Planetary and Space Science 63–64 (2012) 15–23

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

The evolution of Venus: Present state of knowledge and future exploration

Eric Chassefière[a,b,*], Rainer Wieler[c], Bernard Marty[d], François Leblanc[e]

[a] Univ Paris-Sud, Laboratoire IDES, UMR8148, Université Paris-Sud, Bât. 504, Orsay F-91405, France
[b] CNRS, Orsay F-91405, France
[c] ETH Zürick Earth Sciences, NW C84, CH-8092 Zurich, Switzerland
[d] CRPG-CNRS, 15 Rue Notre Dame des Pauvres, BP 20, 54501 Vandoeuvre Les Nancy Cedex, France
[e] Laboratoire Atmosphères Milieux Observations Spatiales/IPSL, CNRS-UVSQ, Université Pierre et Marie Curie, Boite 102, 4 Place Jussieu, 75005 Paris, France

ARTICLE INFO

Article history:
Received 14 January 2011
Received in revised form
30 March 2011
Accepted 12 April 2011
Available online 27 April 2011

Keywords:
Venus
Terrestrial planets
Formation
Evolution
Noble gases
Stable isotopes
Balloons

ABSTRACT

A detailed characterization of the formation and evolution of Venus is a key link to the study of terrestrial planets, and to their divergent evolutions. While Earth and to a lesser extent Mars (thanks to the analysis of SNC meteorites) are extensively studied in a comparative planetology context, the history of the most Earth-like planet of the Solar System, Venus, is still poorly understood. For how long has Venus been in its current extreme climate state? When and how did it diverge from a (possible) early Earth-like state? Has Venus been a potentially habitable planet at some time of its early history? Did a "cool early Venus" stage occur between the end of accretion and the late heavy bombardment, like suspected for Earth? What are the implications of the Venus/Earth comparison for the nature and evolution of habitable terrestrial planets throughout the universe? A major observational missing link in our understanding of Venus' climate evolution is the elementary and isotopic pattern of noble gases and of stable isotopes in Venus' atmosphere, still poorly known. The concentrations of heavy noble gases (Kr, Xe) and their isotopes are mostly unknown, and our knowledge of light noble gases and stable isotopes is incomplete and inaccurate. In this paper, we summarize our present understanding of Venus' early evolution, including the crucial question of knowing if water ever condensed at the surface of the planet. Then, we assess the potential contribution of a precise measurement of noble gases, their isotopes and stable isotopes to improve of our understanding of Venus evolution, and list the main questions that noble gases and isotope measurements would help to answer. Finally, we show how future exploration of Venus could allow to gain a glimpse into the early evolution of Venus through a small in-situ mission based on a single balloon probe, called EVE (European Venus Explorer), proposed in the frame of the ESA Cosmic Vision program.

1. Introduction

It is generally believed that Venus received similar amounts of volatiles from the proto-planetary nebula as the Earth did. The atmosphere of Venus contains about twice as much carbon and nitrogen as the atmosphere, hydrosphere and sediments of the Earth (Lécuyer et al., 2000). The low quantity of water in the present atmosphere of Venus could result from a combination of crustal hydration and past escape processes. The present value of the deuterium/hydrogen (D/H) ratio on Venus, larger than that on Earth by a factor of 150 (Donahue et al., 1982; De Bergh et al., 1991), suggests that hydrogen escape has played an important role in removing water from the Venus' atmosphere. Recent results from the ASPERA instrument on Venus Express show that oxygen is escaping at a rate about half that of hydrogen (Barabash et al., 2007a), suggesting that both H and O have escaped significantly through non-thermal processes during Venus' history. Although thermal escape is no more effective at the present time, in the form of hydrodynamic escape it could have removed very large amounts of water (the content of one or several terrestrial oceans) during the few first hundred million years (Kasting and Pollack, 1983; Gillmann et al. 2009). Volatile loss could have also occurred through catastrophic early impacts (Zahnle, 2006). These primitive episodes of atmospheric losses, which probably also affected Earth's and Mars' atmospheres, are suggested by noble gas elemental and isotopic data, which remain quite incomplete for Venus. The presence of an early massive atmosphere of water vapor on Venus, which further escaped to space, and/or was trapped in the interior in the form of hydrates, is generally considered to have initiated the strong greenhouse effect observed today (Shimazu and Urabe, 1968; Rasool and

---

* Corresponding author at: IDES, Univ. Paris-Sud, CNRS, France. Tel.: +33 1 69 15 67 48; fax: +33 1 69 15 49 11.
E-mail address: eric.chassefiere@u-psud.fr (E. Chassefière).

0032-0633/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2011.04.007

de Bergh, 1970). This massive H_2O atmosphere may have resulted, (i) either from the evaporation of a primordial water ocean, followed by hydrodynamic escape of hydrogen (Kasting, 1988), (ii) or the outgassing from the primordial magma ocean, not necessarily followed by the formation of a (transient) water ocean (Gillmann et al., 2009).

In the present state of knowledge of the primitive Venus' atmosphere, with large uncertainties on the results of existing radiative transfer codes of H_2O–CO_2 massive atmospheres, it is unclear if the surface temperature has ever been low enough to allow the condensation of water, even in reduced solar illumination conditions prevailing at the beginning of the Solar System. But, even if thermodynamical conditions allowed the formation of an ocean at some early stage, the necessary condition for such an ocean to have formed is that large amounts of water have been available in the atmosphere. It could not have been the case, for example if Venus was initially endowed with less water than Earth, as it occurs in some existing accretion simulations (see e.g. Raymond et al., 2006), and has been rapidly dessicated through the combined effects of the progressive crystallization of the magma ocean, releasing water to the atmosphere, and of hydrodynamic escape removing this water from the atmosphere to space (Gillmann et al., 2009).

We will first summarize the present state of our understanding of the early evolution of Venus' atmosphere. In a second step, the potential contribution of a precise measurement of noble gases and their isotopes as well as stable isotopes of elements like H, C, O and N, to the improvement of our understanding of Venus' evolution, will be described. Then, the main questions that noble gases and isotope measurements would help to answer will be detailed. Finally, we will show how future exploration of Venus could allow to gain a glimpse into the early evolution of Venus and its atmosphere through a small in-situ mission based on a single balloon probe, called EVE (European Venus Explorer), proposed in the frame of the ESA Cosmic Vision program (Wilson et al., 2008; Chassefière et al., 2009a, b).

2. Early evolution of Venus' atmosphere and hypothesized formation of a transient water ocean

According to a classical picture, the strong greenhouse effect that is responsible for very high temperature and pressure at the surface of Venus has been initiated by the evaporation of a water ocean in earlier times (Shimazu and Urabe, 1968; Rasool and de Bergh, 1970), that is a few 100 Myr after the formation of planets, resulting in a runaway (or moist) greenhouse (Kasting, 1988). It is nevertheless unclear if the conditions at the surface of Venus ever allowed liquid water to be stable. According to radiative-convective models developed twenty years ago (Matsui and Abe, 1986; Abe and Matsui, 1988; Kasting, 1988), the solar flux at Venus' orbit early in solar system history could have been close to the critical value required to trigger a runaway greenhouse. The critical point of H_2O is located at 647 K. According to Matsui and Abe (1986), the surface temperature of Earth at the end of accretion could have been ~600 K, which is lower than the critical temperature, and therefore water would have been able to condense. From the same authors, the temperature of Venus' surface at the end of the accretion was ~700 K, larger than the critical temperature, potentially preventing atmospheric water from condensing out. According to Kasting (1988), the presence of clouds could have resulted in a critical value of the solar flux definitely larger than its effective value, allowing liquid water to remain stable. These models are very sensitive to the H_2O absorption coefficients in the infrared, which are quite uncertain in such high temperature and pressure conditions. Based on these models (Abe and Matsui, 1988; Kasting, 1988), a new, more sophisticated 1D radiative–convective model of a thick ($P \sim 300$ bar) H_2O–CO_2 atmosphere is presently being developed for a later inclusion in a coupled magmatic–atmospheric evolution model of primitive telluric planets (Marcq et al., 2010).

Much progress has been made in the last ten years in our understanding of Earth-like planet formation, significantly modifying our view of the delivery of water to the terrestrial planets. According to recent accretion simulations, the initial water endowment of terrestrial planets would have been provided by a few planetary embryos in a relatively late stage of accretion (Morbidelli et al., 2000). In typical scenarios, accretion started at ~10 Myr after Sun ignition. Most of the water supplied by asteroids has been delivered between 10 and 35 Myr, a time when the mass of the planet did not exceed 50% of its final mass. A maximum of 1 terrestrial ocean (1 TO; TO: Terrestrial Ocean) has been provided by asteroids, but further collisions probably removed a significant fraction of this water. In the time between 35 and 70 Myr, accretion has been completed and large amounts of water delivered to the planet by a few large accreted embryos coming from large distances to the Sun (>2.5 AU), where water is efficiently trapped in planetesimals. At later times, comets from the Uranus–Neptune region and from the Kuiper-Belt may have supplied a late veneer of 10% of the present water content of the Earth.

From existing simulations, a Venus-type planet builds up in typically ~20–30 Myr from embryos formed close to 1–2 AU, most of the water being brought lately (30–70 Myr) by relatively small embryos formed at larger distances (Raymond et al., 2006). The cumulated supply of water is of the order of 15–70 TO for an Earth-type planet, and about 2–3 times smaller (5–30 TO) (Raymond et al., 2006) for a Venus-type planet, consistent with the fact that the feeding zone for the Venus-type planet does not extend significantly beyond 2.5 AU. Using the five simulations of Raymond et al. (2006), and the four simulations of O'Brien et al. (2006), the histogram of the Venus versus Earth water depletion factor shows an average depletion factor of ~3, or more (Fig. 1). But in one case twice the amount of water is accreted by the Venus-type planet than by the Earth-type planet, and one other simulation shows similar endowments. It is due to the highly stochastic character of the accretion process at late stages. Indeed, most of the water is delivered by only a small number of planetary embryos, typically a few tens (Raymond et al., 2006). It cannot be therefore excluded that Venus has been endowed with as much water as Earth (or even more), but the case of a lower endowment, by a factor ~3 or more, is the most likely one according to existing simulations. The estimated amount of water in Earth mantle is in the range 0.3–2.8 TO (Lécuyer et al., 2000), showing that a maximum of ~4 TO remained in Earth crust and mantle. On Venus, the present water content may be 1–3 TO, all in the mantle, assuming that the Venus mantle is similar to that of the Earth. Taking into account the escape of oxygen atoms,

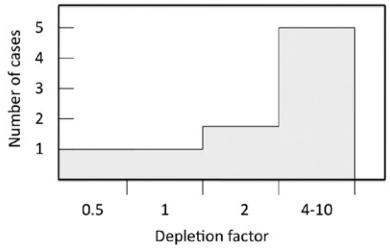

Fig. 1. Histogram of the water endowment depletion factor of Venus with respect to Earth based on nine high resolution accretion simulations (from Raymond et al., 2006; O'Brien et al., 2006).