

Preface

After more than four decades of space exploration and data gathering by various spacecraft, plausible hypotheses can be developed which may answer why Venus and Mars evolved so differently compared to the Earth. The Earth is unique in the sense that it has a nitrogen-dominated atmosphere, kept its liquid water oceans since ~ 4.4 Gyr ago, has continents and has been geophysically active since its origin. Due to these conditions, approximately 3.5–3.8 Gyr ago simple microbial and later complex multi-cellular life forms could originate and inhabit the planet's hydrosphere, subsurface and surface. Up to now, Earth is the only example of a known habitat where such a great variety of life forms could develop.

One important factor in this cosmic puzzle regarding Earth's evolution to a habitat where higher life forms could evolve is related to the fact that the planet orbits around the Sun, which is a GV2 star, within the so-called continuously habitable zone. The classical concept of the stellar habitable zone is a spherical shell around a main sequence star where a planet with an atmosphere can support liquid water at a given time. The width and location of this region depends on the stellar luminosity that evolves during the star's lifetime and is closer, compared to solar-like G-type stars, when the star is cooler (M- and K-types) and further out when the star is hotter (F-type).

Venus orbits slightly outside the inner edge of the habitable zone at a distance where the planet's initial water inventory most likely always remained in vapor form due to greenhouse conditions until it was lost to space. Mars on the other hand orbits at the outer edge of the habitable zone, where a maximum greenhouse effect fails to keep the global surface temperature of the planet above the freezing point of H_2O so that CO_2 can condense. Because Earth has also been geophysically active since its origin the carbonate–silicate cycle works, and CO_2 could be weathered out of the atmosphere via its continents and oceans into a carbonate deposit in the lithosphere. The amount of CO_2 in the atmosphere depends on the orbital distance where CO_2 can be considered as a trace gas close to the inner edge of the habitable zone but a major compound in the outer part of the habitable zone.

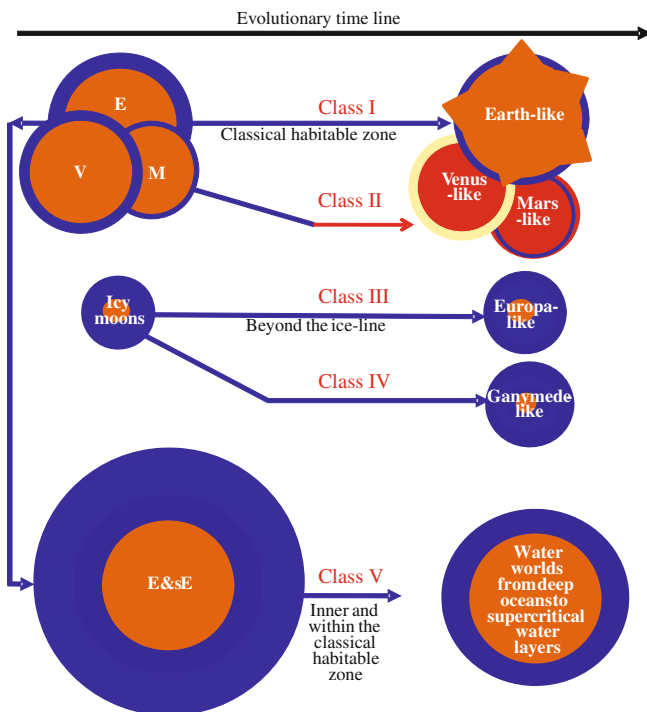


Fig. 1 Illustration of Earth-analogue class I, martian-type class II, icy moon-type classes III and IV and water world class V habitats

Due to my main scientific expertise in atmospheric escape processes and the evolution of planetary atmospheres, in 2003 I became involved in the European Space Agency (ESA) Terrestrial Exoplanet Advisory Team (TE-Sat). One of the main tasks within this international team was related to the extension of comparative planetology from Solar System planets to exoplanets, aeronomy and habitability. It soon became clear that the classical concept of the habitable zone and its related questions of what makes a planet habitable is much more complex than having a big rocky body located at the right distance from its host star. Because the classical habitable zone concept does not really indicate if life could evolve on a terrestrial planet, it is better to classify potential habitats (see Fig. 1). According to an interdisciplinary study which was coordinated by me and published in 2009 in *Astronomy and Astrophysics Review* (17:181–249, 2009) four potential habitat classes have been identified:

- Class I habitats represent planetary bodies on which stellar and geophysical conditions allow Earth-analogue planets to evolve so that complex multicellular life forms may originate and inhabit the planets hydrosphere, surface and subsurface environments.

- Class II habitats include bodies on which life may evolve but due to astrophysical and geophysical conditions, these planets rather evolve within their habitable zones towards Venus- or Mars-type worlds where complex multicellular life forms may not develop.
- Class III habitats are planetary bodies where subsurface water oceans which interact directly with a silicate-rich core exist below an ice layer.
- Class IV habitats have liquid water layers between two ice layers or liquids above ice.

However, since the publication of this study, exoplanets such as GJ 1214b or Kepler 11b have been discovered which may represent an additional fifth habitat class. From the radius–mass relation of these super-Earth-type planets one can expect that a rocky core is most likely covered by a very deep liquid water ocean but without continents. Thus, this new type of planets can be classified as:

- Class V habitats which correspond to bodies which have huge water layers above a rocky core but no solid surface. In some cases the environmental conditions may allow envelopes of supercritical water above a rocky and perhaps Earth-like nucleus.

A careful study of various astrophysical and geophysical aspects indicate that Earth-analogue class I habitats have to be located at the right distance of the habitable zone from their host stars, must lose their protoatmospheres during the right time period, should maintain plate tectonics over the planet's lifetime, should have nitrogen as the main atmospheric species after the stellar activity decreased to moderate values and finally, the planet's interior should have developed conditions that an intrinsic strong global magnetic field could evolve.

The recent discoveries of numerous planetary candidates by NASA's Kepler space observatory indicate that there may be millions of smaller terrestrial-type planets within orbit locations inside the habitable zones of their host stars in the Galaxy. However, preliminary but careful studies of potential habitats point in a direction that class I habitats should occur much less frequently compared to more exotic class II, III, IV and V habitats.

This brief monograph addresses the physical and chemical processes that underpin these findings for an interdisciplinary scientific readership and students which are interested in habitability and the escape-related evolution of planetary atmospheres. Initially, different hypotheses about the origins of protoatmospheres are discussed. Because the escape and evolution of atmospheres are strongly connected to the radiation and plasma environment of the age of a planet's host star the latest knowledge in the stellar age-activity relation is discussed. Therefore, the most important physical and chemical processes which are responsible for the evaporation and erosion of planetary atmospheres are described in detail. Atmospheric evolution scenarios for early Venus, Earth, Mars, terrestrial exoplanets and the implications for the search of Earth-analogue class I habitats are also addressed. Finally, powerful methods which are based on future UV transit

observations of Earth-size exoplanets within orbits of dwarf stars together with advanced numerical modeling techniques, which can be used for the test of the atmosphere evolution hypotheses, are presented.

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Implications for Habitability

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