The Early Evolution of the Atmospheres of Earth, Venus, and Mars

1 Abstract

The atmospheric and surface conditions of Earth, Venus, and Mars formed as a result of a chain of astrophysical and geophysical/chemical processes. The end results were the formation of a habitable environment on the Earth and highly inhospitable environments on Venus and Mars. Understanding these processes will improve our understanding of the formation of life on Earth and help us achieve a general understanding of how habitable planetary environments form. *We propose an ISSI team to study the early evolution of the atmospheres of Earth, Venus, and Mars as test cases for the formation of habitability on terrestrial planets. Our team contains a unique combination of expertise in the evolution of planetary interiors and surfaces, atmospheric formation processes, the Sun's activity evolution, planetary atmospheric loss mechanisms, and atmospheric chemistry.*

Many of the most critical processes took place within the first 100-200 Myr of solar-system formation and were highly intertwined. Initial H/He envelopes (protoatmospheres) may have remained on planets from their formation during the protoplanetary disk phase, preventing rapid cooling and the formation of a secondary atmosphere. However, solar radiation and the solar wind should have eroded such envelopes, and the cooling magma ocean surfaces eventually led to crust formation, outgassing of secondary atmospheres including heavier species such as H_2O, CO_2 and N_2, and the collection of liquid water oceans, thus setting the stage for the operation of plate tectonics on Earth; the latter in turn helped remove potentially massive amounts of greenhouse-active CO_2. A delicate timing of events and well adjusted amplitudes of solar and geophysical influences were thus critical for the Earth - and may have failed on Venus due to its closer proximity to the Sun, preventing rapid cooling, the formation of oceans and therefore plate tectonics. The atmospheres of Earth and Venus thus evolved very differently, yielding a CO_2 dominated atmosphere on Venus, and an N_2 dominated habitable atmosphere on Earth. *How these mechanisms interact to form habitable planetary environments, or why they may fail to do so, will be the major focus of this ISSI team.*

2 Major topics and work packages addressed by the team

2.1 Formation of Earth, Venus, and Mars

The first crust (the primordial crust) on Earth and Venus is believed to have formed during the solidification phase of the magma ocean within the first 150-200 Myr of our solar system (Elkins-Tanton 2012; Hamano et al. 2013; Lebrun et al. 2013). On both planets, however, the primordial crust did not survive due to resurfacing processes (of either magmatic or tectonic origin). On Earth, the oldest minerals found are zircons, which are more than 4 Gyr old (likely up to 4.4 Gyr; Wilde et al. 2001). On present-day Venus, the oldest surviving crust forms the tessera terrains; although their age has not yet been determined, it is believed that they formed not too long ago (i.e. only a few hundred Myrs ago; Hansen & López 2010), and it has been suggested that they could be of felsic origin similar to Earth's continental crust (Muller et al. 2008). Members of our team use numerical models to investigate the possible evolution of the interior of Earth, Venus and Mars, including the convective behaviour in the mantle, resulting surface-shaping processes like plate tectonics and other resurfacing mechanisms (Tackley 1998; Gillmann & Tackley 2014; Noack et al. 2012). *A major goal of the proposed ISSI team will be to study the importance of these processes to the formation of planetary atmospheres.*

2.2 Atmospheric formation

If the terrestrial planets formed to significant masses in the first few Myr after the Sun's formation, they would have collected large atmospheres (Lammer et al. 2014; Stökl et al. 2015), insulating the planetary cores. Recently, we have observed a large number of terrestrial exoplanets that likely have such atmospheres (Rogers 2015). *The proposed ISSI team will investigate the formation and losses of primordial atmospheres and their possible interaction with the solid part of terrestrial planets, focussing* *on Earth and Venus. We will discuss possible constraints on the lifetimes of these atmospheres from our knowledge of the early evolution of the surface of the Earth.*

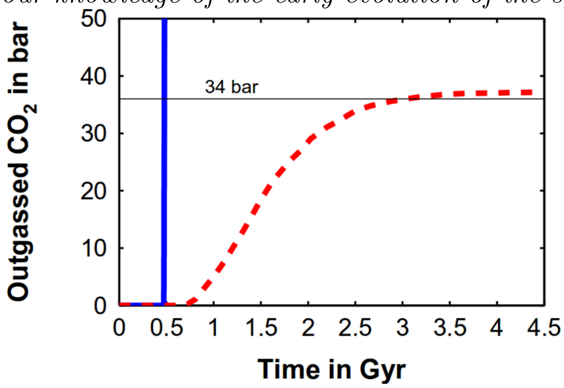

Figure 1: Volcanic outgassing of CO_2 for a case with plate tectonics (blue line) or stagnant lid case (red line) for a planet similar to Earth. From Noack et al. (2014).

The terrestrial planets formed from accretion of materials that partly contained volatiles (Schönbächler et al. 2010). These volatiles were released to form a *secondary* atmosphere during the formation of Earth (Hashimoto et al. 2007), subsequently during magma ocean solidification (Elkins-Tanton 2008), and through volcanic outgassing driven by convection in the silicate mantle (Noack et al. 2014).

At this point in time, the interplay between greenhouse-driving water vapor and planetary cooling became essential. On *Venus*, outgassed H_2O likely remained in vapor form (Hamano et al. 2013; Lebrun et al. 2013). According to Gilmann et al. (2009), the main phase of hydrogen atom escape likely ended after $\leq$500 Myr when all the accreted water and hydrogen was gone. After this period, water delivered by comets (Grinspoon & Lewis 1988) was lost, with a residual of O_2. It is possible that the present atmospheric D/H, ^{20}Ne/^{22}Ne and ^{36}Ar/^{38}Ar isotopic ratios and the absence of significant amounts of oxygen can be explained if early Venus was surrounded by an outgassed steam atmosphere during the first 50 - 100 Myr (Gillmann et al. 2009). At *Earth's* orbit, the outgassed steam atmosphere cooled faster and H_2O condensed rapidly, thus forming early oceans (Lammer et al. 2011; Lebrun et al. 2013).

Numerical models can simulate the thermal evolution of the silicate mantle and resulting magmatic events, leading to secondary atmosphere build-up (Gillmann and Tackley, 2014; Noack et al., 2014). Fig. 1 shows an example simulation for an Earth-like planet for either a stagnant lid case or a case where plate tectonics initiates after about 400 Myr. Secondary atmospheres with high concentrations of hydrogen have much smaller redox ratios. Atmospheres with small redox ratios are perfect environments for prebiotic chemistry (Rimmer & Helling 2016; Bains & Seager 2012). The resulting species are essential for the photochemical production of nucleic and amino acids (Patel et al. 2015).

The proposed ISSI team will discuss how the formation times of the atmospheres of Earth, Venus, and Mars would have depended on the presence of primordial atmospheres and how the evolving compositions of such atmospheres could impact later prebiotic chemistry. The reproduction of today's atmospheric isotope ratios will be used for the determination of the atmosphere formation timescales. We will discuss organic molecule formation in Earth's early atmosphere and its relation to the young Sun's X-ray/EUV activity. These conclusions will be extended to atmospheric formation in habitable zone exoplanets.

2.3 Stellar activity evolution and atmospheric loss

To study the formation of primordial and secondary atmospheres further, we distinguish between two classes of loss mechanisms: *thermal* and *non-thermal* losses. Thermal losses are mostly induced by stellar XUV (= extreme ultraviolet and X-ray) irradiation heating the planet's upper atmosphere and likely dominate the losses for hydrogen atmospheres (Kislyakova et al. 2013). An important non-thermal loss mechanism is stripping of upper atmospheres by interactions with the ionized stellar wind; this process is likely more important for atmospheres made of heavier species.

The Sun started out orders of magnitude more active than it currently is, and as it evolved, its X-ray/EUV luminosities and winds decayed (Güdel et al. 1997; Ribas et al. 2005; Airapetian & Usmanov 2016). However, based on their initial rotation rates, stars can follow very different evolutionary tracks in magnetic activity (Johnstone et al. 2015a; Tu et al. 2015). Possible evolutionary tracks for XUV luminosity are illustrated in Fig. 1-left for a solar-mass star.

The evolutionary track that a solar mass star takes can significantly influence the early evolution of a terrestrial planet's atmosphere (Johnstone et al. 2015b). This is demonstrated for an example case in

Fig. 1-right. We presently have no clear information on which evolutionary track in rotation/activity the Sun took and we do not understand how the different activity tracks would have influenced the early development of the solar system terrestrial planets. *The proposed ISSI team will address the influences of the different possible solar activity tracks on the atmospheric photochemistry and evolution of Earth, Venus, and Mars and discuss if the Sun's activity evolution can be constrained by the current and past conditions on these planets.*

An atmosphere's composition can significantly influence its loses. Lichtenegger et al. (2010) found that an N_2 atmosphere on early Earth would have been difficult to retain given high loses due to enhanced EUV and winds of the young Sun. They suggested that enhanced levels of atmospheric CO_2 (such as that of current Venus) could have cooled the upper atmosphere and protected it from erosion (Fig. 4). Knowledge of the composition of the early Earth, its formation times, and the evolution of the Sun's activity are therefore crucial to understand the evolution of the Earth's surface. *The proposed ISSI team will attempt to combine knowledge of the early atmospheric formation of Earth and Venus with the Sun's activity evolution to understand possible atmospheric loss histories for these planets.*

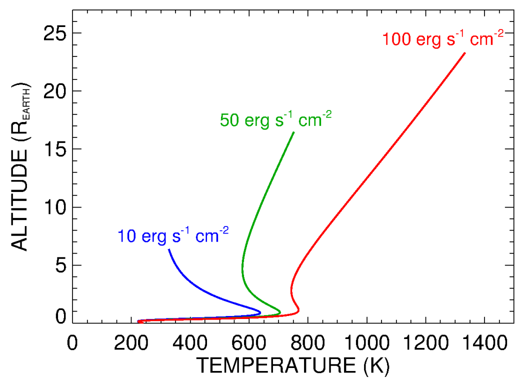

Figure 2: Hydrodynamic upper atmosphere models (from our team) for Earth with a hydrogen atmosphere assuming different stellar XUV fluxes.

2.4 Putting things together: Critical Timing and Interactions

As summarized above, the early evolution of terrestrial planets toward habitable conditions depends critically on the favorable interaction between planetary interiors, crust formation, secondary-atmosphere outgassing, the presence of water (eventually in liquid form) and astrophysical driving of atmospheric processing and escape. The sequence and timing of crucial events and the magnitude of various influences determines the fate of planetary habitability, but they are not well understood and must be studied in an interdisciplinary context. Our ISSI Team brings together experts in these fields to work towards this goal based on theoretical and numerical strategies; the team will in particular address,

- What is the timing of protoatmospheric loss, planetary growth, magma ocean solidification, secondary-atmosphere outgassing, water ocean formation, and atmospheric processing under the influence of the evolving solar irradiation?

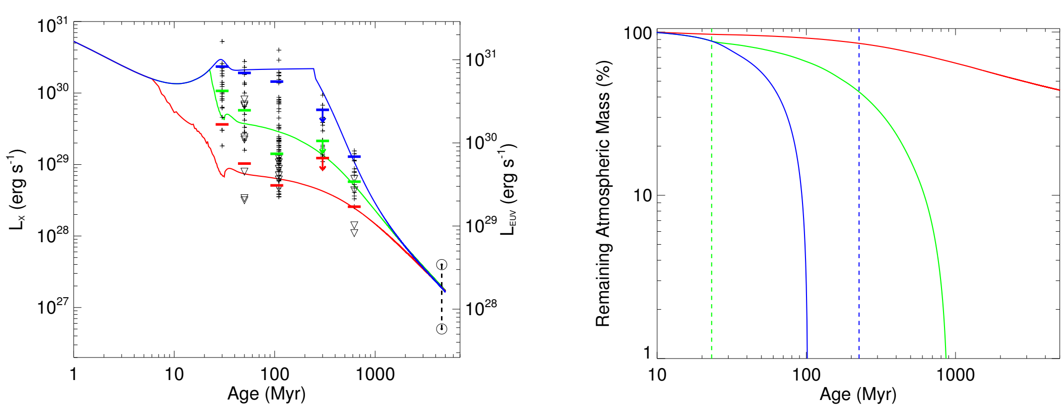

Figure 3: *Left panel:* possible X-ray/EUV luminosity tracks for a solar-mass star assuming different initial rotation rates (red, green and blue correspond to slow, medium and fast rotators) from Tu et al. (2015); note the wide range of possible tracks at 10–1000 Gyr. *Right panel:* Evolution of atmospheric mass for a $0.5 M_{\rm Earth}$ core with a $5 \times 10^{-3} M_{\rm Earth}$ atmosphere, derived using the $L_{\rm XUV}$ tracks in the left panel (Tu et al. 2015).

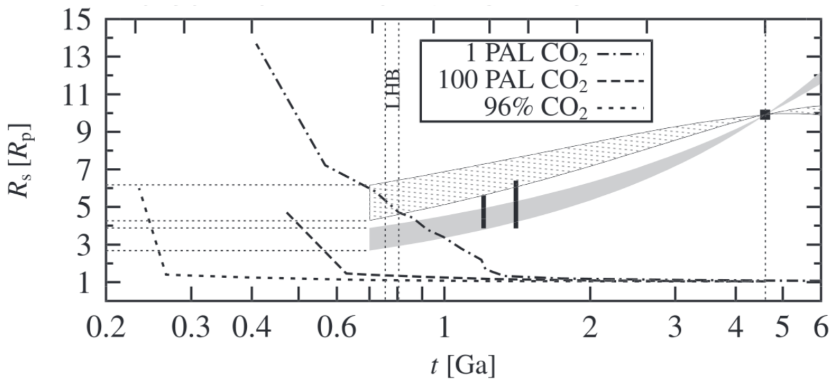

Figure 4: Figure reproduced from Lichtenegger et al. (2010) comparing predicted radii for the Earth's exobase with predictions for the magnetopause radius at different ages. The dot-dashed line shows the Earth exobase radius assuming the current atmospheric composition. The dashed and dotted lines show the predictions assuming elevated atmospheric CO_2 contents of 100x present values and of 96% of the entire atmosphere. These lines are therefore lower due to the strong cooling effects of the additional CO_2. The shaded areas show different predictions for the magnetopause radii based on different assumptions about how the Earth's magnetic field has evolved in time.

- How do planetary interiors and secondary atmospheres interact to create habitable conditions?
- What are the conditions for solar activity, planetary atmospheric composition and outgassing rate to form Earth's atmosphere and keep it habitable to the present day?
- What can we infer for Venus' early evolution? When, where and why did it differ from Earth's?
- What can we learn about the formation of habitable conditions outside of the solar system from the cases of Earth, Venus, and Mars?

3 Synergies and Expected Outcomes

Summary of Interdisciplinary Goals of our Study: The most important interdisciplinary aspects include: the removal of protoatmospheres previously accreted from protoplanetary disks; chemical and physical processing and erosion of outgassed secondary atmospheres by the action of winds and radiation from the evolving host star; and interactions between planetary atmospheres and surfaces/interiors that lead to plate tectonics and the buildup of liquid water oceans.

Apart from these interactions, a full understanding of the sequence of events, their relative timing and their time scales is needed. For example, the disappearance of a possible hydrogen envelope is relevant for the evolution of secondary atmospheres, the cooling of the crust, and eventually the accumulation of liquid water and the onset of plate tectonics. To accomplish this goal, a multidisciplinary study is needed and timely.

Expected Collaborative Work Resulting from the Meetings: We expect the proposed ISSI meetings to be the seeds of closer collaborations between the team members. Our goal is to establish a principal methodology to address how a habitable environment evolved on Earth, and by analogy to understand how Venus and Mars reached their present state. Partial collaborations have taken place in the past between some of the team members, but now is the time to bring them all together.

Methods and Expected Scientific Breakthroughs: The proposed team brings deep expertise with leading numerical codes for computation of planetary interiors, plate tectonics, volatile formation and chemical processing, atmospheric erosion by solar high-energy radiation and winds (hydro and particle codes); we will be able to compute critical mechanisms in greater context and link simulations using a variety of input parameters.

We expect two major outcomes from the proposed ISSI meetings. First, by summarizing present knowledge and ongoing research in the different disciplines, we aim at collecting enough information to develop a methodology toward computing conditions for habitability on evolutionary timescales. This will then form the basis for extensive future collaborations to address all relevant issues. And second, the collected information presented during the ISSI meetings will be transformed into a review article, summarizing the present status of knowledge and reviewing the outstanding questions.

We note that several team members are also members of specialized collaborations relevant for this topic, thus profiting from a large pool of knowledge in their fields of expertise.

Proposed Schedule: *We request three meetings of a 3-day duration spread over ∼18 months.* the first meeting taking place shortly after approval of the team proposal. During the **first meeting**, the three major groups of the team (astrophysicists - atmospheric physicists - geophysicists/geochemists) will first summarize the present knowledge about the "Early Earth" and the young stages of Venus and Mars, focusing on topics laid out in the proposal above. Then the relevant open questions will be described and discussed in an interdisciplinary way. Finally, we will devote time to defining action items towards a first set of calculations/simulations on magma oceans/outgassing/secondary atmospheres/atmospheric loss requiring input from all areas. We will discuss plans towards a review article on the topic.

The **second meeting** will discuss intermediate results and rediscuss the approaches, including improving the setup of the simulations.

In the **third meeting**, we will discuss the generalization of our approaches to include any type of terrestrial planets, including known rocky exoplanets in or close to habitable zones. We will also further vary models of interiors and compositions of assumed atmospheres. This should lead to general publications about early evolution of habitability.

Facilities and Financial Support: We require only standard ISSI facilities, i.e., a room for 12 participants, a beamer, and internet access. We request standard support for accommodation and per diem. We will propose three young scientists to participate: Lin Tu (Vienna) and Manuel Scherf (Graz), both PhD students who will be partly funded from other sources, plus one more from outside Austria. We apply for travel support for the team leader.

Added Value of ISSI Support: The topic of this team is interdisciplinary and highly compatible with the ISSI mission: Two areas are focusing on Earth sciences, planetary sciences and magnetospheric physics dealing with the interior and surfaces of terrestrial planets including the generation of magnetospheres. The third topic addresses solar and heliospheric physics, solar-terrestrial sciences, space plasma and magneospheric physics and astrophysics. All subtopics overlap significantly, and it is these interfaces that we would like to exploit during the team meetings. ISSI therefore provides a unique venue for these meetings, offering the required infrastructure for interdisciplinary studies in these fields.

List of confirmed members:
This ISSI team project combines three groups of experts into one interdisciplinary team:

Geoscientists: Hervé Martin (U. Blaise Pascal, Aubière, F), Lena Noack (Royal Observatory of Belgium, BE), Maria Schönbächler (ETH Zurich, CH), Paul Tackley (ETH Zurich, CH);
Atmospheric Scientists/Aeronomists: Maxim Khodachenko (IWF Graz, A), Kristina Kislyakova (IWF Graz, A), Helmut Lammer (IWF Graz, A), Paul Rimmer (U. St. Andrews, UK);
Astrophysicists: Vladimir Airapetian (NASA GSFC, USA), Alex Glocer (NASA GSFC, USA), Manuel Güdel (U. Vienna, A), Colin P. Johnstone (U. Vienna, A), Theresa Lüftinger (U. Vienna, A)

This proposal is motivated by a network project "Pathways to Habitability" based in Austria with several international collaborators. This project includes the Austrian based people mentioned above.

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