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Thermal migration of lunar radon atoms and the distribution of lead-210

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Introduction

Radon and its decay products are studied on Earth and on Mars as tracers of subsurface and atmospheric properties, such as radioactive element contents, volcanic activities, presence of water [1, 2]. On the Moon, the lack of water and the cold nighttime temperatures slow down the diffusion of radon gas to the surface, where it is bounded by gravity until it decays [e.g. 3]. Rn-222 (half-life of 3.8 days) and its daughter Po-210 have been detected at the lunar surface by 3 orbiters that measured their characteristic alpha particles [4, 5].

Chandrayaan-1 High-Energy X-ray spectrometer (HEX) [6] provides a new detection opportunity through Pb-210, another decay product of Rn-222.

Lunar Radon

Three distinct processes must be considered [e.g. 7]: (1) The emanation of radon out of minerals; (2) Its diffusion through the regolith to the surface; (3) Its migration by successive ballistic hops in the collisionless lunar atmosphere.

Radon emanation

Rn-222 is formed by radioactive decay of Ra-226 (U-238 series). It may emanate from the mineral into the porous space by recoil or diffusion. It seems however that the emanation rate is low for lunar soils (less than 1% [8]), which may be attributed to the lack of water and chemical weathering [9, 10]. By contrast, some U-rich phases in lunar rocks may accumulate radiation damage, which increases radon emanation rates [8].

Radon diffusion

Once mobilized into the pore space, radon atoms can move by Knudsen diffusion. However, this is an inefficient process to reach the surface: the elevated heat of adsorption of the lunar fines under vacuum conditions (30 to 40 kJ/mole [7, 9]) implies long sticking times on the grains at each collision. Alternatively, radon atoms can be swept when other gases are vented to the surface from depth [9, 11], which is also supported by the comparison of radon and polonium distributions that suggest non-steady emission rates from particular geological units [12, 5].

Radon migration

It is assumed that radon atoms reaching the surface behave like free atoms having enough thermal energy to migrate on the surface until they are lost to the system. Thermal velocities are insufficient to escape the Moon gravity, therefore they migrate through a random suite of ballistic bounces, and they eventually decay. Ionization and acceleration up to the escape velocity seems to be a negligible effect for radon [13]. In this work, we propose a simulation of the radon migration in the exosphere.

Lead-210

The time to reach decay equilibrium between Rn-222 and Po-210 is controlled by the 22.3 years half-life of the intermediate Pb-210.

When Pb-210 atoms decay, they emit gamma-rays at 46.5 keV that should be detectable by HEX, provided enough lead has accumulated in the cold traps of the lunar poles [6]. A positive detection would be a tracer for recent geologic activity, gas venting, and volatile transport [6, 11].

Modelling and Assumptions

We developed a simple Monte Carlo simulation of radon migration at the surface of the Moon. We used the same equations than for other volatile migrations [14, 15]. It basically places the atoms on a sphere, calculates the successive ballistic hops, and evaluates the probabilities of loss either by radioactive decay or by capture in cold traps.

Our simulation consists of tracking 500,000 atoms starting at random local times on the dayside. Thermal equilibrium with the surface is assumed, and the temperature is function of the solar zenith angle [15]. The velocities follow a modified

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Maxwellian distribution [14], while the directions are isotropic (polar angle varying like the arcos of a random number). Alternatively, we tried a cosine distribution for directions [16]. The lunar rotation is ignored, but for atoms reaching the nightside, the time necessary to wait for dawn is taken into account. The decay probability is evaluated after each step (bounce, night, and sticking time for a total duration: Δt) with $P=1-\exp(-\lambda\times\Delta t)$, where λ is the Rn decay constant: the tracking is stopped if P is greater than a random number.

The atoms were first distributed in U-rich regions, defined with a global thorium map [17]. Alternatively, a single source centred on Aristarchus, a good candidate for gas venting [11], was simulated.

After each bounce, the atoms are adsorbed and stick to the surface for some time; we chose a heat of adsorption of 35.5 kJ/mole. More importantly, there is an unknown probability of reincorporation in the soil [18] taken here as a free parameter.

The traps are defined with the hydrogen map [19] as regions having H content greater than 140 ppm poleward of 80°. They cover 0.2% of the lunar surface. A trapping test based on the permanently shaded craters [15, 20] lead to similar results.

Further necessary steps

In the future we shall take into account the emanation rate, the lunar rotation, the escape probability for each alpha decay in the chain, refine the reincorporation analysis, and introduce a better evaluation of the adsorption [21, 22].

Results

Only 3% of the atoms reached the cold traps (a few more when directions follow a cosine law). Although the atoms covered, on average, more than 35,000 km in about 1,650 bounces, the mean distance between starting and ending positions is only 860 km due to the random walk (fig.1). Many more bounces seem necessary to reach the poles when the atoms originate only from Aristarchus, decreasing the chances of being trapped to 1%.

Our simulation suggests that radon atoms travel easily at the lunar surface in the absence of reincorporation. However a small fraction ends in the cold traps because of the random walk process and the small areas of the traps. Even less Pb-210 atoms would remain trapped if the loss by successive alpha decays was considered.

The introduction of the reincorporation process has dramatic effects. Up to 50% of the atoms may be reincorporated after each bounce, due to the regolith porosity [18]. Varying this parameter from 0 to 10 and then to 50% decreases the number of bounces by two and three decades, respectively. In such conditions, the atoms would only travel a few tens of kilometres, leading to trapping probabilities at the poles as low as 0.2%. However a fraction of the reincorporated atoms will be released again after some time. HEX may help constrain these parameters and the frequency of gas release in the last 20 years, though these observations will be difficult due to the predicted low-level of accumulation of radon daughters at the poles.

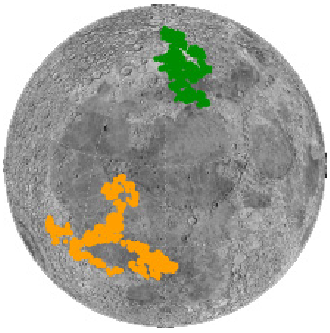

Figure 1: Two examples of radon tracks. Green: starts at a thorium hot spot (Imbrium rim); ends trapped at the North Pole. Orange: starts at Aristarchus; ends by decay at the equator.

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