting radon-daughter products. Decay of $^{210}$Po is delayed by 21 yr half-life of $^{210}$Pb.

TABLE I

Results from the observation of lunar radon emanation with the Apollo alpha particle spectrometer

<table>
<thead>
<tr>
<th>Spatial variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite level of $^{222}$Rn, $\sim 10^{-3}$ terrestrial</td>
</tr>
<tr>
<td>Hot spots apparently associated with sites of ‘transient lunar phenomena’ examples: Aristarchus, Grimaldi</td>
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<tr>
<td>$^{222}$Rn higher in maria than highlands</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Temporal variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{210}$Po levels exceed amount in equilibrium with $^{222}$Rn</td>
</tr>
<tr>
<td>$^{210}$Po concentration highest in sea of fertility</td>
</tr>
<tr>
<td>Maria ‘edge effect’, enhancement of $^{210}$Po at boundaries of Maria</td>
</tr>
</tbody>
</table>

Two types of events as illustrated in Figure 1 have been detected so far in the Apollo data: (1) alpha particles from $^{222}$Rn in association with two prompt daughters ($^{218}$Po and $^{214}$Po) and (2) alphas from $^{210}$Po. The ratio of intensities of $^{222}$Rn and her prompt daughter alpha activities are established after $\sim 10$ min of $^{222}$Rn emission at a uniform rate. Since the half-life of $^{222}$Rn is 3.8 days, any measurable signal from these three elements is expected to vanish 10–15 days after diffusion to the surface has stopped. Detection of $^{210}$Po constitutes an entirely different class of observation.
because its production is held up by the 21 yr half-life of $^{210}\text{Po}$. The presence of $^{210}\text{Po}$ along with $^{222}\text{Rn}$ and daughter products implies a continuing radon diffusion, whereas detection of $^{210}\text{Po}$ alone indicates diffusion which has ceased days to years previously. A non-uniform distribution of $^{210}\text{Po}$ implies localized $^{222}\text{Rn}$ emanation in the recent past. However, a single measurement of $^{210}\text{Po}$ activity is insufficient to determine whether $^{222}\text{Rn}$ emanation has occurred continuously/sporadically for $\sim 21$ yr, or whether there was a single large event of short duration.

Fig. 2. Top: Comparison of spectra from lunar longitudes 40–80°E (solid) vs 110–170°E (dashed). Bottom: Difference between the two regions, showing excess $^{210}\text{Po}$ and $^{222}\text{Rn}$ in the region 40–80°E. The difference in the energy range where contamination predominates ('CON') vanishes as expected.
Table I lists several results obtained thus far relating to the spatial distribution and time variability of lunar radon.

2. Detection of Radon

The method of radon detection depends on the energy resolution of the alpha spectrometer. The energy spectra from two regions of the Moon (normalized to equal time) observed during Apollo 16 are shown in Figure 2. The spectral difference between the two regions is also shown. This difference between the two regions is confined

**SPATIAL VARIATION OF $^{222}$Rn$^*$**

**APOLLO 15 GROUND TRACK**

![Graph showing spatial variation of $^{222}$Rn](image)

* plus two prompt daughters

Fig. 3. Distribution of $^{222}$Rn plus prompt daughters across the Apollo 15 groundtrack as a function of lunar longitude. Data is from orbits No. 34–46 of Apollo 15. Dashed line shows whole Moon average.
to the characteristic energies of alpha particles from $^{222}$Rn and $^{210}$Po. In the energy range where background predominates (channels 50–65), the difference is essentially zero. The difference is also zero in an energy range where there are alphas due to an unintentional contamination of the instrument with a calibration source prior to flight. Both the background, which is probably cosmic-ray induced, and the contamination should exhibit no spatial dependence which is reflected in the fact that differences between regions vanish.

3. Spatial Dependence of $^{222}$Rn

Figure 3 shows the spatial distribution of $^{222}$Rn across the Apollo 15 ground track. This channel includes $^{222}$Rn, her two prompt daughters $^{218}$Po plus $^{214}$Po and an unknown amount of background which is not varying. Both large scale and fine scale spatial features can be identified. The most striking feature is the occurrence of the largest count rate in the bin that includes the crater Aristarchus (plus Schroeter's Valley and Cobra head). On the basis of Poisson statistics the probability of observing a count rate this large of larger at this location from a spurious fluctuation is less than $10^{-4}$. Figure 4 illustrates this point by showing that the Aristarchus point is well off the normal distribution of deviations. The effect is localized to a 5° region of longitude (Figure 5). The limited number of counts do not permit better localization. Although it is not obvious that evolving $^{222}$Rn would remain as well localized as 5° during its 3.8 day half-life, other localized effects described below do indeed in-

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**APOLLO 15 ALPHA PARTICLE SPECTROMETER**

**DISTRIBUTION OF DEVIATIONS FROM THE WHOLE MOON AVERAGE**

FOR RADON-222 (+DAUGHTERS) DATA FROM 111 GET TO 220 GET

![Graph showing distribution of deviations from average count rate of $^{222}$Rn plus prompt daughters. Deviation of Aristarchus data is indicated at lower right.](image)

**Fig. 4.** Distribution of deviations from average count rate of $^{222}$Rn plus prompt daughters. Deviation of Aristarchus data is indicated at lower right.
Fig. 5. A portion of the data of Figure 3 shown superimposed on a photograph of the Moon. The dashed line represents the average Apollo 15 groundtrack for orbits No. 34-46 and is also the baseline for the data.
dicate that 5° is a characteristic distance for the diffusion of free radon. The bin with the second largest rate is located at a longitude of 130°–135° which is in the vicinity of the crater Tsiolkovsky. The counting statistics are not as compelling as in the case of Aristarchus, but they are still very suggestive particularly with respect to the local background which is lower than the lunar average.

In addition to the one and possibly two highly localized features, we note a particular large scale variation of $^{222}\text{Rn}$. The average level for each lunar quadrant is significantly different. In compiling the average for 0–90°W (mostly Mare Imbrium and Oceanus Procellarum), the Aristarchus point was not included, but this is still the largest of the four. The second largest average value is the quadrant 0–90°E which contains the smaller front side maria. The rate is lowest over the highlands. There are several possible explanations for this variation. One is that we are seeing the variation of uranium concentration across the Apollo 15 groundtrack while the radon emanation is constant. The spatial variation of $^{222}\text{Rn}$ does correlate at least in a gross sense with the results from the gamma-ray spectrometer which measures the uranium concentration directly (Metzger et al., 1972). One of the interesting jobs for the future will be to compare these two sets of measurements in detail. However, it is also possible that we are seeing an effect suggested by Heymann and Yaniv (1971), that $^{222}\text{Rn}$ tends to be highest at the sunrise terminator. During Apollo 15 the sunrise terminator was in the quadrant 0–90°W.

4. Temporal Variability in Radon Emanation and Spatial Dependence of $^{210}\text{Po}$

In Figure 2 it is apparent that the two regions differed much more strongly in $^{210}\text{Po}$ than $^{222}\text{Rn}$. As explained above $^{210}\text{Po}$ is a descendent of $^{222}\text{Rn}$. Since its activity with respect to $^{222}\text{Rn}$ is much higher than equilibrium we can conclude that there has

![Fig. 6. Measured count rate across the Apollo 16 groundtrack at energy corresponding to lunar $^{210}\text{Po}$.](image-url)
Fig. 7. Rate of $^{210}\text{Po}$ decay superimposed on a photograph of the Moon. The dashed line represents the average Apollo 16 groundtrack and is the baseline for the data.
been more localized radon emanation sometime during the past 21 yr. Thus we have positive evidence that the greater activity of one region as compared to the other is a result of time varying radon emanation. The maps of $^{210}$Po activity on the lunar surface are determined by the integrated history of radon emanation during the 21 yr, whereas $^{222}$Rn indicates emanation at the actual time of the observation.

A strong spatial variation of $^{210}$Po is evident in the Apollo 16 data shown in Figure 6. In general, there is an increase starting at 90°W (Oceanus Procellarum) and continuing to increase across the front side of the Moon and reaching a maximum over Mare Fecunditatis and Mare Smythii. The rate drops dramatically to the east of Mare Smythii and remains low throughout the lunar farside. Another increase (60–70°W) occurs in the vicinity of the crater Grimaldi and/or the southwest edge of Oceanus Procellarum.

5. Association with Sites of Transient Lunar Phenomena

In light of the fact that the $^{222}$Rn peak is at the crater Aristarchus, the $^{210}$Po peak at Grimaldi is another example of a possible association between a localized radon source and a crater that appears in historical records as a site of ‘transient lunar phenomena’ (TLP) (Middlehurst, 1967). Data in the vicinity of Grimaldi are shown superimposed upon a photograph of the Moon in Figure 7. The counting statistics are as good as in the Aristarchus case giving us reasonable confidence in the reality of the effect, but there is a possibility that the peak is not due to Grimaldi but to a general phenomenon to be described below that occurs at the edges of virtually all the maria. The Apollo 16 orbit did not pass directly over Alphonsus, another TLP crater of historical record, but interestingly there is a broad maximum in the count rate at the points nearest to Alphonsus. So although we have no positive evidence of localized emanation from Alphonsus, our data are consistent with it.

Since we know from terrestrial experience that increased venting of gases will include a proportionate enhancement in radon it is possible to conjecture that there has been an outward flux of gas from the TLP craters within the past 21 yr and that the flow included trace amounts of radon. At the time of Apollo 15 there was actually a small flux from Aristarchus. If the $^{222}$Rn peak at Tsiolkovsky (Figure 2) is significant, then in light of the association between TLP craters and radon sources, we suggest that the Tsiolkovsky would be another one of the historical TLP sites if it were located on the frontside.

6. Maria Edge Effect

Another phenomenon appears in our data. There is generally an increase in $^{210}$Po activity at the edges of almost all maria although the intensity of the phenomenon varies considerably among the maria. This occurs both in Apollo 15 and Apollo 16 observations (cf. Bjorkholm et al., 1973). The best example is Mare Fecunditatus shown in Figure 8. The rate is significantly higher at the interface between the maria.
Fig. 8. Rate of $^{210}$Po decay as a function of longitude across Mare Fecunditatis. Dashed line shows background level.

Fig. 9. Rate of $^{210}$Po decay as a function of distance from edge of mare for Maria Fecunditatis, Smythii, Nubium, Cognitum and Oceanus Procellarum. The same data are shown twice in reflected form for illustrative purposes.
and highland than it is in either the highland region or the interior of the maria. Figure 9 shows superimposed data from several maria observed on Apollo 16; Apollo 15 data looks similar. Thus we have a positive indication of activity at the present time at the edges of the maria. The effect may very well involve gas venting or some other kind of internal activity. It is also possible that at the edges of all maria there exist many smaller TLP craters which are difficult to recognize individually and that we are observing their cumulative effect. In particular, Salisbury et al. (1968) have suggested that dark-haloed craters are volcanic in origin. Those which they identify are at the edges of the maria. It is entirely possible that our $^{210}\text{Po}$ signals are an indication of gas venting from these craters.

7. Previous Measurements of $^{210}\text{Po}$

Our global observations of the lunar surface from Apollo provide the context for understanding previous measurements of $^{210}\text{Po}$. The techniques used were both in situ measurements and terrestrial laboratory analysis of returned samples. These measurements are summarized in Table II and a large spread is noted. Prior to our

<table>
<thead>
<tr>
<th>Investigator</th>
<th>Location</th>
<th>Method</th>
<th>Result (dps/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kraer et al. (1966)</td>
<td>Average</td>
<td>Theoretical, terrestrial</td>
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<tr>
<td></td>
<td></td>
<td>model</td>
<td></td>
</tr>
<tr>
<td>Turkевич et al. (1970)</td>
<td>Tranquillitatis</td>
<td>In situ Surveyor 5</td>
<td>0.042 ± 0.014</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In situ Surveyor 6</td>
<td>&lt; 0.021</td>
</tr>
<tr>
<td>Turkевич et al. (1970)</td>
<td>Sinus Medii</td>
<td>In situ Surveyor 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tycho</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Economou and Turkевич (1971)</td>
<td>Oceanus Procellarum</td>
<td>Returned Surveyor 3 Visor</td>
<td>&lt; 1.3 $\times$ 10⁻²</td>
</tr>
<tr>
<td>Lindstrom et al. (1971)</td>
<td>Tranquillitatis</td>
<td>Returned Lunar Soil and Rock</td>
<td>&lt; 4.5 $\times$ 10⁻⁴</td>
</tr>
<tr>
<td>Brodzinski (1972)</td>
<td>Procellarum</td>
<td>Returned Solar Wind Composition Foil</td>
<td>(2.4 ± 0.4) $\times$ 10⁻³</td>
</tr>
<tr>
<td>This experiment</td>
<td>Apollo 15/16</td>
<td>Orbiting Alpha Spectrometer</td>
<td>Avg = (1.5 ± 0.4) $\times$ 10⁻³</td>
</tr>
<tr>
<td></td>
<td>Groundtrack</td>
<td></td>
<td>Peak = (4.0 ± 0.8) $\times$ 10⁻³</td>
</tr>
</tbody>
</table>

global observations it was very difficult to reconcile these widely divergent data points. They could not be explained by variation in the concentration of uranium, the original sources of $^{210}\text{Po}$. Our orbital data clearly indicate that there are large spatial and temporal variations in $^{210}\text{Po}$ concentration. Thus it is not surprising that measurements made at different places and at different times do not agree.
8. Summary and Conclusions

The observations of the Apollo alpha-particle spectrometer show that there are a number of well localized features in the spatial distribution of lunar radon and that the process of radon emanation is varying in time. There is an apparent association between highly localized sources of $^{222}$Rn or her daughter $^{210}$Po and craters cited throughout history as sites of transient lunar phenomena. There are sources at Aristarchus, Grimaldi, and possibly Alphonsus. The far-side crater Tsiolkovsky is another possible radon source.

In addition to localized sources there is a diffuse component of $^{222}$Rn that is slowly varying across the Moon. The diffuse component may be correlated with the concentration of uranium.

There is an enhancement of $^{210}$Po activity at essentially all maria-highland interfaces. This phenomenon unequivocally demonstrates the existence of activity at the edges of the maria, taking place at the present time. The activity may be caused by an internal process that results in the release of gas.

References