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Lennart Bengtsson · Roger-Maurice Bonnet
David Grinspoon · Symeon Koumoutsaris
Sebastien Lebonnois · Dmitri Titov *Editors*

Towards Understanding the Climate of Venus

Applications of Terrestrial Models to Our Sister Planet

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Foreword

Back in 2003, ISSI organized one of its regular internal reflexion meetings and invited a few scientists to share for two days their views on the future orientations of the scientific activities of the institute. Their scientific expertise covered a broad range of disciplines and interests, from astronomy to solar physics, planetology, and Earth sciences. One important recommendation of that meeting was to open ISSI activities to Earth sciences, in particular to atmospheric physics and dynamics, and also to the solid Earth, to volcanology and desertification, insisting that they be considered in the broader context of comparative planetology. A few years later these recommendations were implemented. A contract was established with the ESA Directorate of Earth Observations, and Lennart Bengtsson, the leading force behind the preparation of this book, was recruited as ISSI Director for Earth sciences. Lennart did not participate in the 2003 reflexion but he rapidly assimilated its conclusions, in particular as to what concerned Earth sciences and comparative planetology, as well as the unique opportunities offered by ISSI for hosting scientific visitors from all around the world and from many areas of space science. He rapidly proposed that ISSI dedicates one of its future Working Groups to the climate of Venus. The study of Venus climate would indeed offer a natural response to the 2003 meeting recommendations. Opening the ISSI program to the field of Earth sciences through comparative planetology was in continuity with the traditional space science orientations characterizing previous ISSI activities. When planetologists are asked to justify their activities and the costs of their space missions some very often respond that the study of planets should improve our understanding of the Earth.

Amazingly, the logics which led Lennart to establishing a Working Group on the climate of Venus is nearly the opposite, as the title of this book explicitly says: "Towards understanding the climate of Venus: Applications of terrestrial models to our sister planet"! The work reported here aims at showing how the modelling of the Earth atmosphere through General Circulation Models helps improving our understanding of Venus. In the Solar System, among all the other planets, the Earth is exhibiting the largest complexity. It is all at the same time: a solid planet, a magnetic planet, a liquid planet, an icy planet, and an atmospheric planet and last but certainly not least a living planet (it hosts life). Venus is indeed often called our sister planet. It is rather our false twin. It was formed at the same time as the Earth 4.6 billion years ago from the same proto-solar nebula. With a diameter 95 % and a mass 80 % that of the Earth, Venus is a little smaller however. Both planets have nearly the same density and chemical composition. They both have an atmosphere and clouds. But they also have marked differences. Contrary to Venus, the Earth evidences plate tectonics, it has a magnetic field, and its surface is covered at 70 % by water. Venus had probably the same amount of water as the Earth but lost it very early in its history. Today, it is an arid desert and its surface temperature is 460 °C as a consequence of the enormous atmospheric pressure and the extreme greenhouse effect produced early in its life by the high concentration of CO_2, re-enforced by the presence of cloud particles and droplets of sulphuric acid. Besides the unbreathable atmosphere, at this temperature, life is impossible. The Russian probes which landed on Venus in 1970 and 1982 could transmit signals and pictures of the surface for no more than 2 h maximum (Venera-13), after which the heat destroyed the equipment. Furthermore, the absence of water that plays an essential lubrification role in Earth's tectonic activity has probably put to a standstill any such activity that might have existed on Venus, now a single-plate planet. Nevertheless, a comparative study of the poorly known atmosphere of Venus based on the models that have been developed for the extensive studies of the Earth atmosphere is an application that may help us understanding their enormous differences and forecasting their long-term evolution. For example, the Earth might follow the same trend as Venus when the increasing luminosity of the Sun at a rate of 1 % per 100 million years would have raised its temperature to the point where as was the case for the young Venus, water molecules would start being photo-dissociated, an irreversible process leading to the end of life in about one billion years. The problem is not that simple however, as the atmospheric circulation, very different on both planets, must play an important role in the process. Therefore, it is of importance to understand atmospheric circulation in the different physical conditions characterizing the two planets.

The work described in this book is unique and well in line with the interdisciplinary approach that characterizes ISSI activities. While the Earth has been observed by several hundreds of artificial satellites, in addition to an enormous amount of in situ measurements, the number of satellites launched to Venus totals today just 40 (mostly Russian) of which only 20 were successful. The similarities and the large differences between the two planets would support a more continuous international effort in Venus exploration. This book offers an excellent basis on which to build the convincing arguments for sustaining such long-term exploration. Let me address my compliments to all the contributors to this book among whom I would like to explicitly mention Lennart Bengtsson who deserves special acknowledgements. Similarly, Simos Koumoutsaris should be acknowledged for his dedication and help in organizing the meetings and in the editing of the book.

Bern, Switzerland Roger-Maurice Bonnet

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Part III Outlook

Chapter 1
Introduction

Lennart Bengtsson

The ultimate purpose of this book is to increase our understanding of the climate of planet Venus. We will endeavor to do so by bringing together recent observations from Venus with the general knowledge of the Earth's atmosphere that has been collected over a long period of time from modeling and data studies.

Superficially, there are many similarities between Earth and Venus when observed from a great distance but a close inspection reveals critical differences that make life on Venus inconceivable. In fact our sister planet is highly inhospitable. Its surface temperature is around 460 °C where lead and tin will start to melt, and it has a cloud cover where the droplets are not water but sulphuric acid. The cause of the high surface temperature is not that Venus is receiving more sunlight than the Earth. In fact it receives significantly less as can be seen in Table 1.1. Instead the high surface temperature of Venus results from the different composition of its atmosphere, consisting of 96 % carbon dioxide, as well as its huge atmospheric mass that is 92 times larger than that of the Earth's atmosphere. There are also marked differences due to the slow rotation of Venus, which means that the Coriolis force that is crucial in determining the dynamical structure of the Earth's atmosphere plays a secondary role on Venus.

The present understanding of Venus is the result of a large number of successful space missions to the planet that started in 1962 with Mariner 1. The latest in the series, to be discussed in more depth in this book, is the Venus Express mission of the European Space Agency. Venus Express, by now has been collecting information since April 2006.

However, our knowledge of planetary atmospheres does not come from empirical studies only but also from theoretical considerations by making use of our general knowledge of fluid mechanics and thermodynamics. This has been the alternative approach for the Earth's atmosphere through the use of physically based general

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Table 1.1 Different physical values for Venus, Earth and Mars

Properties	Venus	Earth	Mars
Distance to sun	0.72 AU	1 AU	1.5 AU
Solar constant	2,622 W/m^2	1,364 W/m^2	589 W/m^2
Albedo	0.76	0.30	0.30
Eq. temperature	− 41 °C	−18 °C	−72 °C
Surf. temperature	+ 460 °C	+15 °C	−63 °C
Diurnal cycle	0 °C	20 °C	200 °C
Atmos. mass	92	1	0.006
Planetary emissivity (%)	0.01	0.59	0.84
CO_2 in %	96.5	0.039	95.3

Note the very high albedo of Venus compared to Earth and Mars. The outgoing radiation from Venus is consistent with a blackbody temperature of −41 °C. The planetary emissivity is calculated as the ratio between the blackbody radiation at the top of the atmosphere and at the surface

circulation models, GCMs. GCMs are based on the fundamental physical equations for energy, mass and momentum including sources and sinks. The first GCMs, developed in the late 1950s, were simple, but present models are highly sophisticated and are the main tools used to determine and predict the Earth's weather and climate. Present capabilities in understanding the climate of the Earth would be impossible without the use of GCMs. They have been the key factor that has transformed climatology from a pure empirical discipline in natural geography to a distinct discipline of classical physics. GCMs have in fact become the main numerical experimentation tool for theoretical analysis of different phenomena in planetary atmospheres. Furthermore, GCMs are also the main tools to study climate change resulting from changing the amount of greenhouse gases and the amount and nature of atmospheric aerosols.

Because of their general form the GCMs have also been applied to the atmospheres of other planets such as Venus, Mars and the Saturnian moon Titan. Venus in particular is a great challenge because of its very slow rotation and its mighty atmosphere consisting mainly of CO_2. Although modeling for different planets is based on the same physical laws as for the Earth, they also include the incorporation of many unresolved, small-scale processes that often are unique for any application and have to be parameterized in terms of available model parameters. Optimizing parameterization schemes requires numerical experiments and systematic testing over a period of time using observational data from the largest part of the planet as possible. That means in practice that certain aspects of a GCM will to some extent be tuned to the planetary atmosphere where it will be used. That is true for the Earth where parameterization of turbulence, moist convection and clouds could hardly be effectively done without detailed observing programs and systematic numerical experiments. As will be clarified in this book this is also the case for the atmosphere of Venus. In this respect observational explorations and numerical experiments should be considered as a combined approach.

The content of the book is organized as follows. We begin in Part I with a review of the present knowledge of Venus including a general background and history of Venus observations. This will be followed by a comprehensive overview of the radiation balance, the composition of its atmosphere and the circulation and dynamics of its atmosphere.

An inspection of its radiation balance compared to the Earth shows large differences. Firstly, despite of its proximity to the sun Venus receives less net solar radiation than the Earth because of its high albedo. Furthermore, because of its high opacity, only a small amount of the solar radiation enters the depth of its atmosphere. At the surface of Venus only a mere $17\,\mathrm{Wm}^{-2}$ is received compared to almost 10 times as much at the Earth. On Venus most of the solar radiation is absorbed in the atmosphere. Most of the absorption occurs in the cloud layer 50–70 km above the surface with a minor part of some $30\,\mathrm{Wm}^{-2}$ in the atmosphere below the clouds. Secondly, there is no condensed surface water on Venus and consequently no latent heat flux from the surface and the sensible heat flux is maximised by the net surface energy. Thirdly, the black body radiation from the surface is some 40 times larger than for the Earth. Due to the high opacity of the Venus atmosphere there is no way for the planet to get rid of its heat by radiation and the upward flux of long wave radiation is more or less fully compensated by the downward long wave radiation flux. There is consequently only a limited amount of energy that is transported from the surface upwards as dry convective energy.

The main reason for the very high temperature of the surface of Venus is its atmospheric composition that consists of some 96 % carbon dioxide as well as other constituents such as clouds of sulphuric acid and water vapor. Another factor is the depth and size of its atmosphere, which insures that the temperature broadly follows a dry adiabatic lapse rate through a depth of some 70 km above the surface.

There are several indications that the composition of the Venus atmosphere has undergone large changes, such as an early runaway greenhouse climate, and it is likely that the planet has lost a large amount of water through dissociation of water in the upper atmosphere due to ultraviolet radiation and the subsequent escape of hydrogen. Later the free oxygen has reacted to create carbon dioxide and sulphur dioxide. The origin of the clouds on Venus and their lifetime is one of the many riddles of that mysterious planet. The source for both SO_2 and in fact also CO_2 can hardly be anything else than volcanic eruptions but no such eruptions have so far been directly observed. One reason could be that the volcanic eruptions could have a different character than on the Earth with either a steady flux from a low level activity or from major eruptions occurring at very rare intervals. There are indications from surface observations that the second alternative is the more likely.

A special aspect of this book is to try to bring some further understanding of the dynamics of the Venus atmosphere and the many puzzling features such as its super-rotation and its intriguing polar vortices. The main reason for the differences between the atmospheric general circulation of Venus and Earth can indeed be explained by the difference in solid body rotation. Numerical experiments as well as experiments with rotating annuli show that the general circulation is very sensitive to the rotation rate. For small rotation rates the Hadley circulation is extended to higher latitudes and the Ferrel circulation created by the activity of travelling extra-tropical cyclones weakens or disappears. Observations indicate that the Venus general circulation is dominated by a huge Hadley cell transporting eddy momentum towards higher latitudes with a sharp transition to the polar vortex that is found on both hemispheres. The most likely explanation of the strong latitudinal jets is momentum transfer through the huge Hadley cell. The wind fields derived from temperature soundings using the cyclostrophic approximation show mid-latitude jets at 65–70 km and at 50–55 ° latitude in both hemispheres. The vortex eye resides inside the 70 °S latitude circle with striking similarity to a huge hurricane type circulation but in size more similar to a stratospheric winter polar vortex in the Earth's lower stratosphere.

Part II of the book is concerned with the modeling of the atmospheric circulation on Venus. The first section, outlined in Chap. 6 provides a detailed overview of the theoretical framework of the dynamics of the general circulation on Venus. The second section, Chap. 7 gives a background to the modeling efforts and some of the early results. The third part, Chap. 8, summarizes the latest achievements in the modeling of the Venus atmosphere by comparing results from recent numerical experiments. The fourth part, Chap. 9 provides a comparison with similar modeling efforts for the Earth using recent model results from the Earth's atmosphere from the troposphere through the stratosphere and the mesosphere.

In Part III of the book we endeavor to outline the prospects for future missions to Venus not the least based on what has been learned from the richness of information obtained from Venus Express.

Part I
What Do We Know About Venus?

Chapter 2
History of Venus Observations

Roger-Maurice Bonnet, David Grinspoon, and Angelo Pio Rossi

2.1 Knowledge of Venus Before the Space Age

Our image of Venus is that of a hellish, hot planet, permanently covered by fast-moving clouds, with its surface inaccessible to any Earth-based observer. But the perception and knowledge of our sister planet has been very different in the recent and more remote past.

Venus has been a prominent object in the sky since pre-historic times, being highly visible both at dawn and dusk. Also, contrary to many other planets, its apparent size did not change dramatically with time, due to a combined and inversely proportional effect of variable distance and phases (Goldstein 1972, and notes therein). In fact, the Latin name for Venus for its dawn appearance is lucifer (star carrying light) and for dusk, vesper (evening star), as derived from pre-existing Greek terms, respectively Phosphoros (Φ*ωσφορος*) and Eosphoros (*Εωσφορος*).

Several ancient civilizations had knowledge of the existence of Venus, including, only to mention a few: Assyrians, who considered the planet under the rule of the Goddess Ishtar, Phoenicians (under the name of Astarte), Hindus (as Sukra), Greek, Roman and Mesoamerican peoples. A summary of the many different names attributed to Venus by various civilizations is provided by Grinspoon (1997).

Such clear visibility and awareness of Venus led to the creation of myths, stories and religious importance. As an example, the great importance attributed to Venus by Maya led them to precisely measure and predict its appearance in the sky.

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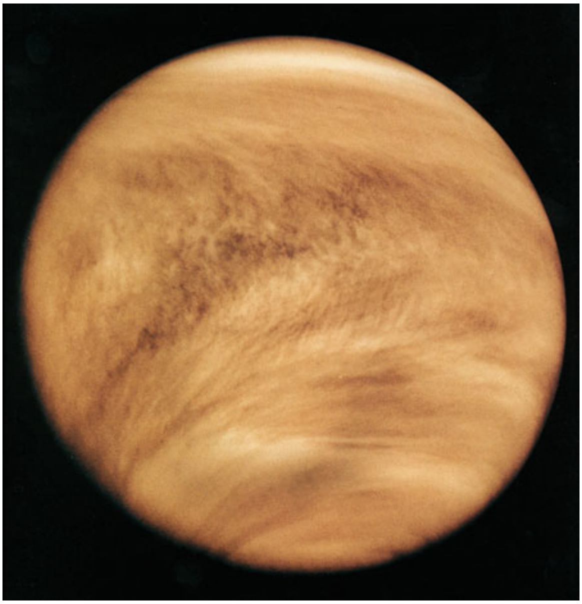

Fig. 2.1 Full disk image of Venus (from Pioneer-Venus, Credit: NASA/JPL)

Besides myths and stories, several accounts of astronomical observations and knowledge of Venus can be found among many different ancient peoples (e.g. Grinspoon 1997), including Babylonian, Greek and Mesoamerican such as the Aztecs, Mayans and Toltecs.

In the Middle Ages, Venus' position in the Ptolemaic system was considered below the Sun by Avicenna.

2.2 Telescopic Observations

Early telescopic observations of Venus, among other planets, were conducted by Galileo Galilei, who first measured Venus' phases in 1610 (e.g. Drake 1997; Palmieri 2001), determining its crescent disc shape and spherical geometry, confirming also its passage behind the Sun and thus validating Copernicus theory. Giandomenico Cassini observed Venus around 1666–1667 (Marov and Grinspoon 1998), detecting albedo variations, which, later in the eighteenth century were interpreted as possible continental and oceanic masses (Figs. 2.1–2.3).

Venus played a crucial role in measuring the distance between the Earth and the Sun, the so-called astronomical unit (AU): at its closest distance, the apparent disk of Venus, assuming to a first approximation the planet to have a size similar to that of the Earth, occupies an angle in the Sky of about 1 min of arc, from which it was possible to derive both the Venus-Earth and Earth-Sun distance, using Kepler's laws.

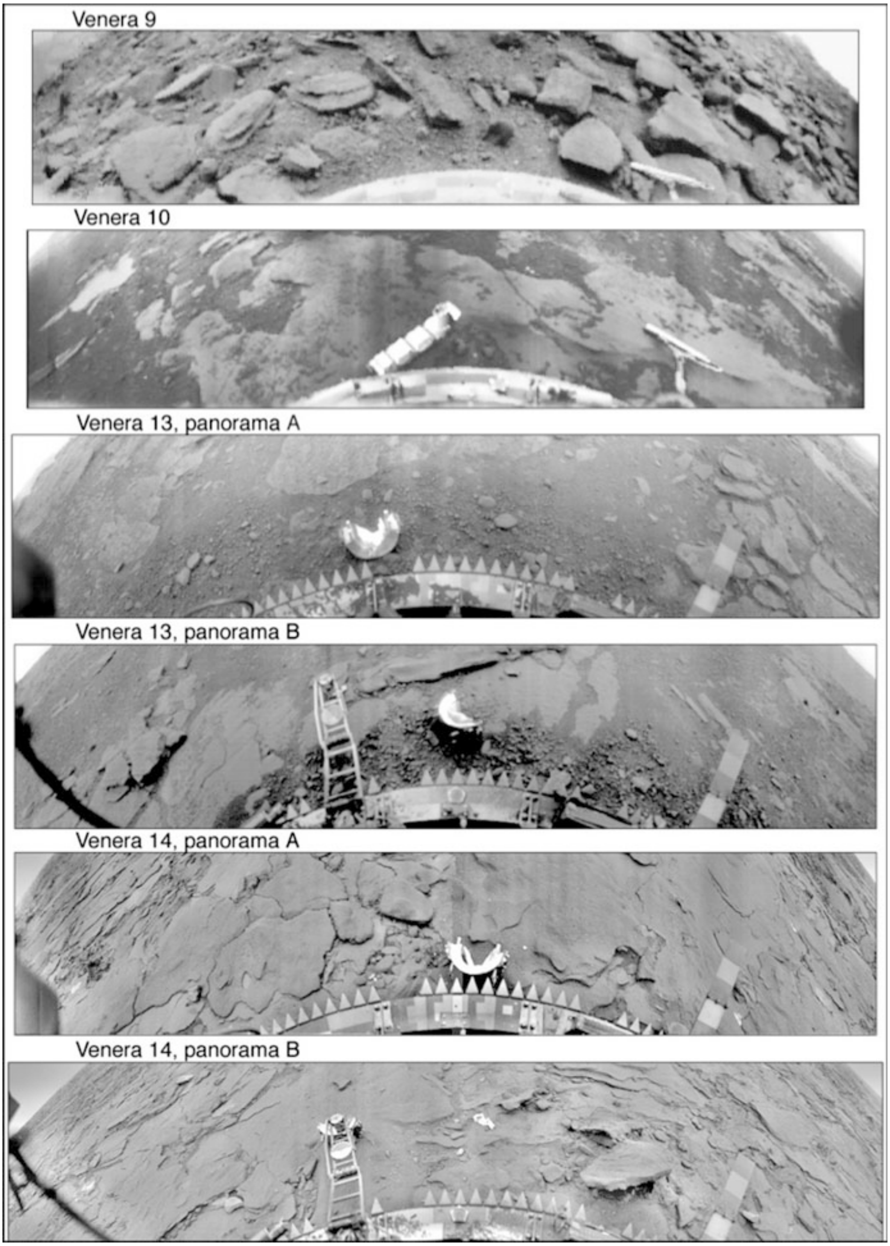

Fig. 2.2 Venera landings (Credit: Courtesy of Russian Academy of Science)

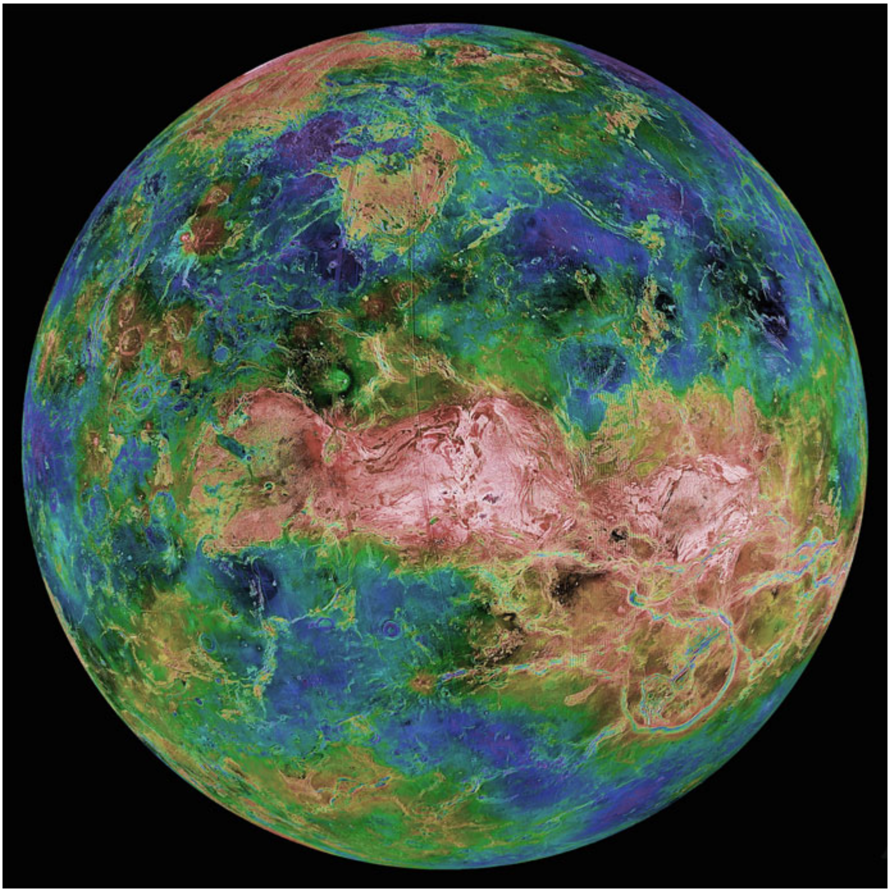

Fig. 2.3 Magellan view of Venus (Credit: NASA)

Transits of Venus in front of the Sun were particularly important for a variety of measurements (e.g. Chapman 1998; Teets 2003). In fact, transits were considered so important that even during exploration expeditions such as those of James Cook in the second half of the eighteenth century, they were studied systematically (e.g. Woolley 1969) and specific expeditions were organized for observing transits under favorable conditions. In fact, thanks to transits, the actual measurement of Venus' diameter was possible. Finally, the determination of the solar parallax, by means of measurements during the transits, was of paramount importance for determining the scale of the Solar System (e.g. Chapman 1998).

Therefore the determination of orbital and geometrical properties of Venus were of great importance for problems much wider than Venus itself, even before any hint about its surface conditions could be obtained.

The discovery that Venus actually has an atmosphere was made by M. Lomonosov in Russia during the observation of the Venus transit in 1761 (Lomonosov 1761; Marov and Grinspoon 1998). In fact, the existence of an atmosphere had already been proposed by William Herschel and Johann Schroter Grinspoon (1997).

Given the very similar sizes of the Earth and Venus, and the closer vicinity of the latter to the Sun, surface conditions were expected to be rather similar, Venus being possible slightly warmer than Earth. Based on the (false) assumption that the thick cloud cover of Venus was essentially due to water vapor, Nobel laureate Arrhenius in 1918 stated that “everything on Venus is dripping wet” which turned out, with subsequent astronomical and planetary exploration, to be far from the truth.

The determination of Venus’ rotation rate, based on the search for surface periodic movements, was unsuccessful, due to its dynamical atmosphere. The first attempt was made by Cassini in 1667 (see Baum and Sheehan 1992). Optical (e.g. Slipher 1903; Richardson 1958) and radar (e.g. Dyce et al. 1967) measurements were performed in last few decades. Earth-based and space observations provided the currently known rotation rate of 243 days for an entire (retrograde) rotation. On a longer timescale, Venus’ rotation itself, due to its chaotic evolution (Laskar and Robutel 1993), could have a resulting limited set of possible states due its dense, thick atmosphere (Correia and Laskar 2001). Compared with the solid planet rotation of 243 days, Venus’ atmosphere rotates extremely fast (about 4 days at the equator). Such ‘superrotation’ was discovered in the 1960’s (e.g. in Schubert 1983), mainly by Doppler experiments on the Soviet Venera 4 to 7 probes (reviewed by Dollfus (1975) and by Earth-based observations (e.g. Traub and Carleton 1975). CO_2 in Venus’ atmosphere was first discovered and measured from the ground ((e.g. Adams and Dunham 1932), although its concentration was underestimated in these early observations. On the other hand, Earth-based measurements of H_2O have been much more challenging, given the strong absorption by the Earth’s atmospheric water vapor: early measurements nevertheless already showed a very low concentration of H_2O (e.g. Spinrad 1962; Dollfus 1964). The discovery of hot millimeter waves radiation omitted by Venus made from Earth-based radioastronomy observations at the end of the 1950’s was the first evidence that Venus is a hot planet Mayer et al. (1958).

2.3 History of Spacecraft Observations

In the space age, the robotic exploration of Venus was long and complicated, with variable, but in general positive results. In fact, the success rate for Venus space missions is higher than 50 % (higher than for Mars, overall): since 1961 space missions, including flybys, orbiters and landers performed successfully in 56 % of the cases, while failing in 44 %. Soviet missions constituted the bulk of these missions, counting for almost 3/4 of the total (43 so far). In addition to NASA (8 dedicated missions), ESA and Japan (JAXA) launched one mission each.