DETECTION OF POLONIUM-210 ON SPIRIT DUST MAGNETS AND IMPLICATIONS FOR THE GLOBAL MARTIAN DUST CYCLE.

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Introduction:

The radioactivity of airborne aerosols, which originates from the attachment of radionuclides produced by radon disintegration, Galactic Cosmic Rays (GCR) or anthropogenic activities, especially fallouts from nuclear weapons testing, can be used to measure the aerosols residence time in the atmosphere and their deposition rate. It is also used to characterize soils erosion rates (Matissof et al., 2002) or to investigate the origin of desert rock varnish (Hodge et al., 2005), to name only a few terrestrial applications. A translation of these nuclear methods to the Martian atmosphere, which is characterized by a very active dust cycle, can provide a unique insight into the present-day recycling of the Martian surface.

Polonium-210 (^{210}Po) is a long-lived decay product of radon-222 (^{222}Rn), a radioactive gas produced in the ground and eventually released into the atmosphere. The long apparent half-life of ^{210}Po is such that its unsupported fraction (i.e., the fraction not in equilibrium with its parents within the grains) is almost entirely attached to the particles that have been in suspension in the atmosphere, especially those characterized by a large specific surface area or by a long atmospheric residence time. Each particle traveling in the atmosphere accumulates some ^{210}Po, and this process is much more efficient than on the ground, because the collection volume around each particle is much greater in the atmosphere. The amount of ^{210}Po attached to the atmospheric aerosol depends on the amount of ^{222}Rn released from the ground over the past few decades (due to the 22.3 year half-life of the intermediate radionuclide ^{210}Pb) and the recycling rate of the dust cycle. Polonium-210 is therefore a valuable tracer of the dust cycle, especially on Mars where no other technique is available to track dust particles.

Analysis of Spirit alpha spectra:

The presence of radon in the martian atmosphere was first inferred by the detection of ^{210}Po on the dust magnets of the rover Opportunity (Meslin et al., 2006). The presence of ^{210}Po is characterized in the alpha spectra of the Alpha Particle X-ray Spectrometer (APXS) by the presence of a peak at ~5.3 MeV, corresponding to the energy of the alpha particles emitted by this radionuclide. This energy is above the energy of backscattered alpha particles (emitted by a ^{244}Cm source) which are of interest for the APXS chemical analysis. The signal at these energies is dominated by GCRs and the detection of a radiogenic signal is much more challenging at the surface of Mars than of the Earth because of a much more severe radiation environment. Hence, in the absence of a background rejection system, long integration times are required. Moreover, the detection efficiency of the APXS was not optimized for this type of passive measurement. Nonetheless, the accumulation of dust on the Capture and Filter magnets concentrates the (possibly) radioactive source on a small area, which makes its detection easier.

After 175 sols of operations, the alpha detectors of the Opportunity rover became contaminated by the ^{244}Cm source, which lead to a significant increase in the background signal at energies $\leq$ 5.8 MeV and prevented any further analysis of possible radiogenic signals. The alpha spectra measured by Spirit APXS also suffer from an anomalous signal at high energies, but do not show any evidence of ^{244}Cm contamination over its six years of operation, leaving hope for the detection of a ^{210}Po signal. We thus performed the analysis of Spirit APXS spectra, corresponding to a total integration time of 3638 hours.

The steps of this analysis are similar to those described in Meslin et al. (2006). The spectra were first sorted and summed by target type, after removal of anomalous spectra: atmosphere (755 hours); rocks (671 h); undisturbed soils (325 h); magnets (202 h); abraded rocks and trenches (371 h). The energy calibration was shown to be very similar to that of Opportunity spectra and a ^{210}Po signal was therefore searched in the same spectral channels. The position of the anomalous peak at high energies was found to be correlated with the sensor head and preamplifier temperature, but was shown not to be associated with a drift of the calibration with temperature. The spectra were therefore simply summed by temperature range, truncated to remove the anomalous peak, and then summed all together. A running average was then used to smooth the signal over an energy range corresponding to the energy resolution of the detector. The resulting gross spectrum obtained on Capture and Filter magnets is shown in Fig.1. A small signal can be seen at the characteristic energy of ^{210}Po. To confirm that a signal was indeed detected, a statistical analysis was performed. Different, independent blank spectra were generated for comparison to the gross spectra (spectra from the background detector; fit of the gross spectrum; spectra measured on abraded rocks and soil trenches, which have not been exposed to unsupported ^{210}Po). In all cases, the net signal (= gross signal – blank) was found to be above the 99% detection threshold (Fig. 2). The net signal was then converted into surface activity (Bq.cm^{-2}) and specific activity (Bq.g^{-1} of dust), using the detection efficiency of the alpha detector calculated with the MCNPX code.

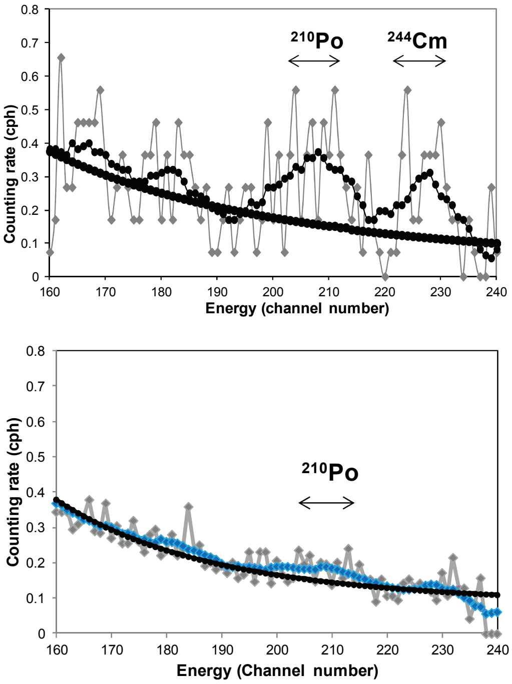

Figure 1: Alpha spectra measured by Opportunity (top) and Spirit (bottom) on the dust Filter and Capture magnets (black and blue lines are running averages, and the continuum is a fit of the spectra over channels [160-200; 215-255]). The similarity between the two continua confirms that Opportunity and Spirit spectra had a very similar energy calibration.

A similar analysis was carried out with spectra measured on rocks and with atmospheric spectra, but the corresponding net signals were not found to differ significantly from the blanks. New upper limits for the ^{210}Po-induced surface activity of rocks and for the radon atmospheric concentration have therefore been derived (9×10^{-5} Bq.cm^{-2} and 3.3 Bq.m^{-3}, respectively). The fact that the dust coating of rocks does not show any detectable ^{210}Po signal suggests that these dust particles are not as active w/r lifting and have not been as much involved in the present-day atmospheric cycle as the dust particles collected by the magnets. Note that non-magnetic dust particles (which represent a minor fraction of dust particles) would also have settled on these magnets, so that the present analysis is not strongly biased.

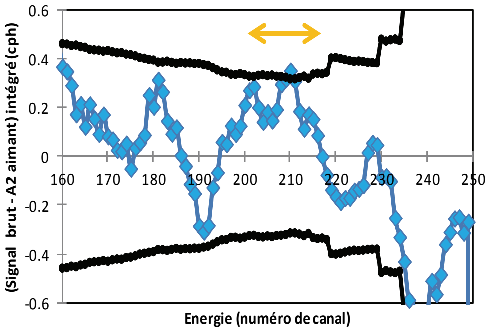

Figure 2: Net signal (= gross – blank) measured on the dust magnets and integrated over an energy range of ~250 keV. An anomaly above the 99% detection threshold (black line – defined here from the blank measured concomitantly with the background detectors) is detected at the energy corresponding to the alpha particles emitted by polonium-210. The net signal is also found to be above the 99% detection threshold obtained from other blank measurements.

Comparison with Opportunity results:

The analysis detailed above confirms the results obtained by Meslin et al. (2006) using Opportunity data that the martian dust is radioactive w/r to polonium-210. The dust radioactivity measured at Meridiani Planum is six times larger than at the Gusev site. This could be indicative of different dust transport histories (e.g., transport through regions characterized by different ^{222}Rn atmospheric concentrations, or differences of average residence time) and/or physical properties, possibly related to the differences in brightness /mineralogy/composition already noted on the dust magnets at the two sites (Madsen et al., 2009). For instance, smaller dust particles, or particles with greater specific surface area, would collect more ^{210}Po during their atmospheric journey, dust collected on Spirit magnets was found to be brighter.

Although spatial variations are observed, averaging the values measured at two locations on opposite sides of the planet is the most reasonable way to estimate the average ^{210}Po-induced radioactivity of the martian dust, until additional measurements are made at the surface of Mars.

Estimation of the load of the active dust reservoir and its recycling rate:

The knowledge of both the average ^{210}Po-induced radioactivity of dust particles and the average radon exhalation rate can yield an estimate of the load of the active dust reservoir (i.e., the load of the reservoir that has been exchanged with the atmosphere over the past few decades) and its recycling rate (i.e., the average time spent by dust particles on the ground before being lifted again).

We use here a box model with two reservoirs: a surface reservoir (q_s), characterized by a residence time τ_s, and an atmospheric one (q_a), characterized by a residence time τ_a (Fig. 3). During its atmospheric journey, the radioactivity of a dust particle increases with an average attachment rate *X* which, at equilibrium, must be equal to the average radon exhalation rate. When deposited on the surface, its radioactivity decreases exponentially with a half-life of 22.3 years. The average ^{210}Po radioactivity of dust particles, $<a_a>$, can be shown to obey:

$$<a_a>=\frac{\Phi}{q_a}\left\{1+\frac{1}{\tau_a\lambda}\left[\left(\frac{(1-e^{-\lambda\tau_a})\,e^{-\lambda\tau_s}}{1-e^{-\lambda(\tau_a+\tau_s)}}-1\right)(1-e^{-\lambda\tau_a})\right]\right\} \tag{1}$$

where Φ is the average radon exhalation rate (atoms.m^{-2}.s^{-1}) and λ the half-life of lead-210. Estimates of q_a and τ_a can be made from measurements of atmospheric opacity and models of sedimentation times (e.g., Elteto and Toon, 2010) or observations of the decay of regional/global dust storms (e.g., Cantor, 2007). The exhalation rate Φ was derived by Mars Odyssey Gamma-Ray Spectrometer (Meslin et al., 2012). At steady-state, mass conservation imposes:

$$\frac{q_a}{q_s}=\frac{\tau_a}{\tau_s} \tag{2}$$

Equation (1) can be solved for τ_s, and Equation (2) then gives q_s. The load of the active dust reservoir is then simply $q_{total} = q_s + q_a$. This model covers two limiting cases:

- a “closed cycle” with rapid recycling ($\tau_s << 1/\lambda = 32$ years), in which case:

$$q_{total}=\frac{\Phi}{<a_a>}=14\ \mu m \tag{3}$$

- an “open cycle”, without recycling (fresh dust particles are constantly injected, and travel only once in the atmosphere before being deposited for good), in which case:

$$q_a=\frac{\Phi}{<a_a>}\left(1-\frac{1-e^{-\lambda\tau_a}}{\lambda\tau_a}\right) \tag{4}$$

Numerical solutions of (2) yield $\tau_s \approx 2$ Earth years (≈ 1 Martian year) and $q_{total} \approx 14$ µm. τ_s is quite sensitive to the value chosen for the average atmospheric opacity, but q_{total} is not. Thus, we find that the martian dust cycle is characterized by a quite rapid recycling rate (Equation 3). Realistic estimates of τ_a in Equation (4) yield atmospheric opacities that are about ten times lower than the measured values. We can therefore rule out the case of an “open cycle”. If we were in such a case, the radioactivity of dust particles would have been much lower than the measured value: indeed, dust particles would only have accumulated polonium-210 during a single atmospheric journey. The only way to increase their radioactivity would be to have a smaller number of particles in the atmosphere (i.e., smaller atmospheric dust opacity), because the whole atmospheric reservoir of radon decay-products would then attach to a smaller number of aerosols.

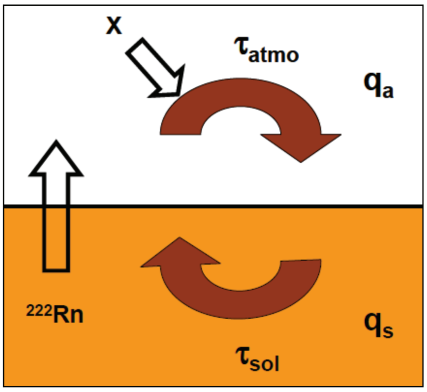

Figure 3. Box model representing the dust cycle: exchange between the surface and atmospheric reservoirs and corresponding residence times.

Implications for the Martian dust cycle:

The load of the dust reservoir that has been active over the last few decades represents a global equivalent layer which is only ~14 µm thick. This is only about 7 times the amount of dust injected in the atmosphere during the 2001 global dust storm (Cantor, 2007). Without recycling, i.e. if only “fresh” dust was injected into the atmosphere, the reservoir would be exhausted after only ~5 years. A large fraction of dust particles present in the atmosphere are therefore dust particles that have been recycled. This is in stark contrast with the Earth, where the recycling of aerosols is negligible (in comparison to the injection of “fresh” particles).

The reason for this is unknown (although it is worth noting that arid regions on Earth are in a “supply-limited” configuration (Macpherson et al., 2008)), but this result has strong implications for the understanding of the Martian dust cycle. For instance, results from GCM that simulate the dust cycle have shown that “infinite” dust reservoirs are required to maintain the observed annual opacity cycle: limited reservoirs are rapidly exhausted, leading to a “low opacity” atmospheric state (Kahre et al., 2005). Since the source regions are not predicted to be efficiently replenished, “fresh” dust needs to be injected to maintain the dust cycle stable over the years (Kahre et al., 2005). Our analysis, however, shows that the Martian dust cycle is not in such an “open” configuration. This means that some feedbacks are not currently modeled properly, or that feedbacks not yet taken into account are actually important. Kahre et al. (2005) mention the possible feedback effect of albedo and surface roughness, for instance. The efficiency of lifting processes may also need to be reconsidered.

GCM models also fail to reproduce the interannual variability of the dust cycle, characterized by the occurrence of global or planet-encircling dust storms (Kahre et al., 2005, 2006; Newman et al., 2002). However, a “limited” dust reservoir, as supported by this study, necessarily implies inter-annual variability, because a substantial fraction of the reservoir is redistributed every year. This observation therefore suggests that the occurrence of global dust storms is constrained by the time taken to replenish the main source regions, which itself is constrained by the average residence time τ_s which we find to be a few years.

Finally, estimates of net deposition rates, and hence estimates of the age of some dust-rich regions, may also need to be reconsidered.

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