**RADON AND POLONIUM AS TRACERS OF LUNAR OUTGASSING, VOLATILES AND DUST: GOING BACK TO THE MOON?** P.Y. Meslin[1], H. He[2], Z. Kang[3], R. Wimmer-Schweingruber[4], J.C. Sabroux[5], J.-F. Pineau[6], N. Yamashita[7], B. Sabot[8], S. Pierre[8], M. Blanc[1], J.-P. Roques[1], I. Plotnikov[1], S. Maurice[1], O. Gasnault[1], J. Amestoy[1], P. Pinet[1], O. Forni[1], J. Lasue[1], A. Guertin[9], V. Métivier[9], N. Michel[9], N. Servagent[9], F. Haddad[10], F. Poirier[10], C. Koumeir[10], J. Flahaut[11], F. Rocard[12], A. Debus[13], K.W. Wong[1], P. Devoto[1], L. Lavergne[1], R. Mathon[1], D. Rambaud[1], E. Carrié[13], B. Dubois[13], N. Striebig[13], M. Belot[13], [1]IRAP, UPS/CNRS/CNES, Toulouse (pmeslin at irap.omp.eu), [2]IGG, CAS, Beijing. [3]CUBG, Beijing. [4]CAU, IEAP, Kiel. [5]IRSN, Saclay. [6]Albedo Technologies, St-Sylvestre. [7]PSI, Tucson. [8]CEA, LNE-LNHB, Saclay. [9]SUBATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes. [10]GIP ARRONAX. [11]CRPG, Nancy. CNES, Paris. [12]CNES, Toulouse. [13]GIS, OMP, Toulouse.

**Historical overview:** Since the Apollo missions, the Moon is known to have a very tenuous exosphere, resulting from a balance between sources and sinks [1]. One of its sources is the release of endogenic gases from the lunar interior. Since the early stages of the lunar exploration, $^{222}$Rn and its progeny ($^{218}$Po, $^{214}$Po, $^{210}$Pb and $^{210}$Po) have been identified as key tracers of the present-day lunar exosphere, and seismic and venting activity. Measurements of their concentration performed both on the surface of the Moon (α-scattering experiments on Surveyor 5, 6 and 7) [2], from the orbit (Alpha Particle Spectrometers (APS) onboard Explorer 35, Apollo 15, 16 and Lunar Prospector) [3-5], and on returned samples (lunar fines from Apollo 11, 14 and 15, camera visor from the Surveyor 3 spacecraft and solar-wind composition foils from Apollo 12, 14, 15 and 16) [e.g., 6] have revealed large temporal and spatial variations. The latter were attributed to the presence of active degassing spots, of time-variable outgassing intensities, which radon and its progeny can help locate. Enrichment of $^{210}$Po at the Mare/Highlands boundary and $^{222}$Rn anomalies over young craters (Aristarchus, Grimaldi, Kepler) have been observed. A statistical analysis has revealed a strong correlation between the locations of $^{222}$Rn and $^{210}$Po anomalies and regions where Transient Lunar Phenomena (TLP) have been observed [7], which suggests that these TLPs could be caused by the sporadic release of gases and dust from the lunar interior. This analysis also reveals a correlation between the locations of deep and shallow moonquakes and the Mare/Highlands boundary. Together with the correlation that exists between the $^{40}$Ar degassing rate and the occurrence of shallow moonquakes [8], there is converging evidence that the present day lunar degassing activity may be controlled by seismicity and-or the presence of fractures, which can help $^{222}$Rn and other gases transit from the lunar interior. More recently, lunar radon gained renewed interest with the Kaguya-Selene (Alpha Radon Detector, ARD) and Chandrayaan-1 (High-Energy X-Ray Spectrometer, HEX) missions. The ARD experiment showed, once again, time variations and radon anomalies associated with the Aristarchus and Kepler craters [9].

Another important result of these observations was the strong difference between the exhalation rate of $^{222}$Rn on the Earth and on the Moon, attributed to the dryness of the lunar regolith [10]. This is also illustrated by the very low emanation factors characterizing lunar samples [11].

**Motivation for measuring radon and its progeny at the lunar surface**: $^{222}$Rn, $^{220}$Rn and their progeny are ideal tracers of the lunar regolith-exosphere exchanges. This is in part due to: a well-identified source term ($^{238}$U and $^{232}$Th), mapped from the orbit [12]; a well-identified loss term (radioactive decay); a limited half-life (3.8 days and 56 sec for $^{222}$Rn and $^{220}$Rn, respectively), limiting their transport around their emission zone; and the absence of exogenous contamination. However, despite the number of experiments that brought information on this gas, it is still presently difficult to have a fully consistent and comprehensive picture of radon outgassing and transport on the Moon from all these datasets. The Surveyor experiments were not designed and optimized to measure these radionuclides (large background due to an onboard $^{254}$Es calibration source and small FOV). Data acquired from the orbit had a large footprint and limited temporal coverage (from ~70 hours of prime data for Apollo 16 to ~230 days for the APS and ~6 months of nominal mode for the ARD). Moreover, some of these measurements were degraded due to a contamination of the detectors by $^{210}$Po or $^{241}$Am sources used for their calibration, and the APS background increased significantly after failure of one of its light filters. The ARD suffered from noise in some of its channels and its anticoincidence detectors dysfunctioned.

Monitoring of the radon cycle at the surface of the Moon would thus provide valuable ground truth for orbital measurements and help address five key issues related to the transport of lunar volatiles and dust:

**1) Study of the transport of gases through the lunar regolith:** After being produced by the decay of radium isotopes, radon isotopes can eventually escape from their mineral host by recoil, with an efficiency that depends on grain size, surface area and radium distribution [10,13]. Once mobilized in the pore space, their transport to the surface by diffusion is controlled by the structural properties of the porous medium and by its adsorption onto the soil matrix, which is a temperature dependent process. Their exhalation rate at the surface is therefore modulated by variations of the surface temperature, and thus by the diurnal cycle. Monitoring their exhalation rate would thus enable us to study the thermal "breathing" of the uppermost meters of the lunar regolith (and uppermost cm with $^{220}$Rn), and thus help understand the dynamics of the exchange of gases between the regolith and the lunar exosphere. Measuring the exhalation rate of radon isotopes can constrain their diffusion lengths and the thickness of their production layer, and be compared to results from transport models (Fig. 1), and to other planetary bodies [14,15].

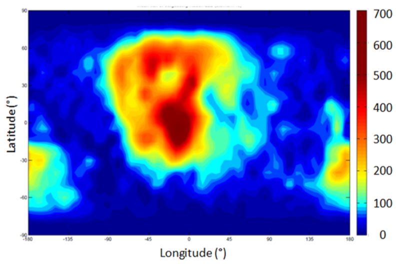


Fig. 1: Predicted map of time-average $^{222}$Rn exhalation rate (diffusion only, in atoms·m$^{-2}$·s$^{-1}$).

**2) Monitoring of the venting activity of the Moon and identification of active outgassing spots:** In addition to transport by diffusion, $^{222}$Rn can also be liberated sporadically from the subsurface by advection along with other gases such as argon, possibly triggered by moonquakes or by the sagging of mare basalt plains, stresses from tides interacting with overlying crust. If such an event were to occur during the timeframe of a mission, an anomaly could be measured at the landing site. Modelling its transport in the lunar exosphere would then help locate its emission site. The detection of active outgassing spots or fracture networks can help identify key targets for future exploration missions. Particularly, some radon anomalies are known, on Earth, to be correlated with helium outgassing and can thus be used for helium sources tracking [16].

**3) Study of the transport of volatiles in the lunar exosphere:** Radon atoms, released into the lunar exosphere, follow ballistic trajectories until they disintegrate. They are slowed down in this dispersion process by adsorption and reincorporation into the regolith. The adsorption process being controlled by surface temperatures, strong diurnal variations of the exospheric concentration are expected, just like those observed for argon by Apollo 17 [8]. Understanding the time variability and transport of $^{222}$Rn would constitute a reference to study the transport of other gases (e.g., $^{40}$Ar, $H_2O$).

**4) Study of the transport of lunar dust:** The $^{210}$Po surficial activity measured at any given time integrates both the variations of the radon exhalation rate and the effects of dust motion over a few decades timescale. Over this period of time, churning processes (from impacts or solar-wind induced electrostatic effects) may involve dust thicknesses comparable to the range of $^{210}$Po alpha particles. This process should thus affect the measured signal and lead to disequilibrium between the $^{210}$Po surface distribution and the time-integrated $^{222}$Rn signal [2].

**5) Refinement of uranium mapping:** The migration of $^{222}$Rn increases the near-surface level of $^{214}$Pb and $^{214}$Bi, two of its decay products that are used to measure $^{238}$U by γ-ray spectrometry. Radon exhalation from the lunar regolith can thus introduce a bias in the measured $^{238}$U content and U/Th ratio. This effect has been observed on Mars and Mercury [14,15]. Measuring $^{222}$Rn at the surface of the Moon is thus also useful to correct possible biases in the $^{238}$U map measured from orbit [12].

**Modeling of radon transport:** In order to simulate the lunar radon cycle, we have developed a 3D thermal model of the lunar subsurface, coupled to a diffusion-adsorption gas transport model. It uses as inputs the Kaguya $^{238}$U map [12], the regolith thickness map of [17], the radon emanation and adsorption coefficient from [11,13,19]. Its ouput (time-variable map of the exhalation rate, Fig. 1) is injected into a Monte-Carlo code simulating the exospheric transport of radon (incl. surface adsorption) and the escape or implantation of its decay products into the surface. We predict a strong diurnal cycle and constrain the lateral transport of $^{222}$Rn from its emission zones.

**The DORN instrument**: To achieve the above objectives, we are developing an instrument, with CNES support and funding, aimed at measuring $^{222}$Rn, $^{220}$Rn and their progeny at the surface of the Moon, by α spectroscopy in the 5–10 MeV energy range. It is named DORN (for "Detection of Outgassing Radon"), after the name of F. Dorn who discovered $^{222}$Rn. It is made of 8 detection units (DU), with a total surface area of 42 cm$^2$. Each DU consists of a pair of 5.3 cm$^2$ silicon detectors in a telescope configuration, and surrounded by a plastic scintillator, to reject and characterize solar and galactic protons coming from the rear-side and from the front-side with grazing incidence angles. The 8 DU are arranged in two subsets of 4 DU with different tilt angle wrt the surface, to cover the near- and far-fields around the lander and gain a better understanding of the background and radon signals (surface vs. sky). This design yields a low limit of detection, making it suitable even for short-lived missions at the surface of the Moon (~0.5 Bq·m$^{-2}$ for an integration time of 48h, corresponding to a radon flux ~1 atom·m$^{-2}$·s$^{-1}$, i.e., an order of magnitude better than orbital measurements). It will be able to derive the local exhalation rates of $^{222}$Rn and $^{220}$Rn, the $^{218}$Po/$^{222}$Rn and $^{216}$Po/$^{220}$Rn ratio, which are indicative of the efficiency of the surface adsorption process, and the $^{222}$Rn/$^{210}$Po ratio, which depends both on the secular variations of $^{222}$Rn in the exosphere and on the mobility of dust over a decadal timescale. Carried onboard long-lived missions, it could record the diurnal cycles of $^{222}$Rn and $^{220}$Rn and possibly detect time anomalies associated to outgassing events. Because of the infinite range of α particles in vacuum, it could also be used to characterize remotely (e.g., from the rim of shadowed craters) the trapping efficiency of very cold spots, possibly associated to radon enrichments. The renewed interest for lunar exploration could provide several opportunities for these measurements.

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