LUNAR sourcebook

a user's guide to the moon

edited by Grant H. Heiken, David T. Vaniman, and Bevan M. French

foreword by Harrison H. Schmitt

The *Lunar Sourcebook,* a concisely presented collection of data gathered during the American and Soviet missions, is an accessible and complete one-volume reference encyclopedia of current scientific and technical information about the Moon. This book provides a thorough introduction to lunar studies and a summary of current information about the nature of the lunar environment. It explores the formation and evolution of the Moon's surface, the chemical and mineralogical nature of lunar rocks and soils, and the current state of scientific knowledge about the nature, origin, and history of the Moon.

The book is written and edited by scientists active in every field of lunar research, all of whom are veterans of the Apollo program. The contributors are from universities, national laboratories, industry, and NASA.

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LUNAR SOURCEBOOK

A User's Guide to the Moon

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To those who have been there —
And to those who will return.

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FOREWORD

Humankind sought and attained greatness with the first field explorations of the Moon between 1966 and 1976. Apollo spacecraft and the various automated probes launched by the U.S. and the U.S.S.R., which successfully collected samples and information from the Moon during this period, pushed the species along its first clear steps of evolution into the solar system and eventually into the galaxy. A sense of reality began to surround a lesson taught to the Pueblo Indians by their ancestors: "We walk on the Earth, but we live in the sky."

Early explorers of the sky took their eyes and minds into space and became the eyes and minds of billions of other explorers on the starship Earth. They also began the long process of transplanting civilization into space. This fundamental change in the course of history has occurred as humans have also gained new insight into themselves and their first planetary home. With the conclusion of the Apollo 17 mission and the Apollo program in December 1972, humankind had reached the "end of the beginning" of its movement into the universe.

Human evolution into the universe began with the 1968 Christmas Eve mission of Apollo 8. The presence of Frank Borman, Jim Lovell, and Bill Anders in orbit around the Moon, and the words and pictures they shared with us, gave human beings a new awareness not only of the Moon but of the Earth's own place as a lonesome, lovely, and potentially fragile life-bearing planet in the black void of space. Hundreds of millions of human beings throughout the world simultaneously thought new thoughts about a familiar object in the night sky—the Moon. The men of Apollo 8 were there, and the Moon would never be the same for anyone.

Now we should realize that the Earth will also never be the same. Through new communication, information, and space technologies, solutions can be found to the age-old problems of the human condition on Earth—ignorance, poverty, hunger, and disease. Opportunities have been created to realize the more modem dream of living permanently in space. Such solutions and opportunities exist, however, only *if* we are wise enough to reach out and grasp them.

President George Bush's statement on the occasion of the 20th anniversary of Apollo 11's landing on the Moon provides a vision of human beings as a perpetual spacefaring species. The President's words implied a commitment to protect the Earth, settle the solar system, and move toward the stars.

The Moon's proximity to the Earth, lack of atmosphere, gravity (only one-sixth that of the Earth), planetary position as the smallest of the terrestrial planets, and potential resources almost certainly assure a role for lunar activities in support of human exploration and utilization of space.

Proximity, one-sixth gravity, and potential resources essential to sustaining human life require that the Moon be considered as both a stepping stone toward Mars and the outer planets and a low-cost supply depot for exploration and settlement. Its planetary characteristics and lack of atmosphere justify the continued use of the Moon as a natural laboratory for comparative planetology and for solar and stellar astronomy.

In the context of these possibilities, as well as in even more general terms, *Lunar Sourcebook* provides an extremely important and heretofore unavailable first reference for those who may consider a return to the Moon for whatever purpose. The information compiled within and the guide to other data provided distills and, in one sense, immortalizes the dedication, imagination, and extraordinary hard work of hundreds of managers, scientists, engineers, and their supporters. Now others can begin to move forward to plan, in President Bush's words, a " . . . return to the Moon, this time to stay . . ."

One can only vaguely imagine the ultimate legacy of the data from Apollo, the automated probes, and Earth-based observation through which *Lunar Sourcebook* guides its reader. The more easily conceived possibilities include permanent and self-sustaining settlements on the Moon, serving solar and stellar observatories and far-ranging lunar surface expeditions; lunar engineering and training sites supporting the development of Mars exploration and settlement; huge solar collector arrays on the Moon producing the energy needed to support lunar activities as well as for potential export to Earth and to stations in space; underground mines in stratified mineral deposits within the mare that provide raw materials to space equipment manufacturing facilities on the Moon or in lunar orbit; and great farms that produce the food required by increasing numbers of men and women living in space, on the Moon, and on Mars.

Perhaps most critically, one can imagine large mobile processing plants, periodically stepping their way across the lunar maria, mining, extracting, and processing solar-wind gases from the regolith, to provide the life-sustaining consumables (H_2, O_2, H_2O, CO_2, NO_X, and ^4He) required by a spacefaring species. From solar-wind materials implanted in the lunar regolith, we may also extract the environmentally benign fusion fuel ^3He, which can be used on Earth to sustain civilization as well as protect the biosphere.

On behalf of those privileged few who helped gather the samples, collect field information, and deploy the experiments that provided the data upon which much of this book draws, I wish to thank the editors and their contributor team for stepping once more into the breach. They have added great new value to the lunar exploration community's efforts. Unless what has been learned as a consequence of our activities becomes accessible, we, like the tree falling in the forest, have made no sound for those not present to hear. *Lunar Sourcebook* not only brings many individual sounds together into the beginnings of a symphony, but it serves waiting and appreciative new generations of composers and audiences.

Harrison H. Schmitt, Apollo 17 astronaut
Albuquerque, New Mexico
September 20, 1990

EDITORS' PREFACE AND ACKNOWLEDGMENTS

Lunar Sourcebook is intended for the post-Apollo generation of scientists, engineers, teachers, and students. It has two purposes. First, it summarizes what we know about the Moon as a result of U.S. and U.S.S.R. lunar missions and the continuing analysis of lunar samples and data here on Earth. Second, it provides a convenient, accessible sourcebook for planning the future study of the Moon and the eventual use of the Moon by spacefaring humans.

This book began in 1984, and we were at the active manuscript-editing stage on July 20, 1989, when President George Bush marked the 20th anniversary of the Apollo 11 landing by initiating what is now called the Space Exploration Initiative (or sometimes the Moon-Mars initiative), a program for the return of humans to the Moon, followed by human exploration of the planet Mars. We hope that *Lunar Sourcebook* will be a timely response to the renewed scientific and exploration interest in our nearest planetary neighbor, the only other world so far explored in person by human beings. We also hope that the book will help in our return to the Moon, and in the intelligent use of the Moon when we establish a permanent presence there.

The task of putting everything we know about the whole Moon into a single book is far more difficult now than it was before the Apollo program. Before Apollo, only a few people were needed to summarize the available information about the Moon, and they could (and did) produce books from their own knowledge. The Apollo and Luna programs, with their intensive close-up studies and the return of samples to Earth, have produced an explosion in lunar knowledge. The available scientific information about the Moon is now scattered throughout many books and thousands of articles in journals from a wide range of scientific disciplines: astronomy, geosciences, nuclear chemistry, space physics, materials science, life sciences, and engineering, to name just a few.

In this post-Apollo age, assembling *Lunar Sourcebook* would have been impossible without help from many different people. We owe the most to our scientist-authors for sifting the immense amount of knowledge in each field, organizing it, and then patiently enduring multiple syntheses, continuing editorial changes, extensive rewriting, and doubts that their work would ever see daylight on a printed page.

The editorial and production staff at the Lunar and Planetary Institute (LPI) in Houston, Texas, worked hard and patiently—literally for years—to turn an overwhelming amount of manuscript pages and disorganized art work into an attractive and readable text. Renee Dotson, as technical editor at the LPI, suffered (with remarkable equanimity) through enough versions of this book to fill her bookshelves. The excellent illustration work by Donna Jalufka, Pam Thompson, Shirley Brune, and others at the LPI, with special notice of the herculean effort and dedication of Steve Hokanson, resulted in a set of polished figures that were often compiled from crude sketches and all too often forced through time-consuming revisions. We also thank our editors at Cambridge University Press in New York, Peter-John Leone and Nancy Seltzer, for their faith in the whole project and their patience with an unexpectedly long process.

The support of NASA, through contract NASW-4066 to the Lunar and Planetary Institute, was critical to this work, and we are particularly grateful for the patience and steady encouragement of Dr. William L. Quaide, Chief Scientist for the Solar System Exploration Division.

At Los Alamos, the continued moral support by Wayne Morris, Wes Myers, and P. W. Keaton made it possible for us to carry through the editing process over many years; Marcia Jones and Barbara Hahn contributed to the word processing when we could not keep up. We also owe a great deal to our families, who gave up countless weekends and evenings for the book. Finally, we especially thank Mary-Hill French for intense and meticulous proofreading, with an uncanny knack for finding errors that had eluded us.

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UNITS AND ABBREVIATIONS*

Unit	Abbreviation	Unit	Abbreviation
absolute permeability	K	Kelvin	K
activation energy	E	kilobar	kbar
angstrom	Å	kilocalorie	kcal
antenna gain	G	kiloelectron volt	keV
ampere	A	kilogram	kg
astronomical unit (1.496×10^8 km)	A.U.	kilohertz	kHz
atomic mass unit	amu	kilometer	km
billion years	b.y.	kilopascal	kPa
bulk density	ρ	kilowatts electric	kWe
centimeter	cm	kurtosis (statistical)	K_G
coefficient of lateral stress	K_o	loss tangent	tan δ
cohesion	c	magnetic field strength	A/m, γ
Cole-Cole frequency distribution		mean (statistical)	$\bar{x}$, M_Z
parameter	α	median (statistical)	Md
compression index	C_c	megaelectron volt	MeV
conductance (1/ohm)	mho	meter	m
conductivity	σ	metric ton (tonne)	t
cone penetration resistance	q	microgram	μg
degree Celsius	°C	micrometer	μm
degree of polarization	P	milligal	mgal
density of water	ρ_w	milligram	mg
depth into regolith (cm)	z	millimeter	mm
equivalent surface area ratio	ESAR	million years	m.y.
electron volt	eV	millisecond	msec
factor of safety	F.S.	milliwatt	mW
ferromagnetic resonance intensity	I_s	minutes	min
flow rate	Q	mole	mol
Fresnel reflection coefficient	ρ	mole percent	mol.%
friction angle	ϕ (degrees)	nanogram	ng
galactic cosmic ray	GCR	nanometer	nm
gamma (10^{-5} oersted)	γ	normal stress	σ
geometrical albedo	p	newton	N
gigaelectron volt	GeV	nucleon	u
gram	g	parts per billion by weight	ng/g
gross pull per wheel (N)	H	parts per million by weight	μg/g
Hertz	Hz	parts per thousand	‰
horizontal stress	σ_h	Pascal	Pa
hour	hr	phase angle (optical)	g
initial relative density	D_{Ri}	phase integral (optical)	q
integrated mass depth	d_m	phi scale (grain size)	ϕ
joule	J	poise	p

* Note multiple uses of the symbols G, k, p, W, α, and σ. Units and abbreviations that are explicitly defined where they are used in the text are not listed here.

UNITS AND ABBREVIATIONS *(continued)*

Unit	Abbreviation	Unit	Abbreviation
porosity (in situ)	n	specific gravity	G
P-wave velocity	α	specific surface area	SSA
radar cross-section	σ	static allowable bearing capacity	q_{all}
received echo power (radar)	P_r	static ultimate bearing capacity	q_{ult}
recompression index	C_r	steradian	sr
relative density	D_R	subradar point	i
relative dielectric permittivity	k	torricelli	torr
seismic attenuation	Q	wavelength	γ
second	sec	wheel load (N)	W
shear strength	τ	vertical stress	σ_v
skewness (statistical)	SK, α_3	void ratio	e
soil compaction resistance		volume percent	vol.%
per wheel (N)	R_c	watt	W
solar cosmic ray	SCR	weight percent	wt.%
sorting (statistical)	σ	year	yr

LUNAR DATABASES AND ARCHIVES

Manned and unmanned missions to the Moon were responsible for an enormous volume of diverse data, ranging from measurements of the tenuous lunar magnetic field to sample analyses. Most of these data and reports are available to researchers, at the cost of transferring the information or images.

Lunar and Planetary Institute (LPI). The best place to begin your search for lunar data is the Lunar and Planetary Institute, 3303 NASA Road 1, Houston, Texas 77058-4399. The LPI was established by NASA as the Lunar Science Institute in 1969 and is managed by the Universities Space Research Association. The Center for Information and Research Services (CIRS) contains lunar and planetary photographs, maps, reports, and lunar sample information. CIRS also maintains a lunar and planetary bibliography and a literature collection to support the bibliography. The LPI Geophysical Data Facility has a selection of Moon datasets.

National Space Science Data Center (NSSDC). Documents, imagery, and geophysical data are available from the NSSDC. For U.S. investigators, the address is National Space Science Data Center, Code 601.4, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771. For researchers outside of the United States, the address is World Data Center A, Rockets and Satellites, Code 601, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771 USA. The database includes images, reports, and geophysical data from the Ranger, Surveyor, Lunar Orbiter, Apollo, Luna, and Zond Programs. A comprehensive catalog was published by W. S. Cameron, E. J. Mantel, and E. R Miller (1977) *Catalog of Lunar Mission Data,* NSSDC/WDC-A-RS Document #77-02, 204 pp.

National Technical Information Service (NTIS). For out-of-print reports, facsimile paper copies or microfiche can be ordered from NTIS, 5825 Port Royal Road, Springfield, Virginia 22152.

NASA Johnson Space Center History Office. Over 30,000 documents from the Apollo program have been saved as an archive for the purpose of historical studies by the History Office, NASA Johnson Space Center, Code BY4, 2101 NASA Road 1, Houston, Texas 77058-3696. The materials are arranged and described according to accepted archival practice and in a computer index. This office has also published excellent histories of the Apollo program [C. G. Brooks, J. Grimwood, and L Swenson Jr. (1979) *Chariots for Apollo: A History of Manned Lunar* Spacecraft NASA SP-4205, 553 pp.; W. D. Compton (1989) *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions,* NASA SP-4214, 415 pp.]

NASA Johnson Space Center Lunar Sample Curatorial Facility. To obtain lunar samples, a researcher must submit a request to the Lunar Sample Curator, Code SN2, NASA Johnson Space Center, Houston, Texas 77058-3696. This request will be reviewed by NASA's Lunar and Planetary Sample Team. Sample histories are also available from the Curator (see Appendix to Chapter 2).

Regional Planetary Image Facilities. The system of Regional Planetary Image Facilities (RPIF) represents a coordinated effort to provide easy access to planetary data products by scientists, students, educators, and the general public. Although each facility has different specific strengths, the close cooperation among RPIF members permits accessing materials without unnecessary trips to more distant centers. The RPIFs are not designed to provide hard-copy products for permanent retention, but are established to provide assistance in both locating the necessary data products and in accessing them through the NSSDC. RPIF facilities are located:

Arizona State University
Department of Geology
Tempe, Arizona 85287

Brown University
Box 1846
Department of Geological Sciences
Providence, Rhode Island 02912

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Ithaca, New York 14853

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*** Note added in proof: These addresses were current at the time of publication (1991). For an updated list of RPIFs, go to http://www.lpi.usra.edu/library/RPIF/index.shtml.**