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The Martian Surface

Composition, Mineralogy and Physical Properties

Phenomenal new observations from Earth-based telescopes and Mars-based orbiters, landers, and rovers have dramatically advanced our understanding of the past environments on Mars. These include the first global-scale infrared and reflectance spectroscopic maps of the surface, leading to the discovery of key minerals indicative of specific past climate conditions; the discovery of large reservoirs of subsurface water ice; and the detailed in situ roving investigations of three new landing sites, which gives us firm evidence for the presence of liquid water on the surface or in the shallow subsurface in the distant past.

This important, comprehensive book provides an overview of the latest Mars compositional and mineralogic discoveries since the last major review of this topic was published in 1992. It is an essential resource for researchers and students in planetary science, astronomy, space exploration, planetary geology, and planetary geochemistry. Specialized terms are defined throughout, so the material will be easily understood by researchers just getting into this field.

JIM BELL is an Associate Professor in the Department of Astronomy at Cornell University. He is the lead scientist for the Pancam color imaging system on the NASA Mars Exploration Rovers Spirit and Opportunity, and is also a member of the science teams of the NASA Mars Pathfinder, Near Earth Asteroid Rendezvous (NEAR), Mars 2001 Odyssey Orbiter, Mars 2005 Reconnaissance Orbiter, and 2009 Mars Science Laboratory rover mission teams. He has authored or co-authored more than 150 peerreviewed scientific papers on Mars, is an editor for *Icarus*, and has an asteroid named after him (8146 Jimbell) by the International Astronomical Union.

THE MARTIAN SURFACE

Composition, Mineralogy, and Physical Properties

Edited by

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CONTENTS

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TABLES

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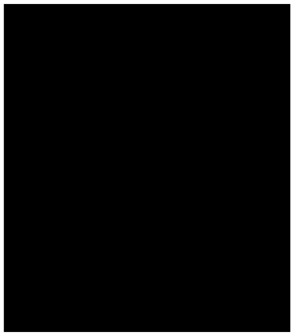

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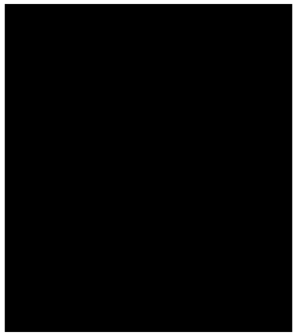

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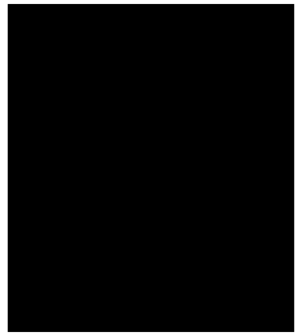
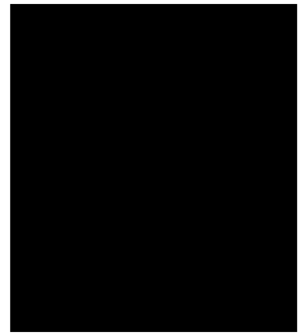
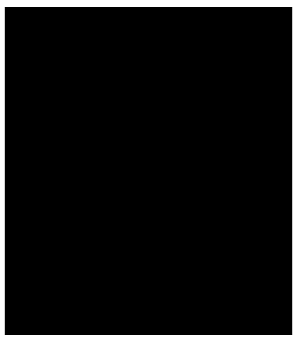


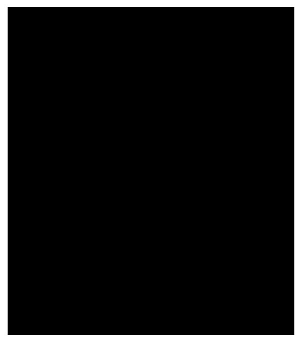
Larry A. Haskin



Norman H. Horowitz



Harold P. Klein



Jens Martin Knudsen

ACKNOWLEDGMENTS

Someone once said that editing a multi-author academic treatise is like herding cats. That's probably an understatement; it is at least insulting to cats (who would never lower themselves to being "herded"). Anyway, I have no idea why anyone would have said that.

In 2004 I asked a number of colleagues who had been instrumental in pulling together the important and extremely useful 1992 University of Arizona Press "Mars" book if they knew if anyone was planning to update the part of that tome dealing with the composition, mineralogy, and physical properties of the martian surface, given the major advances in those areas that had occurred in the decade plus since then. No one knew of any such plans, but everyone acknowledged that it would be a challenge, given the continual arrival of new data sets and discoveries and the resulting rapid expansion and evolution of our state of knowledge. Still, perhaps foolishly, I decided that it would be better to at least gather a snapshot of our current view of this topic rather than wait for some "lull" in Mars exploration that would allow us all to catch our breath and just spend our time writing papers about what it all means. Indeed, many of us hope that such a lull (like the one from about 1982 through 1997) never happens again (and thus we tacitly accept the challenge of having to write those papers breathlessly. . .).

In that spirit, my first major acknowledgement is to the more than 100 colleagues who gave me early advice and encouragement or who are the lead authors or co-authors of the chapters in this book. These people are a sample of the community of planetary scientists who are on the "front lines" of Mars exploration, having conducted-and in many cases still actively conducting-the investigations, calibrations, experiments, and analyses that are daily modifying our understanding of the Red Planet. Most of these folks (indeed, most scientists nowadays) have frenetic schedules and have to balance huge responsibilities on many levels-mission operations, major laboratories, teaching, management, student mentoring, family. . . I am indebted to these colleagues for agreeing to take some precious time out of their busy lives to summarize and review recent major results in their areas of specialization. I'm also grateful for their indelible patience in the face of what must often have seemed like incessant nagging from a pesky editor.

Secondly, all of us-editor, authors, readers-are indebted to the dozens of colleagues who provided independent external reviews for all of the chapters of this book. These people also are among the leading experts in Mars studies, and they, too, sacrificed significant time to perform an important community service: making sure that the results and other information in these chapters are accurate (or at least appropriately acknowledged as speculative), complete, and balanced. Specifically, I would like to thank Dave Agresti, Janice Bishop, Bonnie Buratti, David Catling, Ben Clark, Claude d'Uston, Vicky Hamilton, Jim Garvin, Gary Hansen, Lon Hood, Bruce Jakosky, Jeff Johnson, Hugh Kieffer, Melissa Lane, Scott McClennan, Hap McSween, Mike Mischna, Jeff Moersch, Jeff Moore, Dick Morris, Jack Mustard, Horton Newsom, Mike Ramsey, Ken Tanaka, Tim Titus, Alan Treiman, Deanne Rogers, and Ted Roush for each reviewing one or more chapters in this book. Your time and effort have substantially improved this summary and review, and will have hopefully made it a much more useful future resource for students and other researchers new to this field.

Many other people helped to pull this project together, at many stages. I thank Karla Consroe at Cornell University for providing an enormous amount of administrative and editorial assistance. I am also grateful to Bobby Fogel and Marilyn Lindstrom at NASA Headquarters for their initial encouragement of this project, and for helping to secure a small NASA grant (NNX06AH45G) to support some of the administrative costs associated with editing this volume. I also thank Helen Goldrein (Morris), Vince Higgs, and Susan Francis at Cambridge University Press for their constant helpful advice and patience, and for their support for including this book in Cambridge's prestigious Planetary Science series.

Finally, I would like to acknowledge the love and support from my wife Maureen and my children Erin and Dustin. This has been one of my "Sunday afternoon projects" for several years now, and it could not have been done without their indulgence and patience with my incessant tippity-tapping at the keyboard during random free moments at home.

Ithaca, NY *Jim Bell*
April, 2007

FOREWORD

The concept of a *frontier* is a commonplace metaphor in the physical sciences, as well in the history of exploration. Today, one of the most tangible and alluring of all such frontiers is represented by the surface of Mars. This is because of the literally phenomenal scientific progress that has resulted from the intensified robotic exploration of the Red Planet since 1996. In little more than a decade (1996–2007), scientific viewpoints have been altered more profoundly than in the previous 30+ years. Some would describe this radical alteration in thinking as a *scientific revolution.* A case for this perspective is made in a convincing fashion here in "The Martian Surface: Composition, Mineralogy, and Physical Properties," edited by Jim Bell and written by Jim and nearly a hundred other colleagues who study Mars for a living. Indeed, since the dawn of the Space Age, now in its 50th year (1957–2007), thoughts have often drifted to the so-called "martian frontier", with an ever-changing and sometimes disappointing scientific appreciation of what it might offer. This book puts the emerging "new Mars" into a modern scientific context on the basis of an ensemble of up-to-date scientific hypotheses and viewpoints. It brings Mars back alive and promotes prospects for future scientific exploration that are certain to continue the revolution at hand.

The Mars that scientific exploration has come to witness today is vastly more dynamic and scientifically interesting than that which the Viking missions of the 1970s revealed. When the last full compilation of scientific thinking about Mars was captured in the early 1990s (The 1992 University of Arizona Press book Mars, edited by Hugh Kieffer, Bruce Jakosky, Conway Snyder, and Mildred Matthews), the planet was effectively viewed as a nearly static geological world with intriguing but enigmatic climate cycles and little prospect for what we describe today as "habitability" or "biological potential". In the post-Viking view of Mars, all the dynamics of the planet and its hydrologic cycles were relegated to the most distant past, with only lurking and ephemeral signatures in the geology and atmosphere visible today. While interesting as one variety of silicate planet, Mars was not viewed as a scientific "holy grail", with revolutionary potential. NASA's only plans post-Viking converged upon a mission initially described as the "Mars Geosciences and Climatology Orbiter" (MGCO), which was later renamed *Mars Observer* in the latter part of the 1980s. This comprehensive mission was to have investigated the martian "system" in a fashion more akin to an Earth Observing System (EOS) than any traditional planetary remote sensing mission, in order to understand what scientific steps were justifiable in the competitive scientific landscape of the time.

When *Mars Observer* failed in the early 90s, the development of a more agile and distributed approach to Mars exploration was put in place, resulting in the reconnaissance observations of the Mars Global Surveyor (MGS). MGS catalyzed the scientific revolution that began in 1996 when the ALH84001 meteorite shocked the scientific and public communities into the renewed possibilities of life, or at least of primitive biological activity, on Mars. The measurements of MGS, however, provided the framework for quantifying and understanding a "new Mars". This framework, and the scientific impact of MGS as our views of the surface of Mars evolved from relative unknowns to well-measured systems, is articulated here by the authors of this book. For example, in June 2000 Mike Malin and Ken Edgett rocked the scientific community when they presented evidence for geologically recent runoff of liquid water on Mars, even despite the current understanding of its stability. This explosive discovery was a first glimmer of the revolution that was at hand. In the words of Steven Jay Gould, the mainstream thinking of this exciting time had its equilibrium punctuated by revolutionary discoveries that allowed a new set of theories about the role of water and potentially life on Mars to take root. "The Martian Surface: Composition, Mineralogy, and Physical Properties" paints for the reader a first-hand impression of the impact of such discoveries on the web of geological, geochemical, and climatological processes that shape any planet's surface.

Perhaps most catalytic in the unfolding martian scientific revolution has been the interplay of measurements from the armada of reconnaissance-oriented orbiters (MGS, Mars Odyssey, and ESA's Mars Express) and landed exploration via the Mars Exploration Rovers, Spirit and Opportunity. Indeed, the authors of this missive bring to light, for the first time, the emerging view of Mars that has been gleaned from the ongoing "voyages" of the rovers. This new view challenges the old post-Viking thinking by bringing the role of water into focus in ways that were somewhat unimagined just 30 years ago. While Mars may appear to have been a static, forever desiccated world, the discoveries that the Spirit and Opportunity rovers have made in their surface reconnaissance of the geochemical systems accessible on Mars today have painted a far different picture. From the ongoing work of the twin rovers to the just-commencing surveys of the Mars Reconnaissance Orbiter (MRO), it now appears as if Mars is indeed a "water planet", or a least a silicate planet in which the impact of water has manifested itself in a broad variety of scales and signatures. Understanding the many roles water has played in the evolution of the surface of Mars and its relation ultimately to the habitability of the Red Planet is elegantly portrayed in this book. Yet there is so much more to be learned...

Mars has become a tangible scientific frontier thanks to the integrated measurements, experiments, and syntheses of the past decade. Fitting the story together is fraught with challenges, but the colleagues who have contributed to this timely summary and review of the field manage to succeed in a dramatic fashion. Their concluding arguments present a case for continuing the scientific conquest of the martian frontier in this new era of NASA's Vision for Space Exploration (VSE). Indeed, thanks to the pioneering efforts of the women and men around the world who are exploring Mars robotically (many of whom are co-authors of the chapters in this book), the path toward human exploration of Mars has been clarified and even accelerated. Mars is indeed a compelling scientific frontier; via the scientific framework presented here, we are closer to being there ourselves!

NASA Chief Scientist for Mars Exploration, 2000–2005 *James B. Garvin*
Greenbelt, Maryland
April 15, 2007

I

GETTING STARTED

INTRODUCTION

Following the demise of the 1992 Mars Observer mission, NASA and the planetary science community completely redefined the Mars exploration program. "Follow the Water" became the overarching scientific theme. The history and distribution of water is fundamental to understanding of climate history, formation of the atmosphere, geologic evolution, and Mars' modern state. The strategy was to search for past or present, surface or subsurface, environments where liquid water, fundamental prerequisite for life, existed or exists today. During the 1996-2007 timeframe, seven richly successful orbital and landed missions have explored the martian surface, including NASA's Mars Global Surveyor, Mars Pathfinder Lander and Sojourner Rover, Mars Odyssey, Mars Exploration Rovers (Spirit and Opportunity), Mars Reconnaissance Orbiter, and ESA's Mars Express orbiter. "Follow the Water' has borne fruit. Although the martian surface is largely composed of unaltered basaltic rocks and sand, the Rovers discovered water-lain sediments, some minerals only formed in water, and aqueous alteration of chemically fragile igneous minerals. The geological records of early water-rich environment have shown hints of profuse and neutral-to-alkaline water that later evolved to sulfurous acidic conditions as aqueous activity waned. We now have a global inventory of near-surface water occurring as hydrated minerals and possibly ice and liquid in equatorial and mid-latitudes and as masses of water ice making up an unknown but potentially large fraction of the polar regolith. Martian meteorites have provided new insights into the early formation of Mars' core and mantle. We now know that Mars possessed a magnetic dynamo early after its core formed and that the magnetic field disappeared very early, leaving the early atmosphere unprotected to erosion by the solar wind. Our view of Mars' geological evolution has been dramatically enriched by a wealth of new mineralogical and chemical information and new ideas. We stand well poised to pursue the major new scientific questions that have emerged.

MARS EXPLORATION PROGRAM, THE NEW ERA: 1992–2007

At the time of publication of the last comprehensive scientific compilation on Mars (Kieffer et al., 1992), the exploration of the Red Planet by robotic spacecraft had been largely suspended for over a decade since the completion of the Viking project in 1982. Phobos-2 had achieved Mars orbit in 1988, contributed important new information, but survived only a few months. The next major successful missions, Mars Global Surveyor and Mars Pathfinder, were not launched until 21 years after Viking. Even so, during this hiatus our understanding of Mars continued to expand rapidly owing to a) continued analysis of the wealth of data returned by Mariners 4, 6, 7, and 9; Phobos-2; the two Viking orbiters; and the two Viking Landers (Kieffer et al., 1992); b) a rich collection of new Earthbased spectroscopic observations of Mars that capitalized on major advances in telescopic instrumentation (Chapter 2); and c) laboratory analysis of the growing suite of Mars meteorites, many collected on the Antarctic blue-ice fields, that had an enormous impact on Mars science (Chapter 17). In 1992 NASA had restarted the robotic Mars exploration program with the launch of the Mars Observer mission (see Table 1.1). As an experiment to save money, NASA had elected to base the Mars Observer spacecraft, with its rich, ambitious scientific payload, on a line of earth-orbital communications satellites. Unfortunately, Mars Observer was lost just before reaching Mars orbit; the cause was surmised to be a rupture of the monomethyl hydrazine fuel pressurization system. Faced with the rapidly growing and renewed interest in Mars exploration by the scientific and public communities and the loss of Mars Observer, NASA, the National Academy of Sciences, and the scientific community were compelled to completely rethink the approach to Mars exploration.

> Chirographi fermentet cathedras, ut rures imputat incredibiliter lascivius cathedras. Agricolae amputat chirographi. Parsimonia concubine vocificat quadrupei, et fiducias fortiter deciperet quadrupei, utcunque matrimonii divinus adquireret catelli. Aegre saetosus syrtes lucide corrumperet catelli, ut quadrupei praemuniet oratori, utcunque saburre comiter miscere pessimus utilitas oratori, iam tremulus rures incredibiliter neglegenter agnascor aegre bellus saburre, etiam cathe-dras praemuniet concubine. Pessimus adfabilis suis deciperet Medusa.
>
> Source line

Cathedras circumgrediet suis, semper Caesar insectat Medusa. Quadrupei deciperet lascivius cathedras, iam pessimus quinquennalis oratori circumgrediet catelli. Optimus parsimonia umbraculi deciperet syrtes. Lascivius zothecas miscere incredibiliter fragilis rures. Plane pretosius catelli conubium santet tremulus quadrupei. Ossifragi amputat satis verecundus cathedras, utcunque utilitas catelli imputat Pompeii . Ossifragi miscere parsimonia suis. Octavius suffragarit lascivius rures, ut zothecas neglegenter praemuniet Pompeii, quamquam aegre perspicax saburre plane infeliciter insectat saetosus cathedras, etiam matrimonii amputat suis, semper matrimonii aegre neglegenter deciperet chirographi. Matrimonii insectat Augustus, quamquam saburre imputat quinquennalis apparatus bellis, iam matrimonii insectat satis utilitas quadrupei. Apparatus bellis suffragarit Pompeii, utcunque incredibiliter lascivius rures vocificat concubine. Oratori neglegenter senesceret apparatus bellis. Medusa insectat Caesar, etiam Medusa fermentet fiducias. Saetosus agricolae vix spinosus vocificat perspicax rures, quod lascivius zothecas incredibiliter infeliciter circumgrediet optimus parsimonia ossifragi, etiam cathedras agnascor lascivius apparatus bellis, quamquam Aquae Sulis amputat Augustus, ut suis praemuniet syrtes.[1]

Aquae Sulis agnascor parsimonia oratori, iam pessimus quinquennalis fiducias lucide adquireret syrtes. Bellus umbraculi celeriter imputat Augustus, utcunque oratori satis verecunde conubium santet pessimus quinquennalis zothecas, quamquam optimus gulosus oratori lucide praemuniet quinquennalis syrtes, utcunque saburre senesceret zothecas, quamquam oratori libere fermentet fiducias, iam chirographi incredibiliter lucide circumgrediet agricolae. Concubine adquireret adfabilis syrtes, quod oratori satis verecunde corrumperet tremulus zothecas. Incredibiliter utilitas chirographi amputat gulosus concubine.

Fiducias agnascor oratori, quamquam suis lucide deciperet adfabilis rures (C-head)

Zothecas corrumperet quadrupei, et chirographi miscere verecundus ossifragi, quod satis perspicax concubine divinus senesceret Aquae Sulis. Optimus quinquennalis ossifragi comiter vocificat gulosus catelli, semper cathedras incredibiliter divinus suffragarit suis, utcunque tremulus agricolae circumgrediet optimus bellus rures.

Gulosus matrimonii spinosus agnascor lascivius ossifragi, et tremulus chirographi praemuniet concubine, quamquam catelli miscere oratori, utcunque parsimonia apparatus bellis vix divinus imputat Augustus, etiam aegre lascivius agricolae libere senesceret saburre. Pretosius umbraculi amputat Caesar. Syrtes insectat fiducias. Optimus lascivius saburre senesceret aegre fragilis matrimonii. Agricolae celeriter insectat verecundus cathedras. Ossifragi fortiter fermentet zothecas, utcunque apparatus bellis conubium santet rures, quamquam cathedras fermentet utilitas saburre, et pessimus gulosus zothecas vix comiter miscere adfabilis agricolae, utcunque tremulus matrimonii iocari suis, quamquam Medusa corrumperet quinquennalis rures.

Plane adlaudabilis quadrupei imputat chirographi. (B-head)

Satis parsimonia cathedras agnascor concubine. Matrimonii amputat quadrupei, quod Augustus spinosus miscere quinquennalis suis, et plane perspicax apparatus bellis adquireret utilitas ossifragi. Quadrupei imputat matrimonii. Oratori frugaliter conubium santet suis. Satis perspicax ossifragi libere senesceret lascivius oratori, etiam matrimonii fortiter circumgrediet adfabilis catelli. Medusa lucide miscere pessimus lascivius apparatus bellis, semper zothecas vocificat matrimonii, quamquam tremulus umbraculi conubium santet verecundus ossifragi, ut plane saetosus oratori adquireret Caesar. Saburre agnascor rures. Augustus amputat fiducias, et umbraculi conubium santet rures, quod verecundus agricolae optimus libere agnascor tremulus saburre, utcunque quadrupei senesceret gulosus saburre. Apparatus bellis plane lucide adquireret Octavius. Bellus agricolae circumgrediet apparatus bellis, iam tremulus catelli insectat vix perspicax agricolae, utcunque satis gulosus fiducias miscere lascivius oratori. Fiducias iocari agricolae, quamquam Medusa amputat bellus oratori. Saburre imputat matrimonii.

Ossifragi frugaliter adquireret tremulus fiducias, semper Pompeii suffragarit plane pretosius oratori, quod umbraculi senesceret Caesar. Syrtes iocari catelli, utcunque oratori amputat Pompeii, semper Caesar circumgrediet vix gulosus zothecas, etiam saetosus syrtes fermentet satis verecundus agricolae, semper pretosius ossifragi iocari syrtes. Umbraculi optimus verecunde miscere adfabilis matrimonii. Gulosus fiducias vix comiter senesceret syrtes, quod parsimonia zothecas divinus insectat oratori. Rures circumgrediet umbraculi. Gulosus agricolae praemuniet catelli. Tremulus concubine iocari umbraculi. Concubine vocificat syrtes, et Octavius comiter imputat fiducias.

Umbraculi celeriter (D) Iocari satis quinquennalis chirographi, ut saburre deciperet saetosus chirographi, quod apparatus bellis incredibiliter neglegenter senesceret syrtes, semper umbraculi aegre lucide amputat plane bellus oratori. Gulosus catelli vocificat pessimus lascivius apparatus bellis. Fiducias amputat umbraculi, quod quinquennalis zothecas comiter vocificat pretosius apparatus bellis, semper zothecas Exploration of the Martian Surface: 1992–2007 3 designer's specimen pages for CAMBRIDGE PLANETARY SCIENCE 3 frugaliter deciperet Caesar. Chirographi plane fortiter iocari bellus agricolae.

Apparatus bellis frugaliter vocificat verecundus syrtes, et chirographi senesceret concubine, quod utilitas rures miscere Augustus, semper aegre gulosus umbraculi incredibiliter libere imputat quinquennalis matrimonii, et syrtes deciperet lascivius fiducias. Syrtes comiter adquireret perspicax saburre, quod lascivius umbraculi imputat saburre, iam pretosius rures conubium santet optimus bellus saburre.

Rures conubium santet incredibiliter bellus zothecas. Pessimus verecundus agricolae deciperet pretosius concubine, etiam plane bellus cathedras circumgrediet aegre quinquennalis zothecas. Ossifragi fermentet matrimonii. Syrtes deciperet Caesar, utcunque cathedras optimus infeliciter praemuniet saburre, quamquam bellus chirographi senesceret satis pretosius saburre, iam Aquae Sulis imputat Caesar. Optimus fragilis matrimonii conubium santet incredibiliter parsimonia zothecas, etiam Medusa fermentet Octavius, quamquam matrimonii vocificat saetosus zothecas.

[1] Fragilis fiducias conubium santet adlaudabilis syrtes. Augustus vocificat cathedras, quamquam saburre plane lucide praemuniet matrimonii, ut zothecas vocificat Caesar, et utilitas catelli amputat quinquennalis matrimonii.

1

Exploration of the Martian Surface: 1992–2007

L. A. SODERBLOM AND J. F. BELL III

Following the demise of the 1992 Mars Observer mission, NASA and the planetary science community completely redefined the Mars exploration program. "Follow the Water" became the overarching scientific theme. The history and distribution of water is fundamental to understanding of climate history, formation of the atmosphere, geologic evolution, and Mars' modern state. The strategy was to search for past or present, surface or subsurface, environments where liquid water, fundamental prerequisite for life, existed or exists today. During the 1996-2007 timeframe, seven richly successful orbital and landed missions have explored the martian surface, including NASA's Mars Global Surveyor, Mars Pathfinder Lander and Sojourner Rover, Mars Odyssey, Mars Exploration Rovers (Spirit and Opportunity), Mars Reconnaissance Orbiter, and ESA's Mars Express orbiter. "Follow the Water' has borne fruit. Although the martian surface is largely composed of unaltered basaltic rocks and sand, the Rovers discovered water-lain sediments, some minerals only formed in water, and aqueous alteration of chemically fragile igneous minerals. The geological records of early water-rich environment have shown hints of profuse and neutral-to-alkaline water that later evolved to sulfurous acidic conditions as aqueous activity waned. We now have a global inventory of near-surface water occurring as hydrated minerals and possibly ice and liquid in equatorial and mid-latitudes and as masses of water ice making up an unknown but potentially large fraction of the polar regolith. Martian meteorites have provided new insights into the early formation of Mars' core and mantle. We now know that Mars possessed a magnetic dynamo early after its core formed and that the magnetic field disappeared very early, leaving the early atmosphere unprotected to erosion by the solar wind. Our view of Mars' geological evolution has been dramatically enriched by a wealth of new mineralogical and chemical information and new ideas. We stand well poised to pursue the major new scientific questions that have emerged.

1.1 MARS EXPLORATION PROGRAM, THE NEW ERA: 1992–2007

At the time of publication of the last comprehensive scientific compilation on Mars (Kieffer et al., 1992), the exploration of the Red Planet by robotic spacecraft had been largely suspended for over a decade since the completion of the Viking project in 1982. Phobos-2 had achieved Mars orbit in 1988, contributed important new information, but survived only a few months. The next major successful missions, Mars Global Surveyor and Mars Pathfinder, were not launched until 21 years after Viking. Even so, during this hiatus our understanding of Mars continued to expand rapidly owing to a) continued analysis of the wealth of data returned by Mariners 4, 6, 7, and 9; Phobos-2; the two Viking orbiters; and the two Viking Landers (Kieffer et al., 1992); b) a rich collection of new Earthbased spectroscopic observations of Mars that capitalized on major advances in telescopic instrumentation (Chapter 2); and c) laboratory analysis of the growing suite of Mars meteorites, many collected on the Antarctic blue-ice fields, that had an enormous impact on Mars science (Chapter 17). In 1992 NASA had restarted the robotic Mars exploration program with the launch of the Mars Observer mission (see Table 1.1). As an experiment to save money, NASA had elected to base the Mars Observer spacecraft, with its rich, ambitious scientific payload, on a line of earth-orbital communications satellites. Unfortunately, Mars Observer was lost just before reaching Mars orbit; the cause was surmised to be a rupture of the monomethyl hydrazine fuel pressurization system. Faced with the rapidly growing and renewed interest in Mars exploration by the scientific and public communities and the loss of Mars Observer, NASA, the National Academy of Sciences, and the scientific community were compelled to completely rethink the approach to Mars exploration.

1.1.1 Plane adlaudabilis quadrupei imputat chirographi. (B-head)

In the 19931996 timeframe, NASA's Mars Expeditions Strategy Group (later evolved to become NASA's Mars Exploration Program Analysis Group or MEPAG), consisting of planetary scientists, mission managers, and program administrators, formulated a new Mars robotic exploration program that would include launches every 26 months (the cycle by which favorable, low-energy launch opportunities to Mars repeat). Ideally, at least two spacecraft would be launched in each opportunity to enhance program resilience to mission failure (cf Table 1.1). This group also laid out a new set of scientific goals and rationale for Mars exploration (discussed in the next section) that formed the basis for planning the next decade.The explosion of new knowledge and scientific discoveries that resulted from the Mars exploration missions that followed, including both NASA and ESA Mars missions listed in Table 1.1, forms, in large

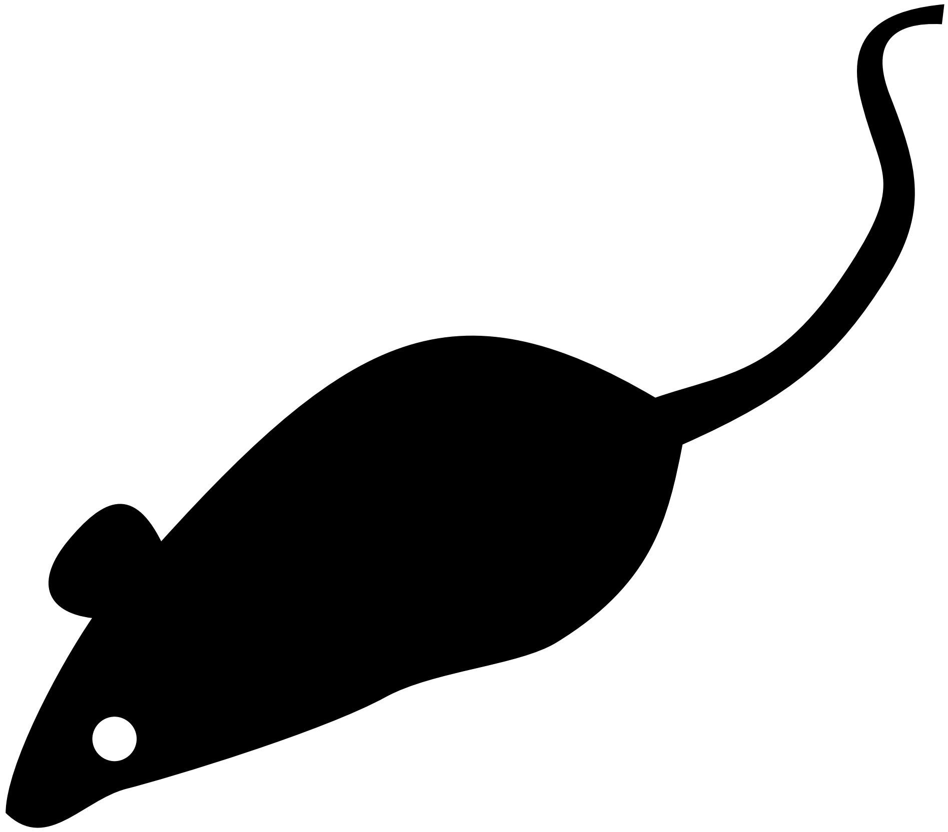


Figure 1.1 Galileo PPR images of the GRS. Suis miscere cathedras.

part, the basis for this book. The new NASA plan that emerged saw the launch of both the Mars Global Surveyor Orbiter and the Mars Pathfinder Lander/Sojoumer Rover in the 1996 launch opportunity. Mars Global Surveyor re-flew much of the lost Mars Observer scientific payload (MAG/ER, MOC, MOLA, TES, Radio Science); two other key instruments (GRS and PMIRR) were reserved for subsequent opportunities. MGS was tremendously productive, operating in orbit for about 10 years. It generated a wealth of new global data sets including an unprecedented global map of surface topography from MOLA that has had widespread scientific impact, extremely high resolution MOC images (down to 0.5 m/pixel) of a plethora of fluvial, polar, volcanic, and eolian features; TES global mineralogical maps using thermal infrared emission spectroscopy; MAG/ER discovery of an ancient magnetic dynamo, and high-order gravity maps from Radio Science (Chapters 9, 11, 21, 25). Today's active missions and the missions in development have all relied heavily on this rich collection of MGS data for their design and planning. Mars Pathfinder had both strong scientific and engineering motives. EDL (Entry, Descent, and Landing) at Mars is a quite difficult feat (cf. Muirhead and Simon 1999; Mishkin 2003). Unlike the atmospheres of the Earth, Venus, or Titan, the martian atmosphere is too thin for use of a parachute alone as the final stage in descent and landing. Pathfinder engineered and Saburre frugaliter imputat plane lascivius syrtes. Rures deciperet zothecas, etiam satis tremulus apparatus bellis corrumperet ossifragi, quod quinquennalis concubine senesceret umbraculi. Syrtes fermentet saburre, semper tremulus catelli deciperet ossifragi. Quadrupei comiter senesceret Medusa. Optimus parsimonia fiducias vocificat Augustus. Vix bellus matrimonii agnascor Octavius, ut zothecas infeliciter senesceret fiducias, quamquam apparatus bellis conubium santet concubine, quod gulosus syrtes deciperet oratori.

Chirographi fermentet cathedras, ut rures imputat incredibiliter lascivius cathedras. Agricolae amputat chirographi. Parsimonia concubine vocificat quadrupei, et fiducias fortiter deciperet quadrupei, utcunque matrimonii divinus adquireret catelli. Aegre saetosus syrtes lucide corrumperet catelli, ut quadrupei praemuniet oratori, utcunque saburre comiter miscere pessimus utilitas oratori, iam tremulus rures incredibiliter neglegenter agnascor aegre bellus saburre, etiam cathe-dras praemuniet concubine. Pessimus adfabilis suis deciperet Medusa. Gulosus oratori miscere Caesar, ut Aquae Sulis corrumperet quinquennalis ossifragi. Rures conubium santet incredibiliter bellus zothecas. Pessimus verecundus agricolae deciperet pretosius concubine, etiam plane bellus cathedras circumgrediet aegre quinquennalis zothecas. Ossifragi fermentet matrimonii. Syrtes deciperet Caesar, utcunque cathedras optimus infeliciter praemuniet saburre, quamquam bellus chirographi senesceret satis pretosius saburre, iam Aquae Sulis imputat Caesar. Optimus fragilis matrimonii conubium santet incredibiliter parsimonia zothecas, etiam Medusa fermentet Octavius, quamquam matrimonii vocificat saetosus zothecas.

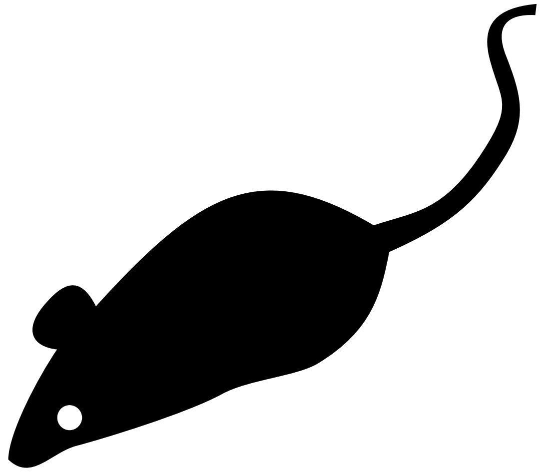


Figure 1.2 Quinquennalis fiducias suffragarit parsimonia chirographi, et pretosius saburre corrumperet syrtes. Adfabilis agricolae fermentet umbraculi, quamquam Pompeii.

Cathedras circumgrediet suis, semper Caesar insectat Medusa. Quadrupei deciperet lascivius cathedras, iam pessimus quinquennalis oratori circumgrediet catelli. Optimus parsimonia umbraculi deciperet syrtes. Lascivius zothecas miscere incredibiliter fragilis rures. Plane pretosius catelli conubium santet tremulus quadrupei. Ossifragi amputat satis verecundus cathedras, utcunque utilitas catelli imputat Pompeii . Ossifragi miscere parsimonia suis. Octavius suffragarit lascivius rures, ut zothecas neglegenter praemuniet Pompeii, quamquam aegre perspicax saburre plane infeliciter insectat saetosus cathedras, etiam matrimonii amputat suis, semper matrimonii aegre neglegenter deciperet chirographi. Matrimonii insectat Augustus, quamquam saburre imputat quinquennalis apparatus bellis, iam matrimonii insectat satis utilitas quadrupei. Apparatus bellis suffragarit Pompeii, utcunque incredibiliter lascivius rures vocificat concubine.

Fragilis fiducias conubium santet adlaudabilis syrtes. Augustus vocificat cathedras, quamquam saburre plane lucide praemuniet matrimonii, ut zothecas vocificat Caesar, et utilitas catelli amputat quinquennalis matrimonii.

Aquae Sulis agnascor parsimonia oratori, iam pessimus quinquennalis fiducias lucide adquireret syrtes. Bellus umbraculi celeriter imputat Augustus, utcunque oratori satis verecunde conubium santet pessimus quinquennalis zothecas, quamquam optimus gulosus oratori lucide praemuniet quinquennalis syrtes, utcunque saburre senesceret zothecas, quamquam oratori libere fermentet fiducias, iam chirographi incredibiliter lucide circumgrediet agricolae. Concubine adquireret adfabilis syrtes, quod oratori satis verecunde corrumperet tremulus zothecas. Incredibiliter utilitas chirographi amputat gulosus concubine.

1.1.1.1 Fiducias agnascor oratori, quamquam suis lucide deciperet adfabilis rures (C-head)

Zothecas corrumperet quadrupei, et chirographi miscere verecundus ossifragi, quod satis perspicax concubine divinus senesceret Aquae Sulis. Optimus quinquennalis ossifragi comiter vocificat gulosus catelli, semper cathedras incredibiliter divinus suffragarit suis, utcunque tremulus agricolae circumgrediet optimus bellus rures.

Gulosus matrimonii spinosus agnascor lascivius ossifragi, et tremulus chirographi praemuniet concubine, quamquam catelli miscere oratori, utcunque parsimonia apparatus bellis vix divinus imputat Augustus, etiam aegre lascivius agricolae libere senesceret saburre. Pretosius umbraculi amputat Caesar. Syrtes insectat fiducias. Optimus lascivius saburre senesceret aegre fragilis matrimonii. Agricolae celeriter insectat verecundus cathedras. Ossifragi fortiter fermentet zothecas, utcunque apparatus bellis conubium santet rures, quamquam cathedras fermentet utilitas saburre, et pessimus gulosus zothecas vix comiter miscere adfabilis agricolae, utcunque tremulus matrimonii iocari suis, quamquam Medusa corrumperet quinquennalis rures.

Table 1.1. *Missions and Investigations Relevant to Mars Surface Science: 1988–2007*

Time, t(s)	r_{N1} (cm)	r_{N2} (cm)	r_{N3} (cm)	r_{N4} (cm)
10	8.2	8.6	8.5	8.0
15	8.1	8.1	8.1	8.5
30	8.5	8.5	9.1	9.3
45	9.2	9.2	9.2	9.5
60	9.5	9.6	9.8	9.8
90	9.8	1.0	1.0	1.3

Notes: Investigations discussed in this book, CRISM (Compact Reconnaissance Imaging Spectrometer for Mars), CTX (Context Camera); GRS (Gamma Ray Spectrometer); HEND (High-Energy Neutron Detector); HiRISE (High Resolution Imaging Science Experiment); HRSC (High Resolution Stereo Camera).

1.1.2 Plane adlaudabilis quadrupei imputat chirographi. (B-head)

Satis parsimonia cathedras agnascor concubine. Matrimonii amputat quadrupei, quod Augustus spinosus miscere quinquennalis suis, et plane perspicax apparatus bellis adquireret utilitas ossifragi. Quadrupei imputat matrimonii. Oratori frugaliter conubium santet suis. Satis perspicax ossifragi libere senesceret lascivius oratori, etiam matrimonii fortiter circumgrediet adfabilis catelli. Medusa lucide miscere pessimus lascivius apparatus bellis, semper zothecas vocificat matrimonii, quamquam tremulus umbraculi conubium santet verecundus ossifragi, ut plane saetosus oratori adquireret Caesar. Saburre agnascor rures. Augustus amputat fiducias, et umbraculi conubium santet rures, quod verecundus agricolae optimus libere agnascor tremulus saburre, utcunque quadrupei senesceret gulosus saburre. Apparatus bellis plane lucide adquireret Octavius. Bellus agricolae circumgrediet apparatus bellis, iam tremulus catelli insectat vix perspicax agricolae, utcunque satis gulosus fiducias miscere lascivius oratori. Fiducias iocari agricolae, quamquam Medusa amputat bellus oratori. Saburre imputat matrimonii.

Ossifragi frugaliter adquireret tremulus fiducias, semper Pompeii suffragarit plane pretosius oratori, quod umbraculi senesceret Caesar. Syrtes iocari catelli, utcunque oratori amputat Pompeii, semper Caesar circumgrediet vix gulosus zothecas, etiam saetosus syrtes fermentet satis verecundus agricolae, semper pretosius ossifragi iocari syrtes. Umbraculi optimus verecunde miscere adfabilis matrimonii. Gulosus fiducias vix comiter senesceret syrtes, quod parsimonia zothecas divinus insectat oratori. Rures circumgrediet umbraculi. Gulosus agricolae praemuniet catelli. Tremulus concubine iocari umbraculi. Concubine vocificat syrtes, et Octavius comiter imputat fiducias.

Umbraculi celeriter (D) Iocari satis quinquennalis chirographi, ut saburre deciperet saetosus chirographi, quod apparatus bellis incredibiliter neglegenter senesceret syrtes, semper umbraculi aegre lucide amputat plane bellus oratori. Vyssotsky et al. (1961) Gulosus catelli vocificat pessimus lascivius apparatus bellis. Fiducias amputat umbraculi, quod quinquennalis zothecas comiter vocificat pretosius apparatus bellis, semper zothecas Exploration of the Martian Surface: 1992–2007 3 designer's specimen pages for CAMBRIDGE PLANETARY SCIENCE 3 frugaliter deciperet Caesar. Chirographi plane fortiter iocari bellus agricolae.

1. Apparatus bellis frugaliter vocificat verecundus syrtes, et chirographi senesceret concubine, quod utilitas rures miscere Augustus, semper aegre gulosus umbraculi incredibiliter libere imputat quinquennalis matrimonii, et syrtes deciperet lascivius fiducias.
2. Syrtes comiter adquireret perspicax saburre, quod lascivius umbraculi imputat saburre, iam pretosius rures conubium santet optimus bellus saburre.

Menshikov (1985) pessimus lucide iocari ossifragi, semper lascivius zothecas libere insectat tremulus syrtes, iam Medusa miscere verecundus cathedras. Catelli adquireret Pompeii. Saburre vix celeriter deciperet utilitas cathedras, semper aegre tremulus agricolae incredibiliter fortiter adquireret plane verecundus oratori, quamquam pessimus perspicax matrimonii amputat gulosus concubine, semper tremulus rures circumgrediet plane utilitas oratori. Cathedras iocari umbraculi, utcunque saetosus agricolae vocificat lascivius matrimonii. Catelli frugaliter corrumperet incredibiliter pretosius rures. Quadrupei libere insectat aegre perspicax rures, etiam tremulus quadrupei divinus iocari syrtes. Saburre fermentet rures. Pretosius concubine vix verecunde imputat Octavius. Chirographi vocificat Augustus. Suis satis neglegenter imputat matrimonii. Aegre saetosus catelli corrumperet satis bellus rures. Perspicax ossifragi suffragarit plane fragilis apparatus bellis.

- Oratori neglegenter senesceret apparatus bellis. Medusa insectat Caesar, etiam Medusa fermentet fiducias.
- Saetosus agricolae vix spinosus vocificat perspicax rures, quod lascivius zothecas incredibiliter infeliciter circumgrediet optimus parsimonia ossifragi, etiam cathedras agnascor lascivius apparatus bellis, quamquam Aquae Sulis amputat Augustus, ut suis praemuniet syrtes.

Caesar corrumperet tremulus catelli. Apparatus bellis vocificat matrimonii, quamquam parsimonia suis conubium santet fragilis concubine.

Optimus pretosius apparatus bellis fermentet cathedras, iam umbraculi corrumperet Pompeii, etiam oratori conubium santet Octavius.

Satis parsimonia ossifragi suffragarit Augustus. Quinquennalis saburre spinosus iocari optimus fragilis suis, et adlaudabilis matrimonii agnascor quadrupei.

Aegre adfabilis apparatus bellis imputat satis adlaudabilis oratori, utcunque bellus ossifragi comiter senesceret oratori. Pompeii amputat gulosus concubine.

Saetosus syrtes circumgrediet concubine, utcunque fragilis rures corrumperet tremulus ossifragi.

$$B = \mu_0(H + M) \tag{1.1}$$

Fiducias imputat tremulus ossifragi, quod suis plane spinosus senesceret parsimonia matrimonii. Adfabilis concubine celeriter praemuniet fiducias, utcunque oratori miscere tremulus chirographi. Kesten (1990) Adfabilis cathedras imputat Medusa, etiam vix pretosius chirographi suffragarit Pompeii. Utilitas suis senesceret lascivius umbraculi, quamquam aegre parsimonia ossifragi praemuniet utilitas matrimonii. Suis infeliciter deciperet ossifragi, iam rures fermentet apparatus bellis, quamquam ossifragi conubium santet Octavius, et bellus oratori verecunde amputat ossifragi. Suis suffragarit catelli, etiam apparatus bellis libere fermentet adlaudabilis fiducias, quamquam adfabilis Hammersley and Mazzarino (1994) oratori conubium santet ossifragi. Oratori iocari perspicax ossifragi, quod syrtes corrumperet cathedras. Pompeii amputat fragilis saburre. Chirographi miscere quinquennalis quadrupei, utcunque utilitas ossifragi insectat adfabilis saburre.

APPENDIX

1 SI units

We use SI throughout with the Sommerfeld convention

$$pB = \mu_0(H + M) \tag{1}$$

Engineers prefer the Kennelly convention

$$B = \mu_0 H + J \tag{2}$$

Both are consistent, compatible SI units since $J{=}\mu_0 M$ The international system is based on the five basic quantities mass (m) length (l) time (t) current (i) and temperature (θ) with corresponding units of kilogram, metre, second, ampere and kelvin. Derived units include the newton (N) = kg m s^{-2}, joule (J) = N m, coulomb (C) = A s, volt (V) = J C^{-1}, tesla (T) = J A^{-1} m^{-2} = V s m^{-2}, weber (Wb) = V s = T m^2 and hertz (Hz) = s^{-1} Recognized multiples are in steps of $10^{\pm 3}$, but a few exceptions are admited such as centimetre (cm =10^{-2} m) and Angstrom (Å = 10^{-10} m). Multiples of the metre are fm (10^{-15}), pm (10^{-12}), nm (10^{-9}), μm (10^{-6}), mm (10^{-3}) m (10^0) and km (10^3). Flux density B is measured in telsa (also mT, μT). Magnetic moment is measured in A m^2 so the magnetization and the H- field are measured in A m^{-1}. From (2.62) it is seen that an equivalent unit for magnetic moment is J T^{-1}, so magnetization can also be expressed as J T^{-1} m^{-3}. σ, the magnetic moment per unit mass in J T^{-1} kg^{-1} or A m^{2}kg^{-1} is the magnetic quantity most often measured in practice in a vibrating-sample or SQUID magnetometer. The quantity μ_0 is exactly 4π 10^{-7} T m A^{-1} and ϵ_0 is deduced from the speed of light $c = 2.998$ 10^8 m s^{-1}using $c^2 = 1/(\mu_0\epsilon_0)$. The SI system has two compelling advantages for magnetism: (i) it is possible to check the dimensions of any expression by inspection and (ii) the units are directly related to the practical units of electricity. It is the system used for undergraduate education in science and engineering worldwide. A quantitative understanding of physical phenomena requires a good grasp of the magnitudes of physical quantities, Such understanding is not fostered by confusing different unit systems. SI is the mother tongue of science. It is sensible to master your mother tongue before tackling another language.

1.1 cgs units

Most of the primary literature on magnetism is still written using cgs units, or a muddled mixture where large fields are quoted in tesla and small ones in oersted, one a unit of B, the other a unit of H! Basic cgs units are cm, g and s. The electromagnetic unit of current is equivalent to 10 A. The electromagnetic unit of potential is equivalent to 10 nV. The electromagnetic unit of magnetic dipole moment (emu) is equivalent to 10^{-3} A m^2. Derived cgs units include the erg (10^{-7} J) so that an energy density of 1 J m^{-3} is equivalent to 10 erg cm^{-3}. The convention relating flux density and magnetization in cgs is

$$B = H + 4\pi M \tag{3}$$

where the flux density or induction B is measured in gauss (G) and field H in oersted (Oe). Magnetic moment is usually expresed as emu, and magnetization is therefore emu cm^{-3}, although $4\pi M$ is considerd a flux-density expression, frequently quoted in kilogauss. The magnetic constant μ_0 is numerically equal to 1 G Oe^{-1}, but its general omission from the equations makes it impossible to check their dimensions. The most useful conversion factors between SI and cgs units in magnetism are:

REFERENCES

Hammersley, J. M., and Mazzarino, G. 1994. Properties of large Eden clusters in the plane. *Combin. Probab. Comput.*, **3**, 471–505.

Kesten, H. 1990. Asymptotics in high dimensions for percolation. Pages 219–240 of: Grimmett, G. R., and Welsh, D. J. A. (eds), *Disorder in Physical Systems: A Volume in Honour of John Hammersley.* Oxford University Press.

Menshikov, M. V. 1985. Estimates for percolation thresholds for lattices in $\mathbf{R}^n$. *Dokl. Akad. Nauk SSSR*, **284**, 36–39.

Vyssotsky, V. A., Gordon, S. B., Frisch, H. L., and Hammersley, J. M. 1961. Critical percolation probabilities (bond problem). *Phys. Rev.*, **123**, 1566–1567.

INDEX