Reports

Radioactivity of the Lunar Surface

Abstract. *Diffusion of radon and thoron from the lunar surface provides a mechanism for production of a radioactive surface layer on the moon. If the radon and thoron flux from the lunar surface is equal to that measured at the earth's surface, the equilibrium activity of this surface layer is estimated as approximately 1 microcurie per square meter, due to radon and its decay products. This activity consists of alpha particles and gamma rays at well-defined energies and of beta rays.*

The U^{238} and Th^{232} radioactive decay series produce as daughter products the radioactive noble gases radon (Rn, Rn^{222}, 3.8-day half-period) and thoron (Tn, Rn^{220}, 56-second half-period) (*1*). These gases are constantly evolved from the earth by a combination of convection and diffusion, supported by the natural concentrations of the parents. The properties and conditions of the release of Rn and Tn from the earth's surface have been well studied (*2–4*). It is of interest to consider the situation at the lunar surface. In the absence of a lunar atmosphere, Rn and Tn will, in general, be evolved from the lunar surface by diffusion. We now report on our examination of the consequences (in the light of recent investigations) of the deposition of decay products on the lunar surface (*5*).

The atmosphere about the earth convects and retains almost all of the released Rn and Tn and their daughter products until decay. The absence of a lunar atmosphere allows Rn and Tn to follow ballistic trajectories after their emission with thermal velocities from the surface, thus to form a radiogenic atmosphere. Because of recoil, half of the radioactive daughter products are directed toward and deposited on the lunar surface. The magnitude and properties of the resulting surface activity are estimated below. "Surface activity" is defined as that measured either by an observer on the lunar surface with a $4\text{-}\pi$ detector or, equivalently, by an observer in near lunar orbit outside the radiogenic atmosphere.

Radon and thoron, evolved from the lunar surface, return to the surface, since the escape velocity for the moon is 2.4 km/sec, whereas the thermal velocity at 300°K for a radon atom is about 0.15 km/sec. Although a distribution of thermal velocities and somewhat hotter daytime temperatures are present, a negligible fraction of the Rn and Tn has velocities above the escape velocity. The height of the Rn and Tn atmosphere is about 10 km. If the emission from the surface is assumed to be isotropic, the time in trajectory for emission at the median angle (60° from normality) is 1 minute. During this time about 50 percent of the Tn decays, while a negligible fraction of the Rn decays. The recoil velocity of daughter products after alpha decay is on the order of 10^2 km/sec; those recoils directed upward, of course, escape.

The Rn atoms, with a 3.8-day half-period, return to the lunar surface after emission, accommodate, and are reemitted. This process is repeated many times, the Rn thus effectively diffusing over the lunar surface and establishing a Rn atmosphere. This phenomenon cannot occur with the Tn because of its short half-period. A Tn atom emitted at thermal velocity at an angle of 45° impacts the surface about 14 km from the point of emission. Hence, if there exist regions of anomalously high (or low) concentrations of thorium supporting high (or low) fluxes of Tn from the surface, this distance indicates the magnitude of definition one can expect from such an anomaly when determined by the Tn alpha activity.

From values of the diffusion coefficient (0.02 cm²/sec), and concentrations of Rn (5000 pc/liter) and Tn (1000 pc/liter) measured in terrestrial surface layers (*3, 4*), and assuming a lunar surface porosity of 0.25, the equilibrium lunar surface activities due to Rn and Tn decays are calculated to be for Rn, 120 pc/cm² or 4 disintegrations cm^{-2} sec^{-1}, and for Tn, 0.3 pc/cm² or 1×10^{-2} disintegrations cm^{-2} sec^{-1}. In the solution of the diffusion equations a negligible concentration of radon at the lunar surface as compared to that at depth has been assumed. This assumption is consistent with a uniform atmosphere extending to an altitude of 10 km.

These rates may be compared with those expected simply from decay of the distributed U^{238} and Th^{232} in a sample having terrestrial concentrations. Because of the short range of an alpha particle in the solid material, the activity measured at the surface of the sample would be only approximately 2×10^{-2} pc/cm² (*6*).

It is noted that the stated estimates of lunar alpha activities are based on conventional diffusion theory (*4*) and do not attempt to account for several possible factors in the lunar environment that may influence the observed activity. The interstitial diffusion coefficient of Rn and Tn in the lunar surface layer may be greater by as much as a factor of 10 than that observed in terrestrial soil layers because of the vacuum condition at the surface. The moon may be of undifferentiated material, and hence it could have U^{238} and Th^{232} concentrations characteristic of the stony meteors, concentrations which are typically lower by a factor of 30 than those found in crustal terrestrial material. This would reduce the calculated activities by the same factor of 30. A measurement of the alpha activity will thus indicate whether the moon is differentiated or undifferentiated.

Uncertainties concerning diffusion coefficients at the lunar surface may be largely eliminated by measuring the diffusion coefficient in soil under vacuum conditions. Some measurements of this type have been performed (see *7*).

The effects of solar wind on a lunar atmosphere have been considered (*8*). In the case of a stable lunar atmosphere the solar wind provides a nonnegligible loss mechanism. However, the total effect on the thin (10^6 atom/cm^2) radon atmosphere proposed here, over its 3.8-day half-period, is the loss of at most only a few percent of the atmosphere by direct or charge-exchange collisions.

Some qualitative remarks may be made concerning the alpha spectra which might be observed from the lunar surface. The predicted alpha intensity is sufficient to produce clear spectra in a practical low- or medium-background alpha-ray spectrometer which could, for example, be orbited about the moon. Although the Tn activity is much less than the Rn activity, it has been shown that a large contribution should be observed by decay of Tn in trajectory. This will appear as a "thin-source" line, sharply peaked. The spectra produced by decay of Rn and Rn-daughter products may not be truly "thin-source" spectra (*9*) since impacting and surface roughness may produce low-energy tails on "thin-source" peaks when observed with an uncollimated spectrometer.

We have tacitly assumed in all of the preceding discussion that the lunar surface is electrostatically neutral. As the recoil ion following alpha decay is charged, the details of deposition in a vacuum are affected by lunar surface or space charges. No estimate has been made of the consequences of this effect.

The surface activities attributable to released Rn and Tn contain gamma and beta activities comparable to the alpha activities discussed.

The effects of sintering of lunar surface materials by energetic solar protons has been discussed by Smoluchowski (*10*). The predicted alpha fluxes at the surface cause sintering effects comparable to those predicted for energetic solar protons.

An astronaut on the moon will acquire a surface alpha activity in two ways. The decay series of Rn includes RaA (Po^{218}) and RaC (Bi^{214}), with relatively short half-periods, and 19.4-year RaD (Pb^{210}), the long-lived parent of RaF (Po^{210}). The short-lived daughters RaA and RaC will reach equilibrium concentrations by direct recoil deposition on his exposed suit area. Long-lived activity will be acquired by pick-up of lunar dust. In either case, if the astronaut presents an exposed suit area of 1 m^2, from the predicted rates he would acquire an activity of about 1 μc. Thus, possible contamination of the interior of a spacecraft or of returned samples should be considered.

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References and Notes

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Comet Tempel-Tuttle: Recovery of the Long-Lost Comet of the November Meteors

A comet, not quite bright enough to be seen with the unaided eye, was discovered by W. Tempel at Marseilles, France, on 19 December 1865. It was found independently by H. P. Tuttle at Washington, D.C., some 2 weeks later. The comet, which was under observation only until 9 February 1866, was named after its discoverers and received also the designation 1866 I. The orbit of the object was found to be an ellipse with an orbital period of approximately 33 years (*1*). Since the comet was under observation for only a short time, the period was uncertain by perhaps 2 years. The comet was not seen again at its subsequent returns to the vicinity of the earth and sun in 1899 and 1932. However, it was recognized that the comet shared a common orbit with the Leonid meteor stream which produces the November meteors. It had turned out that the Leonid meteors also had a period of 33 years, and the maxima were found to coincide with times when the comet was close to the sun. It was also pointed out by Hind (*2*) that the comet seen in 1366 by Chinese astronomers may have been an earlier appearance of the 1866 comet. Observations of the 1366 comet have been described in a recent translation (*3*) and permit the determination of an approximate orbit (*4*). The proposed identity is favored by this orbit and also by the fact that a strong shower of meteors was reported at almost the same time (*5*). Although the identity offered a possibility for correcting the uncertain orbital period in 1866, no successful use of this could be made in former times on account of the enormous amount of computation needed.

Nowadays the numerical integration of the system of differential equations, which contains the attractive forces of the major bodies in the solar system, can be done on an electronic computer. So it is possible to compute the motion of a small body over a long time interval. Brian Marsden (*6*) made use of this; his predictions of the returns of seven long-lost comets have already led to two successful recoveries.

B. G. Marsden drew my attention to the 1965 return of Comet Tempel-Tuttle and to the opportunity for using the supposed identity for a reliable prediction. The problem consisted in selecting from the permissible values of the orbital period for 1866 the correct one, which represents not only the observations of that year, but also the Chinese observations of 1366. Several values had to be adopted for the period, and for each of them a backward computation by numerical integration was necessary over the interval of five centuries. A special computer program had already been provided by