EPSC Abstracts
Vol. 7 EPSC2012-564 2012
European Planetary Science Congress 2012

Escape of protoatmospheres and their role in atmosphere evolution

H. Lammer (1), K. G. Kislyakova (1,3), N. V. Erkaev (2), P. Odert (3),•Yu. N. Kulikov (4), M. Güdel (5), M. L. Khodachenko (1), A. Hanslmeier (3)

(1) Austrian Academy of Sciences, Space Research Institute, Schmiedlstr. 6, A-8042 Graz, Austria, (2) Institute of Computational Modelling, Siberian Division of Russian Academy of Sciences Akademgorodok 28/44, 660036 Krasnoyarsk, Russian Federation, (3) Institute for Physics/IGAM, University of Graz, Universitätsplatz 5, A-8010 Graz, Austria, (4) Polar Geophysical Institute, Russian Academy of Sciences, 183010 Murmansk, Khalturina Str. 15, Russian Federation, (5) Institute of Astrophysics, University of Vienna, Türkenschanzstr. 17, 1180, Austria (helmut.lammer@oeaw.ac.at)

Abstract

We discuss the origin and evolution of the atmosphere of early Venus, Earth, Mars and super-Earths. It will be shown that the formation age of a terrestrial planet, its mass and size, as well as the planet's lifetime in the EUV-saturated early phase of its host star play a significant role in the escape of the planet's protoatmosphere and related atmosphere evolution.

1. Introduction

For understanding how planetary atmospheres originated and evolved, one has to study its potential sources and sinks, which contributed to their initial formation. The first protoatmosphere scenario can be connected to the capture of hydrogen- and He-rich nebula gas envelopes from around a growing protoplanet, before its accretion ended [1, 2]. Additional protoatmospheres are produced by degassing of volatiles after the young planet finished its accretion and the planet's magma ocean solidificated. By using bulk compositions related to primitive and differentiated meteorite compositions, outgassing alone can create protoatmospheres ranging from ≤ 1% of the planet`s total mass up to ~6% by mass of hydrogen, to ~20 mass % of H_2O, and/or ~5 mass % of carbon compounds [3, 4, 5]. Addionally to the outgassing scenarios impacts will also contribute to the delivery of volatiles.

2. Escape of Protoatmospheres

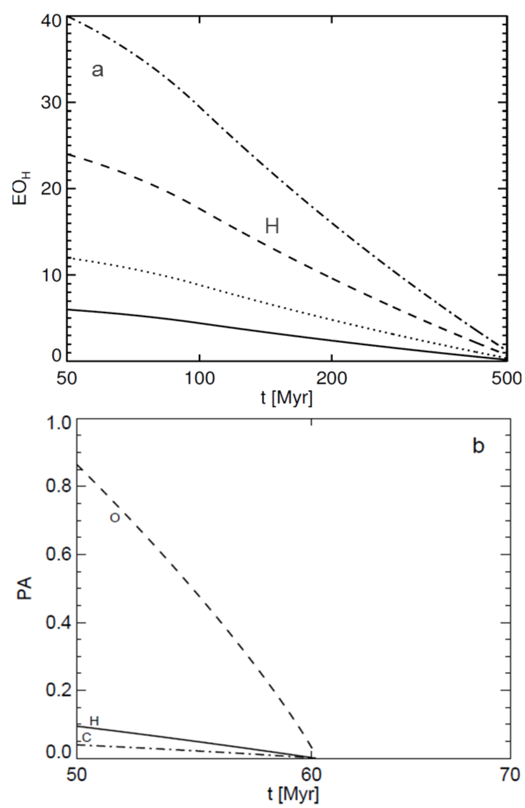

Figure 1: a) H atoms in units of Earth ocean (EO_H) equivalents that can escape via blow off from an Earth-analogue planet as a function of heating efficiency. Solid line: 15 %, dotted line: 30 %, dashed line: 60 %, dashed dotted line: 100 %. b) normalized escape of a protoatmosphere from early Mars as a function of time. PA=1 corresponds to the total pressure of 82 bar.

As shown by [6] during the early period of the active young Sun/star a hydrogen-dominated upper atmosphere of an Earth-like planet experienced the most efficient atmospheric escape process, namely so-called blow off. This condition develops if the mean thermal energy of the upper atmosphere exceeds the gravitational energy at the exobase level. Under this extreme condition the atmospheric escape is very efficient because the whole exosphere evaporates and is refilled as long as enough gas is delivered from below. For example, Figure 1a shows the maximum amount of atomic hydrogen in units of Earth ocean (EO_H) equivalent amounts. that could escape during blow off from an Earth-like hydrogen-rich planet during a 100 times higher EUV period of the young Sun/star compared to the modern Sun and by using different heating efficiencies of 15 %, 30 %, 60 % and 100 % Figure 1b shows the loss of an initially outgassed martian hydrogen- or water vapor-rich protoatmosphere. Due to the strong hydrodynamic escape of light H atoms heavier species such as O, C and N can also be dragged and lost due to the planetary hydrogen wind.

3. Summary and Conclusions

Our studies of planetary protoatmospheres and their related escape indicate that captured nebula-based hydrogen envelopes, which might remain from the earlier stage of the planet formation, cannot be removed if the planet reached a certain mass domain. Super-Earths are potential candidates for such scenarios. In some cases a terrestrial planet can also accumulate a dense abiotic oxygen-rich upper atmosphere, or otherwise it will become a sub-Neptune-type body, even within the habitable zone of its host star. On the other hand, if a terrestrial planet's atmosphere evolved during the high EUV phase of its young host star to a nitrogen-rich Earth-like atmosphere too early, then all of its atmospheric nitrogen inventory can be lost. This indicates that the nitrogen-inventory of the Earth might have been protected from escape by a higher amount of IR-cooling CO_2 in the thermosphere, or by a dense hydrogen envelope. In case of a dense hydrogen envelope surrounding the very early Earth or similar planets, the scale height of the H atoms would be much larger compared to molecular nitrogen or other heavier species, which would populate the lower atmosphere close to the surface, so that nitrogen would not reach the stellar wind interaction region, similar as on present Earth. As long as enough hydrogen is in the thermosphere the extended upper atmosphere would act as a shield against the loss of heavier particles. If a planet originates too dry, the young star might be active enough to remove the planet's less dense initial atmosphere and the planet might have ended up with a present-day Venus or Mars-like CO_2 atmosphere.

Acknowledgements

H. Lammer, K. G. Kislyakova , M. Güdel and M. L. Khodachenko, acknowledge the support by the FWF NFN project S116 "Pathways to Habitability: From Disks to Active Stars, Planets to Life", and the FWF NFN subprojects, S116 604-N16, S116606-N16, S116607-N16. P. Odert acknowledges the FWF project P22950-N16. N. V. Erkaev acknowledges support from the RFBR grant N 12-05-00152-a. H. Lammer, K. G. Kislyakova, M. L. Khodachenko and P. Odert thank also the Helmholtz Alliance project "Planetary Evolution and Life."

References

[1] Hayashi, C., Nakazawa, K.: Earth's melting due to the blanketing effect of the primordial dense atmosphere, Earth Planet. Sci. Lett. Vol. 43, pp. 22–28, 1979.

[2] Ikoma, M., Hori, Y.: In-situ accretion of hydrogen-rich atmospheres on short-period super-Earths: implications for the Kepler-11 planets, ApJ submitted, arXiv:1204.5302v1, 2012.

[3] Elkins-Tanton, L. T.: Linked magma ocean solidification and atmospheric growth for Earth and Mars, Earth and Planet. Sci. Lett. Vol. 27, pp. 181–191, 2008.

[4] Ekins-Tanton, L., Seager, S.: Ranges of atmospheric mass and composition of super-Earth exoplanets, ApJ Vol. 685, pp. 1237–1246, 2008.

[5] Elkins-Tanton, L. T.: Formation of water ocean on rocky planets, Astrophys. Space Sci. Vol. 332, pp. 359-364 2011.

[6] Lammer, H., Kislyakova, K. G., Odert, P., Leitzinger, M., Schwarz, R., Pilat-Lohinger, E., Kulikov, Yu. N., Khodachenko, M. L., Güdel, M., Hanslmeier, A.: Pathways to Earth-like atmospheres: extreme ultraviolet (EUV)-powered escape of hydrogen-rich protoatmospheres, Orig. Life Evol. Biosph. Vol. 41, pp. 503–522, 2012