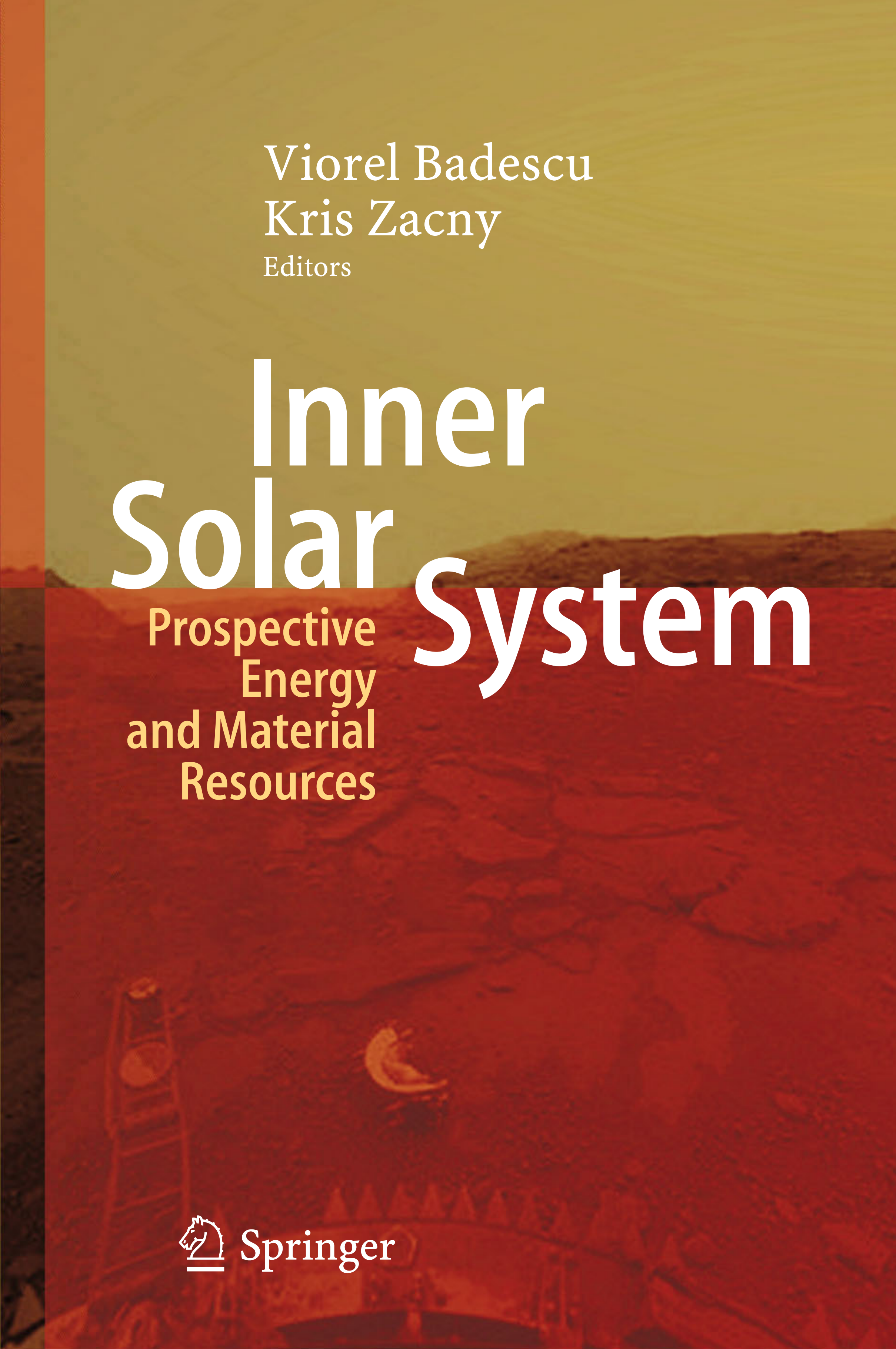
Viorel Badescu
Kris Zacny
Editors

# Inner Solar System

## Prospective Energy and Material Resources



Springer

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## Prospective Energy and Material Resources

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*This book is dedicated to the past, present,*
*and future explorers of Venus and Mercury.*

# Foreword

Throughout history, voyages of discovery and exploration have been followed by periods of relative quiet, as people absorb the new findings, but were often "motionless," fearing to follow in the footsteps of these courageous individuals, or simply not knowing what to do. Then came tentative expeditions of assessment of the new lands, reporting back on the nature and beauty of the landscape and its potential. And then, attempts at settlement and living off the land, and finally, exploration for natural resources to support an ever-increasing population and complex infrastructure.

The well-known exploration of the American West comes to mind. Early explorers were followed by Lewis and Clark, sent by insightful leaders to map and assess the potential of the land. Then followed wagon trains, cowboys and ranchers, sodbusters and homesteaders, railroads to connect the country, and finally even greater infrastructure to support an ever-increasing and organized society and the cities they came to live in.

What must it have been like to be Captain James Cook, setting sail on his first voyage of exploration in 1768, a whole new and unknown world awaiting? Imagine yourself being Captain Cook, setting off to the vast Pacific Ocean, not knowing the location and magnitude of landmasses, with only the Sun and stars as your guide. Who could have dreamed that a mere 250 years later, we could visit any place on the planet with Google Earth.

Critical to this rapid evolution on Earth were several factors:

(1) brave explorers venturing into the unknown,
(2) insightful governments funding expeditions of discovery and assessment,
(3) scientists driven by a desire to explore the unknowns of nature,
(4) entrepreneurs anxious to locate and develop potential resources,
(5) technologists at the forefront of innovation developing ways to apply the latest capabilities,
(6) engineers anxious to create new and useful designs and infrastructure, and most importantly,

(7) dreamers, living in the world of the future, unencumbered by the chains of short-term reality.

Today we stand on the verge of the next two centuries of exploration of the inner solar system. Twelve humans have ventured to the surface of the Moon. Completed or underway are missions with heroic names bringing to mind our earlier mythical explanations of nature and exploration history, such as Mercury, Gemini, Apollo, Mariner, Viking, Magellan, Surveyor, and MESSENGER. In a manner analogous to our earlier epiphany that the Earth was indeed round, we now know the basic characteristics and broad histories of the Solar System. In the last 50 years, Solar System objects, planets, satellites, comets, and asteroids have changed from astronomical objects to geological objects. We know where they are, what they are made of, and broadly, how they came to be. Astronomical objects are now planets orbiting other stars, being discovered by the hundreds. Our own Solar System has become the neighborhood, and the Earth, our Home Planet.

But what next? What will we find in our Solar System neighborhood in the *next* century? What will be the infrastructure necessary to take the next steps to explore, exploit, and live on or around these other planetary bodies? We still have many, many unanswered questions, as exemplified by the name of the latest Mars rover, The Mars Science Laboratory "Curiosity." But who will be the scientists, entrepreneurs, technologists, engineers, and most importantly, the dreamers of the future?

The *Inner Solar System: Prospective Energy and Material Resources* brings these individuals together for an exciting glimpse into the future. In this remarkable volume you will find syntheses of the current knowledge of planets and their interiors, presentation of outstanding questions to drive future exploration and exploitation, assessments of new techniques to undertake human and robotic exploration of Venus and Mercury, imaginative engineering and systems approaches to explore through drilling, orbiting, floating in balloons, insightful infrastructures for providing infrastructure and power, as well as shielding from harmful radiation, and finally, business plans and models that begin to explore the reality of how all these inevitable steps might be financed.

But what ultimate motivation for these visions of the future? Many years ago I had a long discussion with Apollo 16 Commander John Young, in which we considered, from my geological perspective, the fact that over 99 % of the species that ever existed on the Earth were now extinct. A man of few, but important words, he thought for a moment and said: "Hmmm… Single-planet species don't survive."

Viorel Badescu and Kris Zacny have gathered the doers and the dreamers to describe their visions for the next steps in the evolution of our species.

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# Preface

This is a fourth volume of a Springer book series making an inventory of the material and energy resources of our Solar system. The first three books, referring to resources existent on Mars, Moon, and asteroids were published in 2009, 2012, and 2013, respectively.

This book presents a present-day perspective on the energy and material resources in the inner Solar System for prospective human use. One investigates the advantages and limitations of various systems thought-out for future mankind utilization. The book collects together recent proposals and innovative options and solutions. It is a good starting point for researchers involved in current and impending Mercury- and Venus-related activities.

The book is structured along logical lines of progressive thought and may be conceptually divided into seven sections.

The first section deals with what *we know about Mercury and Venus* and contains four chapters. After the introductory Chap. 1, treating the origins and interiors of the Inner Planets, Chap. 2 shows the Significant Results from MESSENGER and Venus Express Missions. Chapter 3 focus on Mercury while Chap. 4 refers to previous and past missions accessing the Venus lower atmosphere and surface.

The second section of the book deals with *transportation from Earth to Mercury and Venus* and consists of three chapters. Chapter 5 refers to Special orbits for Mercury observation while Chap. 6 examines the low-thrust Earth–Venus trajectories. The estimation of the fuel consumption for space trip to Venus and Mercury is made in Chap. 7.

The third section of the book, dealing with the *drilling techniques,* consists of two chapters. Chapter 8 focus on drilling and sample transfer mechanisms for potential missions to Venus while Chap. 9 treats in detail pneumatic drilling and excavation in support of Venus science and exploration.

The fourth section of the book, referring to *power systems,* consists of three chapters. Chapter 10 describes the past, present, and future power system options for Venus exploration missions. Chapter 11 deals with production of energy for Venus by electron wind generator and Chap. 12 refers to photovoltaic power resources on Mercury and Venus.

The fifth section of the book, referring *exploration and exploitation of Mercury and Venus resources,* consists of five chapters. Chapter 13 describes flight apparatuses and balloons in Venus atmosphere while Chap. 14 refers to conditions on Mercury and Venus that could be of use to engineers who are tasked with designing structures for robotic operations and human habitation on these planets. Chapter 15 treats deployable structures for Venus surface and atmospheric missions and Chap. 16 presents a systems approach to the exploration and resource utilization of Venus and Mercury. Artificial magnetic fields for Venus are proposed in Chap. 17.

The sixth section of the book, dealing with the *management of the Inner Solar System*, consists of Chap. 18, with business concerns and considerations.

The seventh section of the book, dealing with the *resource utilization of Mercury and Venus in the far future,* consists of four chapters. Chapter 19 refers to the Economic Development of Mercury in Comparison with Mars Colonization. Chapter 20 refers to terraforming of Mercury while Chap. 21 proposes a method of terraforming Mercury and Venus. Living on Venus is treated in Chap. 22.

More details about the 22 chapters of the book are given below.

Chapter 1, by Marvin Herndon, shows that the presently popular description of planetary formation in our Solar System, an updated version of the Chamberlin-Moulton planetesimal hypothesis began as assumption based models nearly 50 years ago and has proven inadequate to explain current heat production and magnetic field generation in small bodies, such as Mercury and Jupiter's moons Io and Ganymede. Moreover, within that framework there exists no logical, causally related explanation why the terrestrial planets have such diverse surface dynamics even though they have more-or-less similar bulk chemical compositions. In 2013, the author of this chapter published a new indivisible planetary science paradigm, a wholly self-consistent vision of the nature of matter in the Solar System, and dynamics and energy sources of planets is described here. Massive-core planets formed by condensing and raining-out from within giant gaseous protoplanets at high pressures and high temperatures. Earth's complete condensation included a ~300 Earth-mass gigantic gas/ice shell that compressed the rocky kernel to about 66 % of Earth's present diameter. T-Tauri eruptions stripped the gases away from the inner planets and stripped a portion of Mercury's incompletely condensed protoplanet and transported it to the region between Mars and Jupiter where it fused with in-falling oxidized condensate from the outer regions of the Solar System and formed the parent matter of ordinary chondrite meteorites, the main-Belt asteroids and veneer for the inner planets, especially Mars. In response to decompression-driven planetary volume increases, cracks form to increase surface area and mountain ranges characterized by folding form to accommodate changes in curvature. The differences between the inner planets are primarily the consequence of different degrees of protoplanetary compression: By contrast to Earth, Mercury and presumably Mars experienced no significant protoplanetary compression. The degree of compression for Venus cannot presently be ascertained. The internal composition of Mercury is calculated by analogy with Earth. The rationale is provided for Mars potentially having a greater subsurface water reservoir capacity than previously realized.

Chapter 2, by Sanjay S. Limaye, states that MESSENGER, the second mission launched toward Mercury became the first orbiter around the planet and Venus Express orbiter have collected vast data on the two planets from orbital observations which are shedding light on many questions about them and raising new ones. This chapter presents some significant discoveries from these two missions that are still being made at present and for years to come.

Chapter 3, by Johannes Benkhoff, reviews the current knowledge about Mercury and gives some details about various spacecraft missions. Mercury is the planet of extremes. It is the smallest among the planets of our solar system and the only planet beside Earth with an internally generated magnetic field. Mercury's density is much higher than densities of all the other planets. Because of its close distance to the Sun, Mercury's surface experiences temperatures up to 700 K. In contrast, the interiors of some large craters close to the poles are permanently shadowed and remain as cold that Scientists believe that the influx of ice from in-falling comets and meteorites could be cold-trapped in these craters over billions of years, even until today. On the other hand the thermal and radiation environment of Mercury is extremely aggressive, which makes a spacecraft mission to explore this planet technically very challenging. Two NASA spacecraft have visited Mercury so far. Mariner 10 flew by Mercury three times during the 1970s. The MESSENGER spacecraft flew by Mercury in 2008 and 2009 before inserted into orbit around in March 2011. In short the European Space Agency, ESA, will launch the BepiColombo mission to explore Mercury. BepiColombo a joint project between Europe and Japan. From dedicated orbits two spacecraft will be studying the planet and its environment. All this will hopefully reveal further secrets on the "sunshine planet" Mercury essential to gain further knowledge about the evolution history of our Solar System.

Chapter 4, by Michael J. Amato, states that Venus was a prime target for atmospheric probes and landers, particularly Soviet spacecraft, in the early days of space exploration. More recently, however, this has not been the case, the last in situ missions (Venera 13 and 14) having landed on Venus in 1982. Even with the later orbital missions, Magellan and Venus Express, our understanding of Venus is very incomplete, and future in situ missions would be critical in filling these knowledge gaps. The first Successful probe into the atmosphere of Venus was the Soviet Venera 4 in 1967. This was followed by more Venera probes which survived penetrations successively deeper into the atmosphere and culminated in a series of landers that survived the torrid conditions long enough to send data back from the Venus surface. A set of NASA Pioneer Venus probes were dropped into various parts of the atmosphere in 1978 and returned data as they fell to the surface. These probes and landers returned valuable information on Venus environmental and surface conditions, but were limited by the technological capabilities of the time. The future of Venus in situ missions is driven by a large set of unanswered science questions that demand better instruments, access to new locations, or longer access to the atmosphere and surface than past missions. Much of the technology needed to address many of the highest priority questions already exists. For the first time in decades, there is a possibility the human race will return spacecraft to the atmosphere of Venus. For example, medium-sized Venus probes and landers have been proposed in the past decade in the U.S. and to European Space Agency opportunities. NASA planetary decadal reports recommend a Venus in situ mission for the NASA mid-tier competed mission program. Examples of more capable and complicated missions are in the U.S. NASA decadal survey, and are driven by long-term science needs at Venus. The National Research Council's Planetary Decadal Survey Inner Planets Panel commissioned three Venus in situ mission studies as part of the 2010 survey that led to the "Visions and Voyages for Planetary Science in the Decade 2013–2022." These mission's science, designs, and cost were studied and reviewed and they serve as an excellent measure of possible near term future missions from NASA to the Venus atmosphere.

Chapter 5, by Generoso Aliasi, Giovanni Mengali and Alessandro A. Quarta, deals with an advanced scientific mission concept in which the existence of suitable positions for the observation and the measurement of the Mercury's magnetotail are investigated. The scientific mission is based on the use of artificial equilibrium points in the elliptic three-body system, constituted by the Sun, Mercury, and a spacecraft, which is modeled as a massless point. The spacecraft motion in the Sun–Mercury system is first discussed under the assumption that the propulsion system provides a radial continuous thrust with respect to the Sun. In particular, the spacecraft is assumed to have a generalized sail as its primary propulsion system. A generalized sail models the performance of different types of advanced propulsion systems, including a (photonic) solar sail, an electric solar wind sail and an electric thruster, by simply modifying the value of a thrusting parameter. The location of the artificial equilibrium points is derived, and their stability is also investigated. It is shown that that collinear artificial equilibrium points are always unstable, except for a range of $L_2$-type points which are placed far away from Mercury. A similar result is obtained for triangular equilibrium points. A control strategy is introduced to maintain the spacecraft in the neighborhood of an artificial equilibrium point. In this context, a simple and effective way to actively control the spacecraft dynamics is by means of a Proportional-Integral-Derivative feedback control law. The latter control law is finally employed in the magnetotail mission scenario, whose fundamental idea is to continuously and slowly displacing the artificial equilibrium point along the Sun–Mercury direction. Numerical simulations show the effectiveness of the proposed mission strategy.

Chapter 6, by Alessandro A. Quarta, Giovanni Mengali and Generoso Aliasi, discusses the simulation results involving the minimum-time trajectories for an Earth-Venus mission transfer using a spacecraft with an electric propulsion system, with both a nuclear and a solar electric power source. The analysis has been performed in a parametric way as a function of some design parameters, such as the available thruster electric power and the initial in-flight mass. Various models have been considered to describe the propulsion system behavior with different levels of approximations and obtain increasingly refined information about the mission performance. Some simplifying assumptions have been introduced in order to make the mathematical problem tractable, to reduce the simulation time and guarantee a thorough parametric investigation of the mission performance. The analysis performed in this chapter is useful to obtain a first order estimate of the mission requirements as a function of the specific thruster characteristics.

Chapter 7, by Alexander A. Bolonkin, researches the most useful space trajectories to Mercury and Venus. It gives the theory of space flights, methods and estimation of fuel consumption for space trips, and trajectories close to optimal (minimum fuel usage). It also provides example computations of fuel consumption for flights to Venus and Mercury. It also gives brief data about former space apparatus and rocket system flight to Venus.

Chapter 8, by Yoseph Bar-Cohen, Xiaoqi Bao, Mircea Badescu, Stewart Sherrit, Hyeong Jae Lee, Kris Zacny, Nishant Kumar, and Erik Mumm describes a device for transferring acquired powder samples. The mechanism uses pneumatic actuation and involves the use of capsules. The inclusion of such a sample transfer system allows the use of science instruments inside the thermally controlled enclosure within the lander. The in situ exploration of our Solar System bodies poses many challenges, and these are unique to each body. Without a doubt, the toughest conditions are encountered on Venus and to some extent on Mercury. Temperatures on both planets are over 400 °C. However, while the temperature on Mercury can drop to −173 °C, which poses its own challenges, the temperature on Venus is constant at 465 °C. This extreme temperature combined with the Venus surface atmospheric pressure of 90 atmospheres (equivalent to pressure at 1 km deep Earth ocean), makes carbon dioxide atmosphere super critical and in turn corrosive. The temperature combined with corrosive atmosphere poses biggest challenge. A key challenged to the in situ exploration is the ability to sample its surface and the subsurface. This chapter covers methods of drilling at high temperature conditions. The methods covered in this chapter include high temperature piezoelectric materials and electromagnetic actuators as well as thermal techniques (thermal-spalling and thermal-melting). Piezoelectric actuated drills with various diameters have been developed to operate at temperatures as high as 500 °C. The use of various piezoelectric materials including LiNbO3 and Bismuth Titanate was tested by fabricating Ultrasonic/Sonic Driller/Corer (USDC) based drills and testing them at high temperatures. One of the drills was designed with a novel method of operating the USDC as a rotary-hammer where the rotation is induced by the vibration of the piezoelectric actuator. The drill driven by Bismuth Titanate was demonstrated to penetrate a brick sample to a depth of 25 mm in 21 min. The chapter also covers more conventional rotary drills powered by two switch reluctance motors (SRM). The two motors were used to rotate the auger with a carbide bit at its end and for advancing the bit into the rock. Tests were conducted at temperatures as high as 460 °C drilling to a depth of 20 cm in approximately 20 min with a maximum power of 45 W.

Chapter 9, by Kris Zacny, Justin Spring, Gale Paulsen, Stephen Ford, Philip Chu, and Steve Kondos, states that Venus is considered to be Earth's sister planet and hence we can learn a lot about Earth by investigating Venus tectonics, volcanism, and atmosphere. The most recent Planetary Science Decadal Survey publication called the Visions and Voyages for Planetary Science in the Decade 2013–2022, recommended Venus In Situ Explorer (VISE) as one of the five candidates for the NASA's New Frontiers mission. The VISE mission was reaffirmed by the Decadal Survey because many questions about Venus cannot be addressed by observations from an orbiter. The VISE mission requires sample acquisition and delivery to remotely located sensors technology. Honeybee Robotics, funded by the NASA's Small Business Innovation Research investigated methods of excavation (Drill or a Trencher), Sample Delivery (Pneumatic Suction vs Blower vs 3 DOF Robotic Arm) and Sampler Deployment (Vertical Z-stage, Spring Loaded Arm, 3 DOF Robotic Arm), in support of the technology development for the VISE mission. This chapter reports on test results and makes recommendations with respect to sample acquisition and delivery for Venus surface missions.

Chapter 10, by Simon Fraser, states that Venus, the planet so close to Earth in terms of distance and size, provides an equally fascinating and challenging environment for atmospheric and surface exploration missions. Venus is actually quite the opposite of Mars, the second one of Earth's two sister planets. Mars has got a very thin atmosphere with low surface temperatures. Venus, on the other hand, has got a very thick atmosphere with pressures exceeding 90 bars and surface temperatures exceeding 450 °C. Exploration missions therefore face completely different ambient conditions than on Moon and Mars; this is reflected in surface lander design and operation profiles. This chapter summarizes the history of Venus exploration missions, and has a special focus on power system solutions applied with the different mission elements. In this, the power system options can be broken down into two sub-categories: first, power systems applied en route to Venus and/or in orbit around Venus; secondly, power systems for descent stages designed to enter the atmosphere, and in some cases even to (soft-) land on the surface of Venus. Selected exploration missions, their scientific payload and their power systems are described in more detail to outline how the challenges of Venus exploration have been addressed in the past.

Chapter 11, by Alexander A. Bolonkin, offers a new method of getting electric energy from wind. A special device injects electrons into the atmosphere. Wind picks up the electrons and moves them in the direction of the wind which is also against the direction of electric field. At some distance from injector, a unique grid acquires the electrons, thus charging and producing electricity. This method does not require, as does other wind energy devices, strong columns, wind turbines, or electric generators. This proposed wind installation is cheap. The area of wind braking may be large and produces a great deal of energy. The author applies this method to Venus's atmosphere, which has higher density and temperature than the Earth's atmosphere.

Chapter 12, by T.E Girish and S. Aranya, addressed the severe challenges for photovoltaic power generation on Mercury and Venus. This includes high daytime temperatures, hazardous radiation environments and long night periods. Some possibilities for utilizing photovoltaic (PV) power resources on these inner planets are also discussed. For short duration Venus missions lasting 80–90 days daytime PV power generation near the top of Venus atmosphere (50–70 km) is preferable using Gr III–V solar cells mounted on balloons. A pilot lander mission to polar regions of Mercury which are significantly illuminated during daytime is suggested where photovoltaic power generation is with triple junction solar cells is relevant during periods of calm space weather conditions such as sunspot minima.

Chapter 13, by Alexander A. Bolonkin, gathered most recent information about Venus and Venus' atmosphere and offers a new tethered aircraft for directed operations within Venus' atmosphere. This airplane can fly for very long time periods. The author has also developed the theory of estimation and computation of the flight of the tethered airplane, capturing energy in Venus' atmosphere and has worked out an example of the estimation and computation for the proposed balloon, tethered airplane.

Chapter 14, by Sushruth Kamath, Jullian Rivera, Michael Garcia, and Haym Benaroya provided a summary of currently known environmental conditions on Mercury, Venus, and Titan that could be of use to engineers who are tasked with designing structures for robotic operations and human habitation on these respective bodies in our Solar System. Recommendations are made for scientific explorations to collect key data necessary for the design and sustenance of engineering systems. A brief overview is also included on the kinds of criteria that are used in the design of hypothetical lunar habitats. Similar criteria will hold for habitats on any extraterrestrial body.

Chapter 15, by Kürsad Ozdemir, documents and assesses the array of deployable components of the Surface and Atmospheric missions to planet Venus. Designed to be transported in a compact layout which is dictated by the conditions of interplanetary space flight, planetary mission hardware systems traditionally include expandable elements. Unfolded, extended, or inflated these units of the exploration architectures deploy to their final operational form upon arrival to their mission environments. Venus, our planet's "hellish twin," with her extreme conditions in terms of temperature, pressure and acidity, is just another stage of operations for deployable structures. The atmosphere is monolithically dense, surface temperatures can reach as high as 465 °C, the atmosphere hosts large amounts of sulfuric acid. Let alone operating deployable mechanisms, even highly robust and rigid structures are challenged by the mentioned environment, resulting in the short life-spans of the surface hardware of the past Venus missions. Yet, instrument arms, buoyancy envelopes, rover sails, and wheels do not cease to deploy, defying the hellish environment of Venus. Ranging from folding instrument arms to inflatable metal-skin balloons bellows, this article presents an overview to the existing and upcoming deployable system concepts and designs of the Venus surface and atmospheric missions. Figures, tables, and trade-off charts provide the readers a comparative insight into the nature of these precious pieces of the planetary exploration clockwork.

Chapter 16, by Dragos Alexandru Paun, states that a total of 38 missions have been launched having Venus as their destination and they have contributed greatly to the knowledge of the planet's atmosphere and surface. The purpose of the present chapter is that of providing an overview of the Venusian importance, its potential resources and of the essential elements required for a successful global exploration of Venus as well as to underline the particular technologies that require further development. A short description is given of previously used architectures of essential subsystems and finally, a short overview of Mercury exploration systems is included.

Chapter 17, by Alexander A. Bolonkin, states that the Earth has a sufficiently powerful magnetic field which protects the people and organic nature of the planet from solar and cosmos high energy particles. But some planets, including Venus, which may in future be populated by humanity, do not have this natural protection and, therefore, will need to have such protection if humans are ever to use them in the same way we utilize Earth. Some scientist believe that Venus, in the past, had more suitable magnetic field—that is, suitable for people—atmosphere pressure and temperature than now. Over the geological timescale, it was lost (and continues to our time, to be lost); atmospheric gases are lost to interplanetary space because Venus does not have the necessarily stabilizing magnetic field. The author estimates the possibility to create an artificial magnetic field around Venus. He shows it is possible if the cost of the equipment and other materials launched from Earth will be significantly decreased.

Chapter 18, by Mike H. Ryan and Ida Kutschera, states that the possibility for commercial activity in space is no longer a question. Various companies regularly engage in commercial operations in space including launch service, satellite systems, and even supply missions to the International Space Station. What remains a question is how extensive commercial operations might become in the future and where they might be possible. Among the more difficult propositions is whether the inner solar system planets of Venus and Mercury might have business potential. The brief answer is perhaps. The reality is that the long-term prospects of using the resources of either planet commercially are quite speculative but not zero. This chapter discusses in detail some of the possible scenarios under which commercial use of Mercury, Venus, and their surrounding space might provide business opportunities. Although the time frames involved are exceptionally long, they are not beyond the realm of possibility especially if new transportation systems were to be developed over the next decade or two. And, as development of business opportunities on Earth has shown, it may never be too soon to consider what the future might bring or to plan for those opportunities.

Chapter 19, by Alexander A. Bolonkin, states that at present-time the main attention of scientists attends the future economic development on Moon and Mars. Mercury has very high temperature at surface (423 °C). The author shows the high temperature of the Mercury surface is not a barrier for human life activity on Mercury. People can easily be protected from the harsh environment by thin-film enclosures with variable reflectivity. Thus, Mercury can be made to have excellent conditions for substantial human life work, agriculture, and solar energy utilization. There, conditions may be better than on Mars or on the Moon.

Chapter 20, by Kenneth Roy, asks about the future role of the planet Mercury, as humanity establishes a space faring civilization and begins to explore and exploit the resources of the solar system. Can it be made habitable by human beings and possibly for most Earth-life currently living on Earth? Mercury is a small planet but its surface area is still about half the total land area of Earth.

Terraforming is a process of planetary engineering directed at an extraterrestrial planetary environment to alter it in such a way to make it fully habitable for human beings. Can Mercury be terraformed? This question is important apart from this one small planet for if Mercury can be terraformed then many other marginal planets orbiting our sun and other stars can also be made into living worlds—and Earth life could have many future homes. This chapter looks at the prospects of terraforming Mercury and concludes that it is possible, given sufficient resources and time. Based on our understanding of science and technology today, this chapter examines how Mercury could be terraformed and what would it take in the form of material and energy resources to do so. What might a terraformed Mercury look like? The ultimate fate of Mercury is left to a future space faring civilization that will be far richer, having advanced energy and propulsion technologies far beyond what is available today, and whose citizens are, hopefully, somewhat wiser than humans today.

Chapter 21, by Alexander A. Bolonkin, states that current physics assumes that vacuum can produce energy and Universes. The basis of any Universe is energy. The author assumes: energy may be positive or negative. Positive energy produces our positive matter, negative energy produces negative matter. Using this effect the author offers terraforming Mercury and Venus, making them suitable for humanity. Negative matter repels our (positive) matter. Using this effect, the author offers a space propulsion system which allows reaching a speed close to the light speed and to enable massive retrieval of extraterrestrial materials to construct various technical works. Such plan may be the best method for human colonization of Mercury and Venus. Concept of negative energy allows solving many, very important macro-problems that humanity faces e.g.: production of any artificial material or food.

Chapter 22, by Magnus Larsson and Alex Kaiser, starts by saying that No one can tell what lies ahead. In the future, a natural or man-made planetary-scale disaster may or may not force us to abandon Earth. Following such a potential forced departure, space colonisation might be our only chance of survival as a species. Prospective heavenly bodies that might support human life include the Moon, Mars, the asteroid belt—and Venus, our acid cloud-veiled sister planet with the hellishly hot surface. As Mark Twain would have it, the secret of getting ahead is getting started, and so we examine the latter option. The Cloud Ten space architecture proposal investigates the unique opportunities offered by a future Venus habitat. Tracing the footsteps of precedent schemes for “floating cities”—lightweight balloon-like structures that soar at the cloud tops some 50 km into the Venusian atmosphere, where the environment is reasonably Earth-like and relatively benign—we envisage the launching of a series of initial capsule structures that contain everything needed to grow—in situ, in space—the materials needed to create the skeleton frames and membrane skins for expandable/deployable cellular structures that increase in size through an adaptation of the famous sequential geometries called the Jitterbug Transformation (invented by neo-futuristic architect and systems theorist Richard Buckminster Fuller). This new paradigm of growing construction materials in outer space is positioned as a an enhanced version of

ISRU (in situ resource utilization), and given its own acronym, ISMG (in situ materials generation). Using a unique combination of swarm intelligence, stygmergy, and evolutionary logics, the cells are then controlled by algorithms connected to live data feeds and allowed to self organise and attach to each other in order to create a full-sized habitat high above the surface of Venus. To produce an outline for how the schedule for a construction of Cloud Ten might be constituted, the process is subdivided into ten phases, from Preparation to Permanent living. In a final coda, Cloud Ten is shown to be the best of paradoxes: a cellular habitat at the intersection of many conflicting aspects—an interstellar lightweight megastructure, an enormous city made from grass and bacteria, volumetrically expanded in an exponential fashion from within, folded into shape through a geometric dance in space, self-assembled as an incredibly intelligent swarm, soaring high in the acid clouds above the most fiendish planet we know—that represents a single instant that coalesces varying strands of an mindboggingly intricate process, while at the same time having the potential to become a true sanctuary in a post-terrestrial universe, offering the clean air and safe environment that we struggle to find on Earth.

The book allows the reader to acquire a clear understanding of the scientific fundamentals behind specific technologies to be used in the inner Solar System region in the future. The principal audience consists of researchers (engineers, physicists) involved or interested in space exploration in general and in Mercury and Venus exploration in special. Also, the book may be useful for industry developers interested in joining national or international space programs. Finally, it may be used for undergraduate, postgraduate, and doctoral teaching in faculties of engineering and natural sciences.

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Kris Zacny

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# Abstract

The Earth has limited material and energy resources while these resources in space are virtually unlimited. Further development of humanity will require going beyond our planet and exploring of extraterrestrial resources and sources of unlimited power.

Thus far, all missions to Venus and Mercury have been motivated by scientific exploration. However, given recent advancements in various space technologies, mining Venus and Mercury for their resources is becoming more feasible.

This book investigates Venus and Mercury prospective energy and material resources. It is a collection of topics related to exploration and utilization of these bodies. It presents past and future technologies and solutions to old problems that could become a reality in our lifetime. The book therefore is a great source of condensed information for specialists interested in current and impending Venus- and Mercury-related activities and a good starting point for space researchers, inventors, technologists, and potential investors.

Written for researchers, engineers, and businessmen interested in Venus and Mercury exploration and exploitation.

**Keywords** Venus • Mercury • Exploitation • Energy sources • Space resources • Material resources • In situ resource utilization • Mining

# Chapter 1
# Inner Planets: Origins, Interiors, Commonality and Differences

**J. Marvin Herndon**

## 1.1 Introduction

There are many among us who remember a time when the surface features of the inner planets, also called terrestrial planets, were known only from blurry, earthbound-telescopic images. In barely more than four decades, that changed dramatically. Now, data and images from orbiting spacecraft and landers have revealed new and unanticipated features of the inner planets that, to use the words of Galileo (1623), "ought to have opened the mind's eye much room for admirable speculation". While space-exploration technology has burgeoned over the past four decades, curiously, understanding the myriad observations and data has posed a serious challenge for planetary investigators. Instead of understanding observations from a framework of discoveries that are securely anchored to the properties and behavior of matter, planetary investigators became accustomed to make computational models based upon assumptions, and to ignore advances that contradict 'consensus favored' models, especially, a model of the internal composition of Earth that had its origin circa 1940 and the so-called 'standard model of solar system formation' that dates from the 1960s. Decades of model proliferation (Raymond et al. 2014) from these beginnings has led to, again the words of Galileo, "dark and confused labyrinths", virtually devoid of logical, causally-related understanding.

Generally, science progresses by replacing less-precise understanding with more-precise understanding. Much of the prevailing confusion in planetary and astrophysical science stems from building upon old ideas, as if they were correct

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ideas, and never reconsidering the validity of those ideas in light of subsequent discoveries (Herndon 2010). Traveling backward in time through the scientific literature, questioning the validity of long-held fundamental assumptions, and making appropriate corrections led me to a different, logical, causally-related understanding of formation of the inner planets: Mercury, Venus, Earth and Mars (Fig. 1.1), including the main-Belt Asteroids. Recently, I published this understanding in a scientific article entitled "New Indivisible Planetary Science Paradigm" (Herndon 2013). This chapter is derived from and amplifies that article.

**Fig. 1.1** Comparison of relative sizes of the inner (terrestrial) planets. From left to right, Mercury, Venus, Earth, and Mars

The popular view of planet formation for decades has been the idea that dust, condensed at low pressures and low temperatures, gathered into balls, then into grains, then rocks, and finally into planetisimals that gathered to form planets. But there are problems with this scheme. Instead, I submit, the massive-core planets formed by condensing and raining-out from within giant gaseous protoplanets at high pressures and high temperatures. Earth's complete condensation included a Jupiter-like stage when its gigantic gas/ice shell, about 300 Earth-masses, compressed the rocky kernel to about 66 % of Earth's present diameter. Super-eruptions from the Sun as it ignited stripped the gases away from the inner planets and stripped a portion of Mercury's incompletely condensed protoplanet, and transported it to the region between Mars and Jupiter where it fused with in-falling oxidized condensate from the outer regions of the solar system and formed the parent matter of ordinary chondrite meteorites, the main-Belt asteroids, and the veneer that added to the outer layers of the inner planets, especially Mars. Here I describe the basis for that new understanding of the origin of the inner planets, the nature and commonality of their internal structures and magnetic field generation, and why their surface dynamics are so different from one another.

## 1.2 Internal Composition of Earth

Interpretations of other planets, their internal compositions and magnetic field origination, are strongly influenced by interpretations of our own, better-studied planet. Part of the present confusion in planetary science stems from interpretations based upon a flawed Earth-model that has been built upon by specialists since 1940. It is therefore important to present in some detail the corrected basis for understanding Earth's composition in a logical causally-related manner.

Wiechert (1897) observed that Earth's mean density (5.5 g/cm$^3$), measured by Cavendish (1798), is too great for the planet to be composed solely of non-metallic rocks and in 1897 postulated the existence of a dense central dense core similar to meteorites composed of nickel-iron metal. Oldham (1906) discovered that earthquake waves travel faster with depth, but at 2900 km they slow markedly upon entering a different material which he postulated is the core. The core was subsequently inferred from earthquake waves to be liquid. In 1936, analysis of records of a surprisingly large earthquake near New Zealand led Lehmann (1936) to discover the Earth's almost-Moon-sized inner core.

The physical structure of Earth's interior is deducible from seismic observations, but the chemical composition of these inaccessible regions must be inferred from meteorites. Abundant data indicate that Earth, our Moon, meteorites and other solar system bodies formed about 4,600 million years ago from "primordial" matter of uniform composition (Dalrymple 1991). That primordial composition is seen today in the outer part (photosphere) of the Sun and in the non-gaseous elements of chondrite-meteorites. The importance of chondrites is that their non-gaseous elements never appreciably separated from one another as they did in other, more changed meteorites. Consequently, chondrites are appropriately accepted to resemble Earth's bulk chemical composition. But, there are three different types of chondrites characterized by strikingly different mineral composition. In my view the incorrect choice of chondrite led to an erroneous assumption of Earth's internal mineral composition. This has long confused geophysicists' ideas about Earth's origin and dynamics which, consequently, led to confusion about planetary interiors.

The three groups of chondrite-meteorites, *carbonaceous*, *enstatite*, and *ordinary* differ markedly in oxygen content and, hence, in mineral composition. Although Lehmann (1936) correctly deduced the presence of Earth's inner core, Birch (1940), on the basis of geophysical understanding in the late '30s and early '40s, incorrectly postulated its composition. The Earth was assumed to be derived from ordinary chondrite material. In the metal of ordinary chondrites, nickel invariably occurs alloyed with metallic iron. And, the solar abundances of elements heavier than nickel and iron, even together, are insufficient to form such a massive inner core. These considerations led Birch (1940) to postulate, analogous to an ice-cube in a freezing glass of ice-water, that the inner core is composed of nickel-iron metal in the process of freezing from the liquid nickel-iron core. The explanation proffered was one of changed physical state, not chemical difference.

By 1940, Bullen (1938, 1940) had recognized a seismic discontinuity in the mantle, an interface where earthquake waves change speed and direction, at a depth of about 660 km, thus separating the mantle into two major parts, upper and lower (Fig. 1.2). Additional seismic discontinuities were later discovered in the upper mantle. Bullen (1949) subsequently discovered a zone of seismic "roughness", called D″, located between the core and the seismically-featureless lower mantle (Bina 1991; Manglik 2010; Vidale and Benz 1993). Generally, seismic discontinuities within the Earth's mantle, including at D″, have been ascribed to physical changes in a medium of uniform composition, *i.e.*, pressure-induced changes in crystal structure, rather than boundaries between layers having different chemical compositions; physics without chemistry.

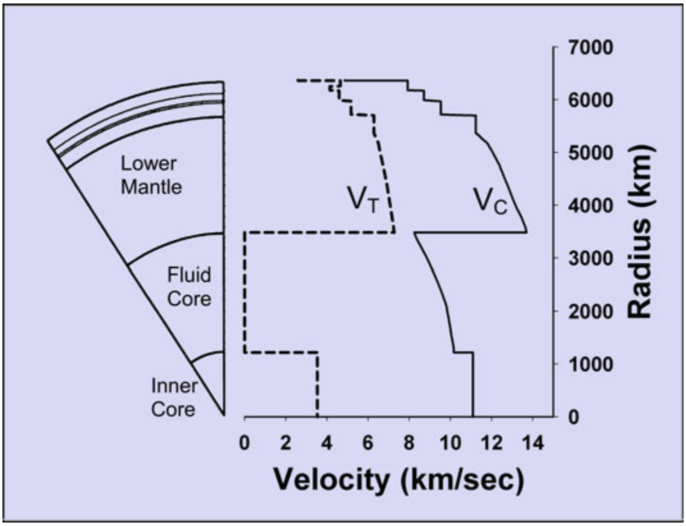

**Fig. 1.2** Seismic discontinuities, *i.e.*, abrupt changes in earthquake wave velocities, indicate structures within the Earth. $V_T$ signifies transverse waves; $V_C$ compression waves

Nearly four decades after Birch's ideas were entrenched in the literature of geophysics, I studied enstatite chondrites. Combined with two 1960s discoveries, my investigations generated a fundamentally different view of Earth's inner core composition. What was the news? (1) Elemental silicon occurs in the metallic iron of enstatite chondrites (Ringwood 1961), and (2) perryite, nickel-silicide, $Ni_2Si$, is present in many enstatite-chondrite meteorites (Ramdohr 1964; Reed 1968). I realized that in Earth's core, silicon in chemical combination with nickel would have settled by gravity to the center and, in principle, formed a mass virtually identical to the relative mass deduced for the inner core. When my nickel-silicide-inner-core concept was accepted for publication (Herndon 1979), Lehmann commented: "I admire the precision of your reasoning based upon available information, and I congratulate you on the highly important result you have obtained" (Herndon 2010).

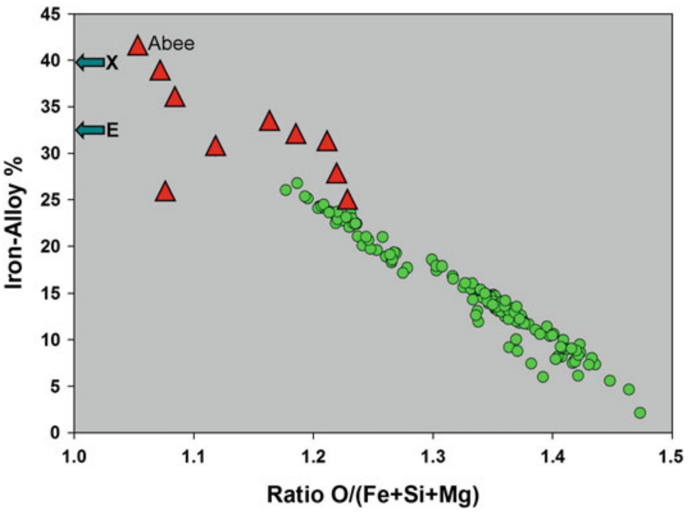

**Fig. 1.3** Evidence that Earth resembles an enstatite chondrite. The percent alloy (iron metal plus iron sulfide) of 157 ordinary (circles) and 9 enstatite chondrite meteorites (triangles) plotted against oxygen content. The core percent of the whole-Earth, "arrow E", and of the core-plus-lower mantle, "arrow X", shows that Earth is like an Abee-type enstatite chondrite and unlike an ordinary chondrite

Next, I showed conclusively that, if the Earth resembles a chondrite meteorite as widely believed for good reasons, then our planet is in the main like an enstatite chondrite, not an ordinary, chondrite (Fig. 1.3) and, moreover, the relative masses of inner parts of Earth, derived from seismic data, exactly match the corresponding, chemically-identified, relative masses of enstatite-chondrite-components, observed by microscopic examination (Table 1.1) (Herndon 1980, 1993, 2011). Aside from

**Table 1.1** Fundamental mass ratio comparison between the endo-Earth (lower mantle plus core) and the Abee enstatite chondrite. Above a depth of 660 km seismic data indicate layers suggestive of veneer, possibly formed by the late addition of more oxidized chondrite and cometary matter, whose compositions cannot be specified with certainty at this time

| Fundamental earth ratio | Earth ratio value | Abee ratio value |
|---|---|---|
| Lower mantle mass to total core mass | 1.49 | 1.43 |
| Inner core mass to total core mass | 0.052 | theoretical 0.052 if $Ni_3Si$<br>0.057 if $Ni_2Si$ |
| Inner core mass to lower mantle + total core mass | 0.021 | 0.021 |
| $D''$ mass to total core mass | 0.09*** | 0.11* |
| ULVZ** of $D''$ CaS mass to total core mass | 0.012**** | 0.012* |

* = avg. of Abee, Indarch, and Adhi-Kot enstatite chondrites
$D''$ is the "seismically rough" region between the fluid core and lower mantle
** ULVZ is the "Ultra Low Velocity Zone" of $D''$
*** calculated assuming average thickness of 200 km
**** calculated assuming average thickness of 28 km
**** calculated assuming average thickness of 28 km
data from (Dziewonski and Anderson 1981; Keil 1968; Kennet et al. 1995)