Robert Malcuit

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How could nature have made Mars more like Earth?

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How could nature have made Mars more like Earth?

A treatise on some important factors involved in assessing the habitability potential of terrestrial planets that may aid us in our search for habitable terrestrial exoplanets

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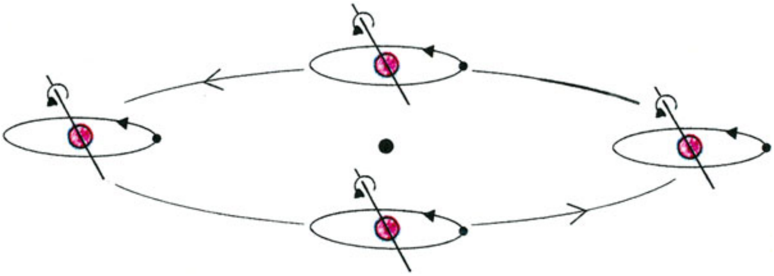

Pictogram illustrating a Mars-like planet in a prograde (counter clockwise) Mars-like heliocentric orbit with a moderately large satellite, about 1/100 the mass of Mars, in a prograde orbit around the Mars-like planet rotating in the prograde direction.

The general theme of the book is that regular tidal action (i.e., both rock and ocean tides) operating over geologic time (in this case marologic time) keeps a planet "alive" by aiding the processes that cycle and recycle planetary resources.

Note also that a satellite helps to stabilize the obliquity (tilt angle) of a planet over multi-thousand-year cycles. The obliquity for this illustration is 30 degrees. The initial obliquity could be more or less than this value but the main point is that it is stable over long periods of time. This stability of obliquity results in a seasonal cycle that is very consistent from year to year, decade to decade, and century to century. This stability of the seasonal cycle, along with other factors such as the presence of liquid water on the surface of a planet, is very conducive to the origin and evolution of life forms.

An extension of the tidal action concept is that the search for potentially habitable planets, in the author's view, should be refocused to the search for terrestrial planets with large satellites relative to the mass of the planet. As with planet Earth, the "Goldilocks" principle can be applied. A satellite in orbit around a Mars-mass planet must be large enough to do the tidal work associated with the recycling of critical planetary resources but not so large that it "despins" the planet to a synchronous spin-orbit condition over a short period of geologic (marologic) time.

This book is dedicated to my wife MARY ANN, for her patience, advice, consolation, and help over these past several decades. We certainly have enjoyed our time on planet Earth. Now, as elder inhabitants of the planet, we are beginning to understand the present environmental conditions on our planet as well as the importance of the operation of the Earth-Moon system.

Preface

Planet Earth has many unusual features. It has oceans of water, an oxygenated atmosphere, a complex biological system, an active magnetic field, a large satellite relative to the mass of the planet, and a prograde rotation rate of about 24 hr/day. Our "twin sister" planet, Venus, also has many unusual features. It has no oceans of water, no free oxygen in the atmosphere, no biological system, no active magnetic field, no satellite at present, and a very slow retrograde rotation rate. Planet Mercury also has a set of special features. It has a very slow prograde rotation rate because of tidal interaction with the Sun, that is, it is locked into a 3:2 spin-orbit resonance with the Sun. It may have an active magnetic field and it definitely has a remnant magnetic signature recorded in its ancient crust. Some of the crater-saturated crust of the planet Mercury probably dates back to the very early history of the planet. Its "sedimentary" rock record consists mainly of overlapping aprons of impact ejecta and it has lava flows of various ages on its surface. Planet Mars has some special features as a planet and, in my view, has the features of a normal terrestrial planet of its size and mass. It has a transparent atmosphere; it has ice caps of a combination of water ice, carbon dioxide ice, and methane ice that wax and wane with the seasons as well as with the long-term obliquity cycle of the planet, and it has evidence of flowing water at the surface. It has both water and wind deposited sediment units as well as a variety of sedimentary rock complexes. It has a great variety of impact craters that have accumulated over the history of the planet and it has some of the largest volcanic constructs in the terrestrial planet realm. It also has two small satellites, Phobos and Deimos, in prograde marocentric orbits. Mars has a prograde rotation rate of about 24.6 hr/day.

A major question is: What are the common features of a terrestrial planet – features to be on a checklist when searching for terrestrial exoplanets? A related question is: How common are terrestrial exoplanets? (About 10/4000 as of August 2019; a reasonable definition of a terrestrial planet is a rocky planet with about two times the mass of Earth or less.) Another unanswered question is: Will the common features of a terrestrial planet yield habitable conditions on a typical terrestrial exoplanet?

The only common feature of terrestrial planets in our Solar System is that they all have rocky surfaces. Mars and Mercury have some portions of their surfaces that are heavily cratered and those surfaces probably date back to their early history. In contrast, Venus and Earth have no portions of their surfaces that go beyond 1 billion years. So how can we attempt to create a story for terrestrial planets that may help us in our search for habitable terrestrial exoplanets?

My basic premise is that moderately massive satellites (1/100 of the mass of the planet, + or – a significant factor) are a necessary, but not sufficient, condition for the development of a habitable terrestrial planet. Details about the mass of the satellite and its direction of revolution are not as important as the presence of a sizeable satellite!

My preliminary analysis of our terrestrial planet group is the following: Mercury is too close to the Sun to yield any reasonable chance for habitability of biota. Our twin sister, Venus, in my view, captured a one-half moon-mass satellite in a sun-stabilized retrograde orbit early in its history and was potentially habitable for about 3 billion years during which the satellite gradually despun the planet and recycled most or all of the surface crustal features into the shallow mantle of the planet. The result is a "Hades-like" planet with a dense carbon-dioxide-rich atmosphere and a very slow retrograde rotation rate. Earth, in my view, captured a moon-mass satellite in a sun-stabilized prograde orbit, and after about 4.0 billion years, we end up with a lunar-mass satellite in a near circular prograde orbit at about 60 planet radii. The prograde rotation rate of the planet over these 4.0 billion years changed from a primordial rate of about 10 hr/day to the present 24 hr/day. The result is something like a "paradise" planet that we have grown to know and love!

So the question of this book is: How could nature make a mars-like planet (a normal terrestrial planet in a mars-like heliocentric orbit) into a planet that could harbor a biological system of some sort for a significant span of geological time? The answer, in my view, is to acquire a massive satellite relative to the mass of the planet and a few chapters of this book suggest different scenarios for accomplishing this task! In short, GEOFORMING MARS!

Chapter 1 introduces some special features of the terrestrial planets and the Solar System as well as suggests a procedure for solving problems in the natural sciences. Chapter 2 is about the early evolution of the Sun and the Solar System and why such a model is very important for an explanation and analysis of the condition of the terrestrial planets and asteroids. Chapter 3 discusses various models that have been suggested for the origin of the current satellites of Mars, Phobos and Deimos, and also discusses the origin of the only other extant natural satellite in the terrestrial planet realm, the Earth's Moon. Chapter 4 presents a prograde gravitational capture model for Mars in which a 0.1 moon-mass planetoid is captured from a heliocentric orbit into a prograde marocentric orbit early in the history of the Solar System. A crucial issue for any capture model is to identify potential Solar System sources for such a planetoid or family of planetoids. Chap. 5 presents a retrograde gravitational capture model in which a 0.1 moon-mass planetoid is captured from a mars-like heliocentric orbit into a retrograde marocentric orbit early in the history of the Solar System. Certain features of prograde and retrograde capture scenarios are similar (both are gravitational capture scenarios) but the long-term effects are as different as Dr. Jekyll and Mr. Hyde. Chapter 6 critiques the Giant Impact Model, which has been a "ruling paradigm" in the Earth and Planetary Sciences for the past three decades. Chapter 7 chronologically develops a Prograde Gravitational Capture Model that appears to offer solutions for many of the outstanding problems of the Earth-Moon system as well as for many other problems of Solar System Science. Chapter 8 ventures into Comparative Planetology under the guise of the GEOMETRY OF STABLE CAPTURE ZONES (SCZs). The discussion focuses on how the SCZ concept can be used to assess the probability of successful capture of satellites of specific masses by terrestrial (and non-terrestrial) planets. In the author's view, stable gravitational capture of sufficiently massive satellites is a major key process for the development of habitable terrestrial planets. Thus, the identification of large satellites should be a major factor in the search for potentially habitable exoplanets. Chapter 9 discusses the factors that are involved in making a planet habitable. There appears to be two categories for habitability: (1) short-term habitability (i.e., 1 or 2 billion years) and (2) long-term habitability (i.e., over 2 billion years). Mars, the normal planet, appears to be in the first category, and some of the features for a normal terrestrial planet are (1) that it has large portions of its primitive crust after 4.6 billion years and (2) that it has no large satellite at present or evidence of the existence of a large satellite in a stable orbit in its past. Planet Earth is in the second category and is a terrestrial planet that (1) has a large extant satellite in a stable orbit and (2) has very little rock, mineral, and chemical isotope evidence that could be considered as relicts of a primitive crust after 4.6 billion years of geological history. A major question emerging from this chapter is: WHAT WOULD PLANET EARTH BE LIKE WITHOUT ITS MOON? A reasonable response is that it would have a prograde rotation rate of about 12 hr/day and that it would have large sections of its primitive crust surviving at or near the surface of the planet after over 4 billion years of planetary evolution. The "normal" earth-like planet in an earth-like heliocentric orbit would have no deep oceans, no mobile continents, and no recycling system for volatiles (such as water, carbon dioxide, methane, and others). Chapter 10 discusses the importance of large satellites being associated with both our set of terrestrial planets as well as terrestrial exoplanets. The author suggests that a "LARGE SATELLITE" paradigm should be added to the "CONTI NENTAL DRIFT/PLATE TECTONICS" paradigm (i.e., the Wegener paradigm) and the "PLANETARY AND ORBITAL PARAMETER VARIATION" paradigm (i.e., the Milankovitch paradigm) for explaining the development of planet Earth. It is the view of the author that these three major concepts (i.e., paradigms or revolutions in thought) are all interrelated and are necessary for a reasonable scientific explanation of the special features of our very habitable "paradise" planet that has supported biological entities for at least 3.5 billion years.

Granville, OH, USA Robert Malcuit

Some Perspectives and Acknowledgments

This project is a progression of my long-term interests in the origin and evolution of the terrestrial planets of our Solar System and of the Solar System in general. Getting closer to home, we all know that the Earth-Moon system is very complex and its origin is still a very debatable issue in the Earth and Planetary Science community. Planet Venus, our sister planet, has a very stable, sun-centered orbit but apparently it has a very complex evolutionary history that is essentially shrouded in mystery. In my view, many scientists in the planetary science community are now only beginning to appreciate the apparent complexities of these two large terrestrial planets as well as the apparent long-term stabilities of their sun-centered orbits. On the inner side of Venus is Planet Mercury with its high specific gravity, elevated eccentricity relative to Earth and Venus, and many other unusual features. Mercury, however, is of very little interest to the biological community because of its proximity to the Sun. Planet Mars, on the other hand, also has many unusual characteristics but one outstanding feature is that its crustal complex dates back to the early history of the solar system. It has a decipherable rock and mineral record dating back some 4.5 billion years. Planet Mars has no serious complications like a large satellite that potentially could have caused the destruction of the surface rock complex and recycled much of it into the Martian upper mantle. Because of this lack of dynamical complexity and a rotation rate that could be very near to its primordial rotation rate, Mars is considered by some scientists, me among them, to be a “normal” terrestrial planet, perhaps a “prototype” of a terrestrial planet to be used as an aid in our search for terrestrial exoplanets.

The purpose of this book is to illustrate how an unusual process like acquiring a large satellite (1) could change the Martian planetary story from fairly simple to complex and (2) could theoretically convert a Mars-type planet into a habitable world.

I want to acknowledge the excellent geological and general education background I received in my undergraduate and graduate years at Kent State University and at Michigan State University. I am especially appreciative of the field work with Richard Hemlich (KSU) in the Bighorn Mountains, Wyoming, which eventually led to my acquaintance through the geological literature and later in person with Preston Cloud (UC, Santa Barbara). Many thanks to Tom Vogel (MSU) for his guidance through the experiences of graduate school and for the permission to do an unusual project in planetary science for a Ph.D. project. At MSU, I did get to meet Harold Urey in person, although very briefly, after a talk he presented on campus on the subject of the origin of the Moon. Harold thought that the body of the Moon was formed away from the Earth and was later captured (somehow) by the Earth. A "STELLAR" CONCEPT in my opinion. He also expressed on several occasions that the Moon may eventually turn out to be a "Rosetta Stone" for interpretation of the history of the inner solar system. I still think that his concept is very commendable. At AGU and GSA meetings while I was a graduate student, I did meet with such notables as Hannes Alfven, Fred Singer, Keith Runcorn, and Harold Masursky, all of whom at some time in their professional lives were proponents of the capture model for origin of the Moon. It is interesting to note that Al Cameron was friendly to the capture model in the early 1970s because it was a "default" model (i.e., fission and co-formation models did not seem to lead to a solution by Al Cameron's reasoning). Then Al went off on a 20-plus year excursion doing world-class computer simulations and other calculations in support of the Giant Impact Model only to find that it did not solve the lunar origin problem. OH WELL, SHUCKS!! Maybe the "default" model of gravitational capture is a reasonable solution for the lunar origin problem after all!

A recent pursuit of astronomers and planetary scientists is the search for exoplanets, especially habitable terrestrial exoplanets. The general theme in the search for potentially habitable planets is to "FOLLOW THE WATER." The general idea is that the presence of liquid water on a planet can lead to the development of life forms. My advice for exoplanet investigators is, yes, look for a planetary environment than can yield liquid water but of equal importance for long-term habitability is the presence of a large satellite relative to the mass of the planet and for a central star that is "not too hot" and "not too cold." We now know that there are many exoplanets out there but we also know that terrestrial exoplanets appear to be rare and that terrestrial exoplanets with both liquid water and a reasonably large satellite could be extremely rare. The bottom line, in my view, is that we humans and our plant and animal friends may be "alone" in a large region of space. We must realize that we live on a special planet and we as an "intelligent" species must develop a "special" attitude toward our planet and its limited resources.

In graduate school I did projects with Gary Byerly (LSU) and Graham Ryder (a long-term associate with the LPI before his premature death in 2002). In graduate school and over the years I had many fruitful interactions at national and international meetings with these two individuals.

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Contents

1 **Introduction** 1
1.1 The Real Evolutionary History Versus "What Could Have Been" for Planet Mars 4
1.2 Discussion of the Primordial Planetary Rotation Rate of Solar System Bodies 5
1.3 The Scientific Method as It Applies to Models in Theoretical Planetology 10
1.4 Some Special Features of Mars as a Planet 11
1.4.1 Does Mars Have a Metallic Core? 11
1.4.2 Did Mars Have an Internally Generated Magnetic Field and When Did It Cease Operation? 15
1.4.3 What Caused the Hemispherical Dichotomy on Mars? 16
1.4.4 Is There Evidence for Oceans of Water on Mars Early in Its History? 18
1.4.5 Was There a Fairly Dense Atmosphere on Mars Early in Its History? 20
1.5 Summary 21
References 22

2 **The Origin of the Sun and the Early Evolution of the Solar System with Special Emphasis on Mars, Asteroids, and Meteorites** 27
2.1 List of Facts to Be Expalined by a Successful Model 28
2.2 Possible Sequence of Events that Leads to the Solar System as We Know It 30
2.2.1 The Nebular Stage 32
2.2.2 Gravitational Infall Stage 32
2.2.3 X-Wind Stage 32
2.2.4 Disk-Wind Stage 36
2.2.5 Formation of Chondritic Meteorites Stage 39

2.2.6 Planetoid Accretion Stage 39
2.2.7 FU Orionis Stage 41
2.2.8 T-Tauri Stage 43
2.3 A Question: What Was Happening in the Outer Solar System While All of This Intense Action Was Occuring in the Inner Solar System? 43
2.4 Summary 44
References 46

3 Models for the Origin of the Current Martian Satellites 51
3.1 List of Facts to Be Explained by a Successful Model 54
3.2 Some Models that Have Been Suggested for the Origin of the Martian Satellites 54
3.2.1 Fission Models 55
3.2.2 Co-Formation Models 55
3.2.3 Capture Models 55
3.2.4 Giant Impact Models 56
3.2.5 Combinations of Models 57
3.2.6 The Magnetic Rock Patterns on Mars and Implications for the Origin of Phobos and Deimos 59
3.3 How Does this Digression on Earth Tide Phenomena Fit in with Our Discussion of the Origin of Martian Satellites? 61
3.4 A Model Featuring Tidal Disruption of Ceres-Type Asteroids During Close Non-Capture Encounters With Mars Early in its History: Implications for Magnetic Field Generation and Origin of the Martian Satellites 61
3.4.1 Orientation Information for Close Encounters that may Result in Partial Tidal Disruption of a Ceres-type Asteroid 62
3.4.2 Definition and Discussion of the Weightlessness Limit for Ceres-type Asteroids Encountering a Mars-Mass Planet 64
3.4.3 Numerical Simulations of Ceres-type Asteroids Encountering Planet Mars 67
3.4.4 A Scheme for Getting Disrupted Material from a Ceres-Type Asteroid into Martian Orbit 67
3.5 Summary 72
References Cited 72

4 A Prograde Gravitational Capture Model for a Sizeable Volcanoid Planetoid (or Asteroid) for Mars 75
4.1 Place of Origin of Candidate Planetoids for Capture 75
4.2 Prograde Gravitational Capture of a 0.1 Moon-Mass Planetoid and the Subsequent Orbit Evolution: An Attempt to Geoform Mars 78

4.2.1 A Two-Body Analysis and a Discussion of the Paradoxes Associated with the Capture Process 78
4.2.2 Post-Capture Orbit Circularization Process 85
4.3 Numerical Simulation of Prograde Gravitational Capture of a 0.1 Moon-Mass Planetoid by Planet Mars 86
4.3.1 Computer Code Information 86
4.3.2 Development of the Computer Code 88
4.3.3 A Sequence of Typical Orbital Encounters Leading to a Stable Capture Scenario 88
4.3.4 Geometry of Stable Prograde Capture Zones for Planetoids Being Captured by Mars 92
4.3.5 Post-Capture Orbit Evolution 95
4.3.6 Summary and Statement of the Fourth Paradox 95
4.4 Numerical Simulation of Prograde Gravitational Capture of a 0.2 Moon-Mass Planetoid by Planet Mars: Another Attempt to Geoform Mars 98
4.4.1 A Sequence of Typical Orbital Encounters Leading to a Stable Capture Scenario of a 0.2 Moon-Mass Planetoid 99
4.4.2 Summary for the Prograde Capture Scenario for a 0.2 Moon-Mass Planetoid 100
4.5 Summary 102
References Cited 102

5 A Retrograde Gravitational Capture Model for a Sizeable Satellite for Mars 105
5.1 Retrograde Gravitational Capture of a 0.1 Moon-Mass Satellite and Subsequent Orbit Circularization: An Attempt to Venoform Mars 105
5.1.1 A Two-Body Analysis of Retrograde Capture 106
5.1.2 Post-Capture Orbit Circularization Process 106
5.1.3 Circular Orbit Evolution 107
5.2 Numerical Simulation of Retrograde Planetoid Capture for Mars and a 0.1 Moon-Mass Planetoid 107
5.2.1 A Sequence of Orbital Encounters Leading to Stable Retrograde Capture 108
5.2.2 Geometry of Retrograde SCZs for Planetoids Being Captured by Mars 110
5.2.3 Post-Capture Orbit Circularization Era 111
5.2.4 Circular Orbit Evolution for a 0.1 Moon-Mass Satellite in Retrograde Orbit 112
5.3 Numerical Simulation of Retrograde Planetoid Capture for Mars and a 0.2 Moon-Mass Planetoid 112
5.3.1 A Sequence of Encounters Leading to Stable Retrograde Capture 113

5.3.2 Post-Capture Orbit Circularization Era 115
5.3.3 Circular Orbit Evolution 118
5.3.4 Summary of the Post-Capture Orbital Evolution of a 0.2 Moon-Mass Satellite (Ubertas) in Retrograde Orbit About a Mars-Like Planet in a Mars-Like Heliocentric Orbit 127
5.4 Summary 134
References 136

6 A History of a Ruling Paradigm in the Earth and Planetary Sciences That Guided Research for Three Decades: The Giant Impact Model for the Origin of the Moon and the Earth-Moon System 137
6.1 Part I: The GIANT-IMPACT MODEL for the Solution of a Number of Problems in the Earth and Planetary Sciences 138
6.1.1 Items to Be Explained By a Successful Model for the Origin of the Moon and the Earth-Moon System 138
6.1.2 A Generalized Chronological Development of a Giant-Impact Model for the Origin of the Earth-Moon System 139
6.2 The Use of Default Models for the Intractable Problems Associated with the Origin of the Moon and the Earth-Moon System 171
6.2.1 Some Quotes from R. Smoluchowski (1973a), Lunar tides and magnetism: Nature, v. 242, p. 516–517 171
6.2.2 P. Lipton (2005) Testing hypotheses: Prediction and prejudice: Science, v. 307, p. 219 172
6.3 An Attempt to Explain a Shallow-Shell Amplifier Model for the Generation of a Magnetic Field to Cause the Observed Lunar Rock Magnetization 172
6.3.1 General Predictions from the Model 173
6.3.2 Two Major Eras of Lunar Rock Magnetization 173
6.3.3 More Detailed Predictions from the Model 176
6.3.4 Summary for Sects. 6.1, 6.2, and 6.3 177
6.3.5 The Prograde Gravitational Capture Model (PGCM) as a Default Model 179
6.4 Part II. Building on Success. Extension of the Giant-Impact Model for the Solution of Other Problems in the Planetary Sciences 179
6.4.1 On the Origin of Planet Mercury 180
6.4.2 Origin and Evolution of Planet Venus Via A Giant Impact Scenario 181
6.4.3 Origin of the Small Satellites of Mars 183
6.4.4 The Origin of Satellites of Asteroids Via Large Impacts Between Asteroids 184
6.4.5 Origin of the Excessive Tilt Angle of Planet Uranus . . . 184

6.4.6 Origin of the Pluto-Charon System 189
6.4.7 Discussion of the Paradigm of Giant Impacts for the Solution of Unsolved Problems in Solar system Science 194
6.5 Summary 194
References Cited 195
Some Numbered References from Quotes from Smoluchowski (1973a) as They Appear in the Reference Section of the Paper 199

7 A History of Satellite Capture Studies As Experienced by the Author: A Chronology of Events that Eventually led to a Somewhat Comprehensive Gravitational Satellite Capture Model 201
7.1 My Time at Kent State University 202
7.2 My Time at Michigan State University 202
7.2.1 A Brief Discussion of the Importance of the Weightlessness Limit 207
7.3 My Early Days at Denison University 211
7.4 The Kona Conference on the Origin of the Moon 222
7.5 The Era of Serious Capture Studies at Denison University 224
7.6 Conference on the Origin of the Earth and Moon 227
7.7 An Era of Important Events for Gravitational Capture Studies . . 228
7.7.1 Vulcanoid Planetoids 228
7.7.2 The X-Wind Model 229
7.7.3 The Cool Early Earth Model 230
7.7.4 The Concept of Recycling the Hadean-age Primitive Crust 231
7.7.5 Summary Diagrams for the Timeframe for Development of the Ancillary Models which are Important for the Tidal Capture Model 236
7.8 Summary 240
References 241

8 Comparative Analysis of the Gravitational Capture Potential for the Terrestrial Planets and Planet Neptune 247
8.1 Geometry of Stable Capture Zones and their Importance to Planetary Science 249
8.2 Planet Mercury 252
8.2.1 Two-Body Representation, Stable Capture Zones, and Orbital Orientation Diagrams for Gravitational Capture Simulations for Mercury 252
8.2.2 Prograde Encounter and Capture Simulations: Inside Orbit 254
8.2.3 Prograde Encounter and Capture Simulations: Outside Orbit 259

8.2.4 Retrograde Encounter and Capture Simulations: Inside Orbit 262
8.2.5 Retrograde Encounter and Capture Simulations: Outside Orbit 266
8.2.6 Summary of the Mercury-Planetoid Simulations 270
8.3 Planet Venus 271
8.3.1 Two-Body Representation, Stable Capture Zones, and Orbital Orientation Diagrams for Gravitational Capture Simulations for Venus 271
8.3.2 Prograde Encounter and Capture Simulations: Inside Orbit 274
8.3.3 Prograde Encounter and Capture Simulations: Outside Orbit 276
8.3.4 Retrograde Encounter and Capture Simulations: Inside Orbit 278
8.3.5 Retrograde Encounter and Capture Simulations: Outside Orbit 280
8.3.6 Summary of Venus-Adonis Simulations 283
8.4 Planet Earth 283
8.4.1 Two-Body Representation, Stable Capture Zones, and Orbital Orientation Diagrams for Gravitational Capture Simulations for Earth 283
8.4.2 Prograde Encounter and Capture Orientation: Inside Orbit 287
8.4.3 Prograde Encounter and Capture Simulations: Outside Orbit 289
8.4.4 Retrograde Encounter and Capture Simulations: Inside Orbit 291
8.4.5 Retrograde Encounter and Capture Orientation: Outside Orbit 293
8.4.6 Summary for Earth-Luna Simulations 295
8.5 Note: The Situation for Capture of Planetoids by Planet Mars Was Covered Extensively in Chaps. 4 and 5. It Would Be Redundant to Repeat this Information in this Chapter 296
8.6 Planet Neptune 299
8.6.1 Two-Body Representation, Stable Capture Zones, and Orbital Orientation Diagrams for Gravitational Capture of a Triton-Mass Planetoid for Planet Neptune 300
8.6.2 Prograde Encounter and Capture Simulations: Inside Orbit 300
8.6.3 Prograde Encounter Simulations: Outside Orbit 306
8.6.4 Retrograde Encounter and Capture Simulations: Inside Orbit 310

8.6.5 Retrograde Encounter and Capture Simulations: Outside Orbit . . . 313
8.6.6 Summary for Neptune-Triton Simulations . . . 317
8.7 Comparative Geometry of the Stable Capture Zones for Mercury, Venus, Earth, Mars, and Neptune . . . 318
8.8 Discussion of the Implications in the Search for Habitable Exoplanets . . . 318
8.9 Summary . . . 321
Appendix . . . 321
References Cited . . . 327

9 Discussion of Some Real and/or Theoretical Effects of Captured Satellites on Both Terrestrial Planets and Gaseous Planets . . . 329
9.1 Implications for Finding Habitable Terrestrial Planets for Algae and Bacteria and Possibly Higher Forms of Life . . . 329
9.1.1 CASE I: The Mars that We Think We Know Something About . . . 330
9.1.2 CASE II. Theoretical Development of a Model in which a 0.1 Moon-Mass Planetoid Is Captured by a Mars-Mass Planet in a Prograde Marocentric Orbit . . . 331
9.1.3 CASE III: Theoretical Development of a Model in which a 0.1 Moon-Mass Planetoid Is Gravitationally Captured into a Stable Retrograde Orbit Early in Martian History . . . 332
9.1.4 CASE IV. Theoretical Development of a Model in which a 0.2 Moon-Mass Planetoid Is Captured by Planet Mars in a Prograde Orientation . . . 335
9.1.5 CASE V: Theoretical Development of a Model in which a 0.2 Moon-Mass Planetoid Is Stably Captured by Planet Mars in a Retrograde Direction. This Case Is the Best Chance of Developing Habitable Conditions on Mars for Significant Portions of Geologic Time . . . 335
9.1.6 Comparison of Models of Martian Evolution to the Evolution of Other Terrestrial Planets as well as Terrestrial Exoplanets . . . 337
9.2 Some Notes on the Situation of Earth, Venus, and Mercury Without a Satellite . . . 343
9.2.1 Earth . . . 345
9.2.2 Venus (Without a Large Satellite in its History as a Planet) . . . 346
9.2.3 Mercury (Without a Large Satellite) . . . 350
9.2.4 Discussion for this Section . . . 352

9.3 Implications for the Analysis of Gaseous Exoplanets in Light of the Models for the Evolution of Planets Neptune and Uranus via Retrograde Capture of Fairly Large "Icy" Satellites for these Planets 352
9.3.1 Analysis of the Situation of Planet Uranus 353
9.3.2 Analysis of the Neptune-Triton System 355
9.4 Summary 355
References Cited 356

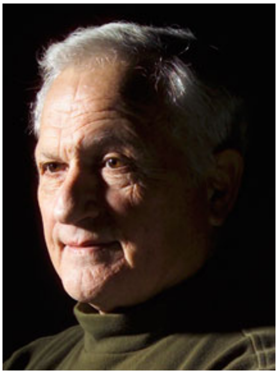
10 A Discussion of Three Major Paradigms in the Earth and Planetary Sciences 359
10.1 The Earth Tide "Paradigm" for Planet Earth 360
10.1.1 A Brief History of the Concept 360
10.1.2 How Does the Lunar Capture Model Relate to the Earth Tide Paradigm? 364
10.2 The Plate Tectonics Paradigm and the Earth Tide Paradigm 368
10.3 The Milankovitch Cycles Paradigm and the Earth-Tide Paradigm 371
10.4 The "Astronomical Metronome" and Planet Orbit – Lunar Orbit Resonances 376
10.5 Discussion of the Compatibility of these Three Models (Paradigms) 381
10.6 Application of these Three Major Concepts to the Operation of Planet Mars 382
10.7 Summary 383
References Cited 384

Glossary 389

Author Index 411

Subject Index 415

Author Biography



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Chapter 1
Introduction

> Mars is believed to be lifeless, but it may be possible to transform it into a planet suitable for habitation by plants, and conceivably humans. The success of such an enterprise would depend on the abundance, distribution and form of materials on the planet that could provide carbon dioxide, water and nitrogen. —From McKay et al. (1991, p. 489).

> Mars is in some ways the type example of a terrestrial planet. It is neither geologically stillborn, like Mercury or the Moon, nor so active that most of the geological record has been destroyed, like Venus or the Earth. —From Nimmo and Tanaka (2005 p. 133).

> We revisit the idea of 'terraforming' Mars – changing its environment to be more Earth-like in a way that would allow terrestrial life (possibly including humans) to survive without the need for life-support systems – in the context of what we know about Mars today.

> Recent observations have been made of the loss of Mars's atmosphere to space by the Mars Atmosphere and Volatile Evolution Mission probe and the Mars Express spacecraft, along with analyses of the abundance of carbon-bearing minerals and the occurrence of CO_2 in polar ice from the Mars Reconnaissance Orbiter and the Mars Odyssey spacecraft. These results suggest that there is not enough CO_2 remaining on Mars to provide significant greenhouse warming were the gas to be emplaced into the atmosphere; in addition, most of the CO_2 gas in these reservoirs is not accessible and thus cannot be readily mobilized. As a result, we conclude that terraforming Mars is not possible using present-day technology.—From Jakosky and Edwards (2018, p. 634).

Planet Mars appears to be a normal terrestrial planet. It still has much of its original (primitive) crust. Its prograde rotation rate, about 24.6 hour/day, is what is expected for a planet of that mass and density (MacDonald 1963, 1964). It has a rarefied atmosphere and a low mass hydrosphere mainly because the mantle of the planet has not been degassed to any significant extent over the last few billions of years. Figure 1.1 shows a typical view of planet Mars.

At this point I need to define some new terms to be used in this book. The traditional term for "engineering" a planet like Mars is TERRAFORMING. By traditional use the term "terraforming" is a project of engineering by humans to make a planet like Mars somewhat habitable for biological forms. After consideration of the information in Jakosky and Edwards (2018) it appears that the term "terraforming" could also be used for the construction of semi-sealed geodesic

R. Malcuit, *Geoforming Mars*, https://doi.org/10.1007/978-3-030-58876-2_1

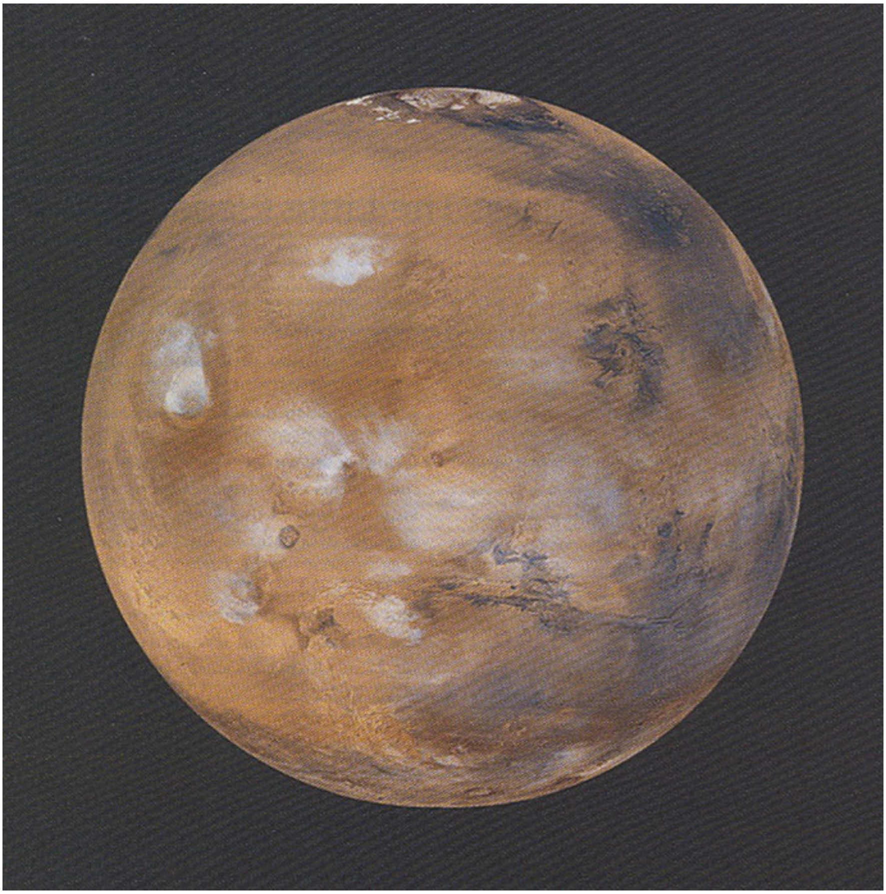

Fig. 1.1 Photo of Mars showing many of the surface features of the planet such as the north polar ice cap, the three major volcanoes of the Tharsis plateau, and Olympus Mons (to the west of the plateau), and Valles Marineris. The thin clouds of Mars are water vapor and the transparent atmosphere is composed mainly of carbon dioxide. (Photo is courtesy of NASA/JPL)

dome communities or perhaps larger projects on Mars for human occupation. Jakosky and Edwards (2018) conclude that planet-wide TERRAFORMING of planet Mars may not be physically possible using current technology and resources on Mars but, in my view, smaller scale projects as described above could be constructed and operated using mainly local resources.

Here I am introducing the term GEOFORMING as a theoretical planetary development process resulting in conditions on a planet or exoplanet that are similar to those on Earth at the present time or at some time in the past or future evolution of planet Earth. Other suggested theoretical planetological development terms are Venoforming, Maroforming and Mercoforming. A VENOFORMED planet would have conditions similar to those on Venus today or at some time in the past or future evolution of planet Venus. A MAROFORMED planet would have conditions similar to those on Mars at the present time or at some time in the past or future evolution of planet Mars. A MERCOFORMED planet would have conditions similar to those on planet Mercury today or at some time in the past or future evolution of planet Mercury.

Some terrestrial planets like Venus and Earth can evolve considerably over geologic time. For example, conditions on planet Earth were significantly different one billion years or two billion years ago than they are at the present time. The same can be said for planet Venus. Other terrestrial planets evolve very little after the initial stages of planet formation: examples of this category, in my view, are planets Mercury and Mars.

The purpose of this book is to summarize the current state of conditions on Mars and then to present some theoretical planetological development processes that could have resulted in conditions similar to those of planet Earth today. In short, we want to GEOFORM MARS.

Planet Earth, in contrast to Mars, has a large satellite that has had major effects on the rotation rate and the degassing history of the planet. The primordial rotation rate of about 10 hour/day (MacDonald 1963, 1964) has gradually changed by rock and ocean tidal interaction with the Moon over geologic time to our present rate of 24 hour/day.

Planet Venus, in contrast to Mars, has undergone a global resurfacing event in the past 0.5–1.0 Ga (billion years) (Herrick 1994; Herrick and Parmentier 1994), the mantle has been degassed significantly [i. e., about 1.6 times that of Earth (Cloud 1972, 1974)], and the rotation rate has been changed, over geologic time, from the expected primordial prograde rate of about 13.5 hour/day (MacDonald 1964) to the present very slow retrograde rotation rate of about 243 earth days/year.

A major question is: Are there any major events in the history of planet Mars that could have resulted in a more complex planetological evolution, an evolution that may have been more favorable for the development of at least a relatively simple biosphere?

In this book we will explore the theoretical ramifications of the gravitational capture of a sizeable satellite of 1/100 the mass of Mars. This mass ratio is very similar to that of the Earth-Moon system which is 1/81. We will also consider the positive and negative effects of capturing an even larger satellite of about 0.02 of the mass of Mars. Along the way we will discover:

- that both prograde and retrograde gravitational capture scenarios for these sizeable planetoids are physically possible for planet Mars,
- that any of these capture scenarios could have had profound effects on the lithospheric, hydrospheric, and atmospheric evolution of planet Mars,
- that a major long-term effect for any stable capture scenario is a very significant change in the rotation rate of planet Mars by way of the rock and ocean tidal history of the planet,
- that any of these capture scenarios would have greatly increased the chances of development of primitive life forms on Mars over geologic time.

1.1 The Real Evolutionary History Versus "What Could Have Been" for Planet Mars

This book on geoforming Mars is partly a work of theoretical planetology but it starts with a set of facts (and some interpretations) about planet Mars at the present time in the scientific investigation of the planet. The early history of Mars (what I call in this book, the pre-capture era) is the same for all five models discussed below because any capture episode would probably occur within a few 100 Ma after the formation of the planet. In general, there are five evolutionary scenarios to consider.

Scenario One: This model begins with a primitive Mars in a mars-like heliocentric orbit with a primitive rotation rate of ~24.6 hr/day and no sizeable satellite (Phobos and Deimos are much too small to make a difference here). This scenario is essentially the Mars that we have today. If planet Venus or planet Earth would undergo an evolution scenario like this it would be a Maroforming process.

Scenario Two: This model begins like Scenario One with a Mars-like planet in a Mars-like heliocentric orbit. Then within the first few 100 Ma of its existence Mars captures a 0.1 moon-mass planetoid from a mars-like heliocentric orbit. The post-capture marocentric orbit circularizes in a few billion years during which the prograde rotation rate of Mars changes from 24.6 hr/day to ~88 hr/day. The rock tidal amplitudes at the time of capture are up to 9 km and rock tidal amplitudes up to 6 km are common for the first few thousand years after capture. But during the orbit circularization of the satellite, the prograde rotation rate of Mars is forever decreasing because of angular momentum exchange with the satellite in prograde orbit. The chances for life forms to evolve in the low to mid-latitude zones are favored by the high rock and ocean tides and associated volcanic outgassing soon after capture but the gradual decrease in rotation rate is not all that favorable for life forms because of the increasingly long, cold nights on the planet. This scenario if an attempt at Geoforming.

Scenario Three: This model is similar to the previous model in that it begins with a Mars-like planet in a Mars-like heliocentric orbit. Then within the first few 100 Ma Mars captures a 0.2 moon-mass planetoid in a prograde marocentric orbit from a Mars-like heliocentric orbit. The rock tidal amplitudes for this capture scenario are about 18 km and the timescale for orbit circularization is considerably shorter. The planet, however, loses much of its prograde rotation rate via tangential tidal action over a much shorter period of time than in Scenario two. Thus the time-frame for evolution of life forms is very favorable over that brief period of marologic time. As in scenario one, the "long-night" syndrome would probably make living condition intolerable within a few billion years of time. This is another attempt at Geoforming.

Scenario Four: This model has a similar beginning to Scenarios one, two, and three with a Mars-like planet in a Mars-like heliocentric orbit. However, in this case a 0.1 moon-mass planetoid is captured into a stable but highly elliptical retrograde marocentric orbit. The timescale for retrograde marocentric orbit circularization is very short relative to that for a prograde orbit and within a few 100 Ma the orbit is circularized to about 30 mars radii. The high rock tides and intense rock and ocean tidal activity associated with the capture event and subsequent orbit circularization would probably result in a large portion of the crust in the equatorial zone of Mars being recycled into the martian mantle. All this rock tide activity would result in massive volcanism and outgassing of mantle volatiles. During this retrograde capture scenario, the rotation rate of Mars decreases rapidly and any biological system on the planet finds itself in the "long night syndrome" fairly rapidly but the rock and ocean tides are forever increasing in amplitude and frequency as the orbit evolution proceeds. Eventually, after about 8 billion years of time (about 4 Ga in the future for Earthians), the satellite breaks up in orbit at the Roche limit for a solid body. The final result is a mars-like body with the environmental conditions of planet Venus today (see Malcuit 2015, Chap. 6). This scenario is an attempt at Venoforming.

Scenario Five: This model is similar to that of Scenario Four but the captured retrograde satellite is twice as massive. Thus the tidal amplitudes are twice as high and the post-capture orbit circularization is somewhat shorter. The planet is despun over a shorter period of time and there is a lengthy period of the "long night syndrome". Eventually the prograde rotation of the mars-like planet decreases to zero and the planet begins to rotate in the retrograde direction. There are high rock and ocean tidal amplitudes as well as a progressive increase in both tidal amplitude and frequency. The increasing retrograde rotation rate of the planet prolongs the lifetime of the retrograde marocentric orbit. THIS IS AN UNUSUAL ORBITAL SCENARIO BUT IT IS THE MOST FAVORABLE FOR THE DEVELOPMENT AND SUBSEQUENT EVOLUTION OF LIFE FORMS ON A MARS-LIKE PLANET! In this scenario the satellite orbit eventually evolves to the Roche limit for a solid body, breaks up in orbit, and the particles, large and small, fall to the surface of Mars. The final rotation rate of Mars, in this scenario, is about 11 hr/day retrograde and the environmental conditions on Mars are similar to those on planet Venus today. This is another attempt at Venoforming.

1.2 Discussion of the Primordial Planetary Rotation Rate of Solar System Bodies

There appears to be two schools of thought to explain the rotation rates of both terrestrial and gaseous planets. School One proposes that there is an "orderly component of planetary rotation" and that this orderly component resulted from the accumulation of small bodies from orbits of low eccentricity by a favored planetary embryo on a circular orbit. Calculations suggest that planetesimals on elliptical orbits from the outer regions of the accretion zone of the planet generally induce a relatively rapid prograde rotation (i.e., prograde rotation rates like we observe today for planet Mars) as well as prograde rotation rates that are in

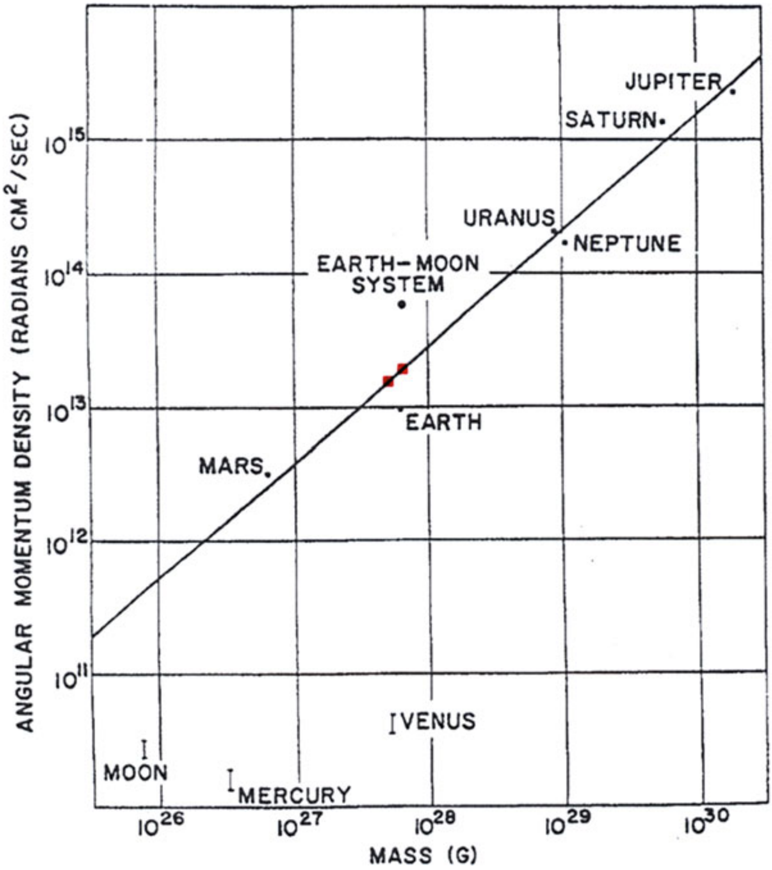

Fig. 1.2 Plot of Angular Momentum Density vs. Mass for the planets of the Solar System as well as for the Earth's Moon and the Earth-Moon system. (Diagram adapted from MacDonald (1963, Fig. 38, with permission from Springer.) The line was placed for the best fit of the information for the rotation rates for the outer planets and Mars. The assumption, which is suggested by the plot, is that Mars has a rotation rate very close to its primordial rotation rate (~25 h/day). If all the angular momentum of the Earth-Moon system is placed in the Earth, the rotation rate would be ~4.5 h/day. If the Earth is rotating ~10 h/day, the Earth would plot on the line between the position of the Earth-Moon system and the Earth (the *red square* symbol on the *right*). This information suggests that the original rotation rate for Earth was ~10 h/day. If the angular momentum of a lunar-mass body in a 30 earth radii circular orbit in a prograde direction is added to the prograde angular momentum of an Earth rotating at 10 hr/day, then that combination plots in the position of the Earth-Moon system on the plot. Likewise, if Venus is elevated to the line vertically above its position on the graph (the *red square* symbol on the *left*), then the original rotation rate would be ~13.5 h/day. The primordial rotation rates of the Moon as an independent planet and that of planet Mercury can be estimated using the same procedure. (Diagram from MacDonald (1963, Figure 38) courtesy of Springer)

agreement with the observational plot in MacDonald (1963, 1964) (see Fig. 1.2). These accretion schemes apply to both terrestrial planets and gaseous planets. Major sets of calculations for this model are in Lissauer and Kary (1991) and Lissauer et al. (1997).

The MacDonald (1963, 1964) plot suggests a primordial prograde rotation rate of about 10 hr/day for Earth and about 13.5 hr/day for Venus. These prograde rotation rates are reasonable initial conditions for explaining a prograde gravitational capture model for the earth-moon system and a retrograde gravitational capture model for a Venus-satellite system. Thus, the history of the four terrestrial planets can be explained in some detail using the "orderly component of planetary rotation" (Lissauer and Kary 1991; Lissauer et al. 1997) in conjunction with the plots of MacDonald (1963, 1964). Johansen and Lambrechts (2017) present a review of the process of the formation of planets by way of the accretion of pebbles; in this review they present calculations demonstrating how prograde rotation of a planetoid results from the accretion of pebbles in a gaseous environment.

Additional support for this "orderly component of planetary rotation" school comes from detailed calculations on the history of the Earth-Moon system when starting with the present conditions of the system. Hansen (1982) did a traceback calculation of the Earth-Moon system which included both the action of the ocean tides and the earth tides. He presented a few different combinations of the positions of the continents, dimensions of the continental shelves, and other characteristics that might affect the tidal friction process. Regardless of the configurations used, he could not get the lunar orbit much smaller than a circular orbit of about 30 earth radii over 4.6 Ga of time which relates to a rotation rate for earth of about 10 hr/d. Webb (1982) did a completely independent traceback calculation using somewhat different assumptions for the parameters of tidal friction and arrived at a similar conclusion. Is it ironic, or coincidental, that our (Malcuit et al. 1992; Malcuit 2015) most reasonable post-capture orbit, after about 600 Ma of post-capture orbit circularization to about 10% eccentricity has the angular momentum equivalent to a circular orbit of about 30 earth radii? Indeed, the angular momentum of a 30 earth radii lunar orbit plus the angular momentum of a primitive earth with a prograde rotation rate of 10 hr/day equals the angular momentum of the Earth-Moon system.

School Two proposes that any systematic (i.e., orderly) component in the planetary accretion process is "overwhelmed" by the random process of accumulation of bodies of various sizes. In this model it is the large impacting bodies that determine both the rotation rate and obliquity (tilt angle) of the resulting planetary unit. Some early calculations for this model are by Wetherill (1985), Tremaine (1991), and Dones and Tremaine (1993a, 1993b). Major support for this stochastic process model is from the promoters of the Giant Impact Model (GIM) for the origin of the Earth's Moon. A prograde rotation rate of about 4.5 hr/day is needed immediately following the tangential impact for the traditional model of the GIM that features a mars-mass body impacting obliquely onto the primitive earth. Thus, for nearly all of these stochastic impact models it is very important to have a large planetoid to impact obliquely onto an earth-like planet. But the question is: "WHERE DID SUCH A LARGE BODY COME FROM???" The place of origin of Theia (the hypothetical mars-mass impactor in the GIM model) has not been determined. Belbruno and Gott (2005) suggest an origin near either the L4 or L5 Lagrange point of the orbit of Earth as a source for the mars-mass body because of the similarity of oxygen isotopes between Earth and Moon. Herwartz et al. (2014)

suggest that Theia had the composition of enstatite chondrites which implies that the body formed in the vicinity of the earth's orbit. Meier et al. (2014) suggest that Theia had an earth-like composition and formed in the vicinity of the orbits of Earth and Venus.

Davies (2008) and Gillman et al. (2016) suggest that the present retrograde rotation of Venus may have been caused by way of impacts with planetoids associated with the Late Heavy Bombardment (LHB) of the inner part of the Solar System. [Note that the LHB is about to become abandoned because of lack of evidence in the rock records of the Earth and Moon (Mann 2018)]. The place of origin for a large impactor, or a covey of smaller impactors, for a GIM model for Venus to explain the retrograde rotation of Venus has not been suggested. The place of origin of the TWO EARTH-MASS BODY to impact on Uranus (Slattery et al. 1992) to cause the obliquity to increase instantaneously to 98 degrees has not been determined or proposed. Although there can be stochastic impactors postulated for nearly all planetary obliquity and planetary rotation problems, not one of these solutions explains the details of planet evolution or planet-satellite system evolution. Furthermore, other solutions have been proposed that do not involve a mysterious giant impactor. (Note: Various features of giant impact models for solving solar system problems will be discussed extensively in Chap. 6.)

In a short note in SCIENCE Dan Clery (2013) summarized the Royal Society of London Meeting on the Origin of the Earth's Moon. The title of the article is "THE IMPACT MODEL GOT WHACKED". In my view the promoters of the GIM have never recovered from that "whacking". According to Mann (2018), the concept of the Late Heavy Bombardment is heading toward the exit as well.

The stochastic impact model for planet formation looked like a very good solution when the Giant Impact Model was presented at the Kona Conference (see Hartmann et al. 1986, for the resulting Conference Volume) because the three traditional models (fission, co-formation, and capture) had "fatal flaws". The "fatal flaw" syndrome is now "infecting" the GIM as well as its replacement, the Syenestia model. As a historical note, it seems like the GIM is now having about as much success for solving Solar System Problems as the STABLE CONTINENT PARADIGM did in the earth science realm in the 1960's. The continental drift/plate tectonics model came up with much better solutions.

Returning to the problems of the evolution of the lunar orbit, Ross and Schubert (1989) presented a model for the "forward" evolution of the lunar orbit. This calculation was based on the evolution of the Earth-Moon system in the aftermath of the GIM. The initial conditions for the calculation were (1) a lunar orbit just beyond the Roche limit (about 3 earth radii) and (2) a rotation rate for earth of about 4.5 hr/d. Using their selected set of body deformation parameters they found that the lunar orbit evolved out to about 50 earth radii in about 2 billion years. But they found that it was very difficult to get the lunar orbit to expand beyond about 53 earth radii in 4.6 billion years. They speculated that the tidal friction associated with the ocean tidal regime must have increased significantly at about that time (i. e., when the lunar orbit was at about 50 to 53 earth radii and the rotation rate of earth was about 16.9 hr/d; *i. e.*, at about 50 earth radii). It is ironic that both Davies (1992) and Stern (2005) suggest the thermal conditions of the upper mantle of earth would be conducive to the initiation of “slab-pull” plate tectonics (i.e., modern style plate tectonics) at about 1.0 Ga ago. Perhaps deeper ocean basins and moderately wide continental shelves would be conducive to increased tidal friction in the 1.0 Ga to recent eras of earth history.

An interesting quote from Ross and Schubert (1989, p. 9540) is:

> With the solid tide dissipation we adapted here, the Moon would never move beyond about 53 R_E were it not for the ocean tide.

On page 9540–9541:

> In fact, numerical models of the ocean tide in backward evolution calculations suggest that when the semimajor axis becomes less than about 40–50 R_E, oceanic dissipation falls sharply and the Moon remains “stuck” at about 30 R_E [Hansen 1982; Webb 1982]. To circumvent the problem, Hansen [1982] proposed a capture origin for the Moon with capture at about 30 R_E! Our results show that such drastic proposals are not required to reconcile formation of the Moon near the Earth with inactive oceanic tides inward of about 30 R_E.

This last quote is a comment against the Lunar Capture Model for the origin of the Earth-Moon system and the authors refer to the Hansen (1982) and Webb (1982) calculations. Hansen (1982) did say that he could not get the lunar orbit beyond 30 earth radii in his trace-back calculation and suggested that the Moon was captured in the early history of planet earth. In my view, this speculation of lunar capture by Hansen (1982) was a good one and our calculations suggest that a highly elliptical post-capture lunar orbit has the orbital angular momentum of a 30 earth radii circular geocentric orbit. Such a prograde lunar orbit in association with an earth-like planet with a prograde rotation rate of 10 hr/d yields the angular momentum of the Earth-Moon system.

A note on the term “drastic proposal” for a capture origin deserves a brief comment. I point out that the standard Giant Impact Model is over 3000 times more energetic than any capture model and the Synestia model is much more energetic than the GIM. So which models are the “DRASTIC PROPOSALS”?

How do these contrasting models for initial planet rotation relate to Planet Mars? Well, the rotation rate of 24.6 hr/d for Mars is very consistent with the Specific Angular Momentum vs. Mass diagram of MacDonald (1963, 1964) in Fig. 1.2. This rotation rate is also very consistent with the concept of Mars being a very normal terrestrial planet (Nimmo and Tanaka 2005), essentially a prototype of a terrestrial planet. Where Mars fits in with the stochastic approach to the problem of planetary rotation is not at all clear.

A quote from Laskar is appropriate here (Laskar 1995, p. 104):

> Mars is far from the Sun, and its satellites Phobos and Diemos have masses far too small to slow its rotation, so that its present rotation period of 24 hours 37 minutes is likely to be close to its primordial rotation period.