FORMATION AND IMPACT "MATURATION" OF THE EARLY ACRID METEOROID ATMOSPHERE OF MARS. M.Maurette[1] and M.Lefort[2], [1]CSNSM, Bâtiment 104, 91406 Orsay-Campus, France, [2]Institut Charles Sadron, BP 84047, 67034 Strasbourg, France. maurette@csnsm.in2p3.fr.

Introduction: In a previous paper on the formation of the Martian atmosphere [1], we already extrapolated to Mars the meteoroid accretion scenario proposed for the Earth, and which is outlined in a companion abstract [2]. It involves a first "shot", i.e., the mega–impact of the last planetary embryo to merge the terrestrial planets at about the same time, t_1 [3]. Therefore, it can be approximated by the age of the oldest lunar rocks (~4.44 Ga) that date the formation of the Moon. It blew off the complex intractable "pre-first-shot" Martian atmosphere. Then, meteoroid volatiles that got released upon atmospheric entry could accumulate until a second mega–impact, at time t_2 ~4.1 Ga, blew them off again. This allowed the accretion of the thin contemporary Martian atmosphere. The recent discovery of hidden mega–impact basins on Mars [4] might support this "2–shots" scenario.

2004: Two "shots" in the Hadean Eon: The composition of a pure meteoroid atmosphere can be expressed in terms of the mass mixing ratio of a given species, **A,** relatively to that of N_2, and such as Ne, H_2O, and C and S that generate CO_2 and SO_2 upon atmospheric entry [2]. It scales as the corresponding concentration ratio measured in unmelted micrometeorites collected in central Antarctica, i.e., Ne/N_2 ~2 x 10^{-5} and H_2O/N_2 ~CO_2/N_2 ~SO_2/N_2 ~130–140. The measured CO_2/N_2 ratios in the atmospheres of the Earth, Mars and Venus are similar to the meteoroid ratio within a factor 2 (Table 1.1, in Ref.5). This suggests a meteoroid origin of their atmospheres.

The total amount, $\mathbf{M_A}(t_1)$, of a meteoroid species, **A**, delivered to Mars since t_1, scales as the product of the concentration of **A** in AMMs, by the integrated meteoroid mass flux accreted by Mars since t_1 , $\Phi_M(t_1)$ ~10^{24} g [2]. Meteoroids delivered ~99% of the Martian atmosphere during the first 200 Ma of the "post-first-shot" period, respectively, when the partial pressures of N_2, H_2O, CO_2 and SO_2 did reach about *0.3*, *70*, *26* and *19* bars, respectively (i.e., assuming no loss of species). A second shot blew off this thick atmosphere at t_2 ~4.1 Ga, when the amplification of the meteoroid mass flux, relatively to the present day flux, dropped to ~800x, as to build up the contemporary partial pressure of CO_2 of about 7–8 mbar (this amplification is discussed in Ref. 2). In 2004, at the time of submission of this paper, there was no visible remnant of these shots!

June 2008: the combination of altimetry and gravimetry reveals the hidden shots: The situation quickly changed in June 2008 [4], when the combination of altimetry (with the MOLA instrument) and gravity revealed the contour of a ~10,000 km wide buried mega-impact basin (Borealis), which covers about ¼ of the Martian surface. Impact models suggested that the impactor was a Pluto sized body (~2300 km wide). At least, the first shot became visible! The discovery of this buried basin reactivated the interest for previous works on giant impacts, which already showed that some large smooth Martian plains turned to be buried impact basins, such as Utopia and Ares (about (~3400 km and 3300 km wide, respectively). But their parent impactors could hardly blow off the Martian atmosphere.

However, about 4 Ga ago, a round of 5 successive giant impacts, likely resulted from the tidal disruption of a ~1000 km size asteroid that was approaching Mars in the ecliptic plane [6]. The corresponding giant impact basins include: (**i**) Hellas and Argire (about 2100 km and 1800 km wide, respectively), both visible in the Southern hemisphere; (**ii**) Isidis, Utopia and Thaumassia (about 1500 km, 3000 km and 600 km wide, respectively), which are still buried under sediments. Each one of these impacts could not blow off the thick Martian atmosphere. However, Genda and Abee [7] showed that the existence of an ocean greatly eases gravitational escape during impact. Firing quickly 4 other successive shots in the already vaporized Martian oceans might have acted as a decisive second shot. But the young age (~3.6 Ga) of the Isiris basin still poses problem.

Extrapolation of the Earth sulfur cycle to Mars: The two first stages of the meteoroid S–cycle were similar on the Earth and Mars (cf. Ref. 2). The hydrous silicates and iron sulfides of meteoroids were likely "geochemically engineered" upon atmospheric entry as follow: (**i**) The giant meteoroid burdens of SO_2 and H_2O (about 800 Mt/yr during 100 Ma on Mars) led to the formation of droplets of acid–sulfate aerosols, which contributed to further cool both planets during the period of faint early Sun; (**ii**) After gravitationally settling they formed highly acidic oceans, which prevented the scavenging of CO_2 as carbonates, and thus enhanced its greenhouse effect.

On the Earth sulfur was gradually scavenged though subduction to the upper mantle (cf. 3rd section in Ref. 2). The pH of the residual water could increase up to the critical value of ~6, beyond which CO_2 started to react to form carbonates and gradually controlled a benign climate. However, on Mars, subduction was "missing" as to shield sulfur at great depths, and the S-cycle was confined within the megaregolith. Hopefully, the Martian Rovers and instruments on board of several space missions might yield new clues about this megaregolith stage specific to the Martian S–cycle.

Constraints from Spirit and Opportunity:

Spirit: At Gusev crater [8], Spirit measured elemental enrichments and/or depletions of 16 elements in the Martian soils, relatively to local rocks (RATs) that were abraded with the "Rock Abrasion Tool". Any meteoroid contribution should be hopefully spotted among the 9 elements (Na, Si, P, S, Cl, K, Ti, Ni, Zn) showing an enrichment in the soils, and not a depletion (Mg, Al, Ca, Cr, Mn, Fe, Br). Sulfur showed the greatest enrichment in all soils. This gave a strong hint about a meteoroid chondritic contamination, as sulfur is about 3 times more abundant in micrometeorites (~5 wt.%) than in the set of 5 abraded Martian rocks from the Gusev crater (~1.6 wt.%). The expected meteoroid sulfur concentration was estimated with the accretion equation (cf. Ref. 2). The missing plate tectonics probably led to the "reactive" storage of the initial meteoroid sulfate aerosols in the porosity of the Martian megaregolith. This acrid regolith also prevented the formation of carbonates, thus forcing CO_2 to accumulate in the "air", getting ready for a second blow-off.

This porosity is characterized by a depth decay constant (e-folding depth), **τ** ~2.8 km [9]. Let us assume a ~100 % retention of these trapped sulfate aerosols during the second shot, up to a depth ~2**τ**, while all volatiles still in the "air" (noble gases, N_2, CO_2 and probably a minor fraction of water not bound to sulfate aerosols), were fully blew off at t_2 ~4.1 Ga. The total burden of meteoroid sulfur delivered after the first shot, yields a bulk sulfur concentration of the megaregolith of ~4.3–2.3 wt.%, for a regolith density of about 1–3 gm cm^{-3}, respectively. This value, which drops to ~2.6–1.5 wt.% for a regolith retentive depth of ~3**τ,** well fit the average S–excess (~1.9 wt.%) found in the soils. This would imply that ~40% of the Gusev soils are made of a CM-type chondritic component. However, they contain too much Al, Cl, K, Ca, Ti, and not enough Mg, Fe and Ni.

C.Engrand and collaborators showed that the elemental composition of micrometeorites collected in Central Antarctica, and defined with 13 elements (Na, Mg, Al, Si, P, S, K, Ca, Ti, Cr, Mn, Fe and Ni), closely matches that of the CM-type chondrites (see Fig. 47, in Ref. 10). For the 3 additional elements detected in the Martian soils (Cl, Br and Zn) we thus used the CM concentrations in the computations. For each element, we estimated a meteoroid "misfit–ratio" (MMR), next reported in bold *italics*, just rationing the predicted meteoroid concentration in the bulk megaregolith to the excess concentration measured in the soils, on the surface of Gusev crater (i.e., the difference between the average concentrations measured in the soils and RATs, respectively). For a ratio of 1 the measured value exactly matches the meteoroid contribution. A dominant meteoroid contribution is observed for Na (***1.3***), P (***1.1***), S (***1.9***), and Zn (***1.1***). Indeed, a misfit-ratio ≤ ***2*** corresponds to a "good" accuracy when moving so far back in time, with elements that differ so much in chemical properties and concentrations. However, large misfits are observed for Cl (***0.1***), K (***0.16***), and Ti (***0.34***), whereas Ni (***38***) shows the highest MMR**.**

Opportunity: At Meridiani Planum [11], excess concentrations are observed for Na (***1.0***), Al (***0.72***), Si (***3.62***), Cl (***0.58***), Ca (***1.04***), Ti (***0.33***), Cr (***1.95***) and Fe (***5***). However, S, P and Zn, which gave the right excess concentrations at Gusev Crater, as well as Ni (***38***), are now depleted at MP! This probably reflects the higher concentrations of these elements in the local RATs. It is thus quite puzzling to note that the bulk average sulfur content of the MP–soils even better fit the meteoroid prediction (MMR= ***1.50***). Sodium is the only winner, yet, in this confrontation to get the best MMR at both Gusev Crater and Meridiani Planum. The erratic soil elemental depletions and/or excesses observed at the two sites still masquerade the chondritic component**.**

Previous scenarios: The Martian atmosphere would mostly result from a classical basalt magma volcanism. In a consensual scenario [12, 13], about 1 bar of SO_2, altogether with "abundant" water and CO_2, were released in ~100 Ma, about 4 Ga ago, during the formation of the giant volcanoes of the Tharsis bulge (assimilated to Hawaiian volcanoes). As SO_2 had a long lifetime in the presence of CO_2, it was the dominant greenhouse gas to warm the Martian atmosphere. Like on Earth, SO_2 generated sulfate aerosols that gravitationally settled to the Martian surface, thus inhibiting the formation of carbonates. This both explains the puzzle of the missing carbonates and offers the strong CO_2 greenhouse effect required to generate at least a few bars of running water. The meteoroid volcanism is much different from the TBV with regard to**:** (**i**) stressing the role of the early heavy bombardment**;** (**ii**) "erupting" from the initial short-lived hot volumes of ~10 km-long shooting stars clustering around the mesopause, and not from basalt magmas**;** (**iii**) its much earlier occurrence**;** (**iv**) a ~30x larger burden of volatiles species delivered during the first 100 Ma of the post-first-shot period, which is required to get *"at least 30–40 bars of water"* [14] to carve the fluviatile features**.**

Summary: The presumed role of the TBV sulfur cycle on Mars climate [12, 13] was enthusiastically commented by Maria Zuber in MIT news (12/27/2008)**.** She concluded**:** "*It is fascinating to think about whether this process may have played a role in the evolution of the early Earth*"**.** Both the meteoroid and basalt magma volcanisms are much better constrained on the Earth than on Mars. Meteoroid volcanism did well work on Earth [1, 2, 10]**.** Moreover, its extrapolation to Mars with the 2–shots scenario did rightly predict both**:** (**i**) the partial pressures of N_2 and CO_2 **;** (**ii**) the concentrations of Na, P, S and Zn observed in the excess concentrations found in Gusev crater soils**;** (**iii**) the missing carbonates**;** (**iv**) the right amount of water to carve fluviatile features**.**

The odd survival through Mars history of the predicted meteoroid burdens of some elements at Gusev crater adds to the fascinating mysteries of the red planet**.** Martian Rovers might help analyzing other sites looking at both Na, S and Ni. Another prospect is to predict the concentration of meteoroid elements that accumulated in the thin regolith (lunar mare type), that formed by impact gardening on top of the megaregolith, since the 2nd shot. During this period, the large amount of water that was stored in the megaregolith since t_1 got probably frozen due to the loss of the CO_2 greenhouse effect during the second shot. The new meteoroid species possibly got only distributed in the top layer of the thin regolith that was penetrated by the solar thermal wave.

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