# Planetary Atmospheres during an Enhanced Bombardment

Detlef de Niem[1], Ekkehard Kührt[1], Alessandro Morbidelli[2], Uwe Motschmann[1,3], [1]DLR Institute of Planetary Research, Rutherford Str.2, D-12489 Berlin, Germany (detlef.deniem@dlr.de), [2]Observatoire de la Côte d'Azur, CNRS, BP 4229, 06304 Nice Cedex 4, France, and [3]Institute of Theoretical Physics, Technical University of Braunschweig, Mendelssohnstrasse 3, D-38106 Braunschweig, Germany

Hadean Earth lacks a clear record from a long-lasting or late heavy bombardment enduring more than ∼600 million years after its formation. Direct evidence comes from the Moon, more specifically from ages recorded in lunar samples returned by the Apollo astronauts [14]. The geological record of large lunar impact basins provides an estimate of the amount of material contemporaneously striking the Earth [9], suggesting a top-heavy size frequency distribution (SFD) of impactors [14, 6, 3]. Rare impacts of very large objects dominated erosion or accumulation of the atmospheres.

Because of the 'statistics of low numbers' consequences as arising in the Nice model [5], for example, have to be found with the help of Monte Carlo simulations rather than with differential equations such as [15]. As a byproduct this allows to compare formation ages of lunar basins arising in different scenarios. The nature of the impactors – asteroidal or cometary – is much debated [6, 5, 3] leading to rather different end-members in terms of planetary atmospheres following the bombardment era. Whereas impact velocities and probabilities are taken to correspond to dynamical simulations, SFDs are fit from models to observations of modern main belt asteroids (MBAs) [2] and Kuiper belt objects (KBOs). Size distributions are the product of a collisional evolution that has been more vigorous at times of a more massive population [3]. Highly simplified physical models for the survival and escape of atmophile gases [13, 12, 1, 4] are compared with results of hydrocode simulations [11, 10]. [11, 10] also provide small-size limits for the objects contributing to atmospheric erosion that are useful to define a reasonable interval of sizes in Monte Carlo runs however care is necessary when this is adapted to the conditions of a thin Martian atmosphere. Scaling properties of the quite different physical models with impactor and target planet/atmospheric parameters are analyzed before implementing them into the Monte Carlo code.

Interesting is to compare at least the Earth and Mars. We show consequences for Mars and the Earth under widely varying assumptions for the nature of impactors [8] and study the atmospheric response at the large-size end of the impactor SFD during a terrestrial LHB with an extented version of our previous multi-material method [7] adapted to spherical coordinates.

We find that accumulation dominates over erosion of atmospheres for the velocity distribution typical in the Nice model and moderate assumptions about volatile content of impactors. Net erosive behaviour is observed only for a bombardment by dry MBAs containing less than about 0.2% by mass CO+$CO_2$, in the case of the Earth whereas a significant contribution by KBOs will accumulate massive atmospheres equivalent to several bars unless these objects are dispersed or degassed on their way to the inner solar system. Consequences for Mars are similar despite the lower escape speed of this planet however the possibility of a significant atmospheric 'late veneer' depends on the ages of the large martian impact basins.

**Acknowledgements:** This research has been supported by the Helmholtz Association through the research alliance "Planetary Evolution and Life".

## References

[1] T. J. Ahrens, *Annu. Rev. Earth Planet. Sci.* **21**, 525-555 (1993).

[2] W. F. Bottke, D. D. Durda, D. Nesvorny, R. Jedicke, A. Morbidelli, D. Vokrouhlicky, H. Levison, *Icarus* **175**, 111-140 (2005).

[3] W. F. Bottke, H. F. Levison, D. Nesvorny, L. Dones, *Icarus* **190**, 203-223 (2007).

[4] H. Genda, and Y. Abe, *Icarus* **164**, 149-162 (2003).

[5] R. Gomes, H. F. Levison, K. Tsiganis, A. Morbidelli, *Nature* **43**, 466-469 (2005).

[6] H. F. Levison, L. Dones, C. R. Chapman, S. A. Stern, M. J. Duncan, and K. Zahnle, *Icarus* **151**, 286-306 (2001).

[7] D. de Niem, E. Kührt, U. Motschmann, *Computer Phys. Comm.* **176**,170-190 (2007)

[8] D. de Niem, E. Kührt, A. Morbidelli, U. Motschmann *Icarus*, (submitted) (2011).

[9] G. Ryder, *J. of Geophys. Res.* **107, No E4**, 5022, 1-13 (2002).

[10] V.V. Shuvalov, *Meteoritics and Planetary Sci.* **44, No 8**, 1095-1105 (2009).

[11] V. V. Svetsov, *Solar System Research* **41, No 1**, 28-41 (2007).

[12] A. M. Vickery, and H. J. Melosh, *Geol. Soc. Am. Spec. Pap.* **247**, 289-300 (1990).

[13] J. C. G. Walker, *Icarus* **68**, 87-98 (1986).

[14] G. W. Wetherill, *Proc. Lunar Sci. Conf.* **6th**, 1539-1561 (1975).

[15] K. Zahnle, J. B. Pollack, and D. Grinspoon, *Icarus* **95**, 1-23 (1992).