ASTEROIDS
Astronomical and Geological Bodies

Asteroid science is a fundamental topic in planetary science and key to furthering our understanding of planetary formation and the evolution of the Solar System. Ground-based observations and missions have provided a wealth of new data in recent years, and forthcoming missions promise further exciting results. This accessible book presents a comprehensive introduction to asteroid science, summarizing the astronomical and geological characteristics of asteroids. The interdisciplinary nature of asteroid science is reflected in the broad range of topics covered, including asteroid and meteorite classification, chemical and physical properties of asteroids, observational techniques, cratering, the discovery of asteroids, and how they are named. Other chapters discuss past, present, and future space missions and the threat that these bodies pose for Earth. Based on an upper-level course on asteroids and meteorites taught by the author, this book is ideal for students, researchers, and professional scientists looking for an overview of asteroid science.

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ASTEROIDS

Astronomical and Geological Bodies

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Dedicated to the People Who Inspire Me Everyday

My Parents

Ahlay and Shahla Hussain

Adam Carolla and Drew Pinsky

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Frontmatter
More Information

Contents

Color plate section is between pages 166 and 167.

Preface

This time period may be the Golden Age of asteroid research. A mission (Dawn) has just mapped the third largest body [(4) Vesta] in the main asteroid belt and is currently mapping the largest [(1) Ceres]. Missions (e.g., Rosetta) routinely image asteroids on their voyages to their target bodies. The Hayabusa mission has returned fragments of an asteroid to Earth. Two asteroid missions (Hayabusa2 and OSIRIS-REx) have just been launched. Both will return samples from near-Earth asteroids back to Earth. Other asteroid missions are in development. News stories on asteroids seem to occur almost every week when these objects make a close approach to the Earth. A number of movies (*Deep Impact*, *Armageddon*, *Seeking a Friend for the End of the World*) have been made about objects potentially striking the Earth.

However, "asteroid" is not a term that is officially defined by the IAU (International Astronomical Union), the internationally recognized body for assigning designations to celestial objects. The IAU uses the term "small Solar System bodies," which refers to minor planets and comets that are not considered dwarf planets (like Pluto). However, scientists and the general public generally refer to small bodies (that are not comets) in the Solar System as asteroids. The word "asteroids" is derived from the Greek word *asteroeides* (star-like) due to their point-like appearance in the sky.

Why are asteroids so important to study? Richard Binzel often gives a talk entitled "Asteroids: Friends or Foes." Asteroids can be considered "friends" because these objects could potentially be mined for important resources such as platinum and palladium (Kargel, 1994) for Earth-based use or water and oxygen for space-based purposes. Asteroids also can be considered "foes" because an impacting body could potentially wipe out our civilization. This book will discuss all characteristics of asteroids to allow us to make our own decision on whether these bodies are "friends" or "foes." Or maybe they are both?

For the longest time (~170 years), asteroids were thought of as just astronomical objects that could only be seen as points of light in a telescope. Only their magnitudes (brightnesses) could be determined and their orbits calculated. Edmund Weiss (1837–1917), the Director of the Vienna Observatory, referred to these bodies as "those vermin of the sky" (Seares, 1930) because asteroid trails would ruin photographic images of "more important" astronomical objects.

Asteroids are now known to be geological bodies. Our impressions of asteroids started to first change to a geological point of view when spectrophotometry (and then spectroscopy) of these bodies in the visible and near-infrared began to become relatively easy to do in the 1970s. Reflected light from these bodies at a variety of wavelengths became relatively easy to measure. Many minerals have characteristic absorption bands in the same wavelength range, and the presence of these minerals could be identified on asteroid surfaces. These spectral observations of asteroids showed that these bodies have a wide variety of surface mineralogies and experienced a wide range of heating.

Starting in the 1990s, spacecraft images showed that asteroids were covered with geological features such as craters, grooves, scarps (cliffs), and boulders. In the 2000s, geochemical analyses of asteroids started to be done remotely by spacecraft, which allowed us to better understand the geological processes occurring on these bodies.

Concurrent with these spectroscopic and geochemical studies of asteroids were high-resolution laboratory analyses of fragments of asteroids (meteorites). Meteorites were found to range from those that melted (e.g., irons, stony-irons, achondrites) to those that experienced minimal heating (e.g., ordinary chondrites, carbonaceous chondrites, enstatite chondrites). Laboratory studies showed that there was a wide variety of geological and chemical processes that occurred during the formation and subsequent alteration of asteroids due to heating and shock events (impacts). Technological advances have led to very precise determinations of when these bodies formed and when different types of alteration occurred.

There also now appears to be a continuum of compositions between all types of small bodies (minor planets and comets) in the Solar System. The distinction between asteroids and comets has blurred in the last few years with some asteroids displaying cometary activity and some comets losing their activity and looking asteroid-like. Many volatile-rich objects have also been discovered past the orbit of Neptune. Because of these new discoveries, Pluto is now classified as a dwarf planet and has been given a minor planet number. All of these small Solar System bodies are thought to be the remnants of the planetesimals that did not form the terrestrial and giant planets at the beginning of our Solar System.

Objects labeled as asteroids will be the primary focus of this book. However because of this continuum between all small bodies, any object labeled as a small

Solar System body or dwarf planet will be discussed. The terms "asteroid" and "minor planet" will be used relatively interchangeably. Meteorites will also be discussed in detail since they are almost all fragments of asteroids.

This book is written as a textbook for an undergraduate class on asteroids or as a reference book for anybody wanting to learn more about small bodies. The content of this book most closely resembles *Introduction to Asteroids* (Cunningham, 1988), a book that covered all aspects of asteroid studies. However, that book was published long before the first spacecraft encounters with asteroids and is almost 30 years out of date. *Asteroids* (Gehrels, 1979), *Asteroids II* (Binzel et al., 1989), *Asteroids III* (Bottke et al., 2002), and *Asteroids IV* (Michel et al., 2015) from the University of Arizona Space Science Series are written more for a graduate-level audience with some previous knowledge of asteroids. A few other books have recently been published. However, *Asteroids: Relics of Ancient Time* (Shepard, 2015) was written for a general audience while *Asteroids, Meteorites, and Comets* (Elkins-Tanton, 2010) was written for a high school audience.

The problem with learning about asteroids is that a background in physics, mathematics, chemistry, geology, and astronomy is really necessary to understand topics specific to asteroids. This book will assume a college-level knowledge of these subjects. But the book is written to give as much introductory information as possible so more complicated topics can be understood.

References are given for topics that cannot be completely covered in this book. For example, sections in many chapters on subjects such as CCD detectors (Howell, 2006), orbits (Curtis, 2014), discovery of Ceres (Cunningham, 2016), meteorites (Hutchison, 2004; Grady et al., 2014), cosmochemistry (Lewis, 2004; McSween and Huss, 2010), isotope geology (Dickin, 2005), crystal field theory (Burns, 1993), radiative transfer modeling (Hapke, 2012b), light curves (Warner, 2006), comets (Swamy, 2010), and cratering (Melosh, 1989, 2011) are covered in much more detail in their own specialized books.

The focus of this book is to give enough background information so results from spacecraft missions to asteroids can be understood. Why were these targets chosen? How were these bodies named? What instruments have been used to study these bodies? How well can we link these bodies to particular meteorite groups? What can be learned from returned samples? Will the spacecraft results allow us to protect the Earth from potential impactors?

The first chapter of this book covers light and how it is detected, since all asteroids are observed using light. The second chapter covers orbits and asteroid discoveries, since all these bodies have different orbits and different designations. The third chapter covers meteorites, minerals, and isotopes, since fragments of asteroids (meteorites) are composed of minerals and contain both radioactive and stable isotopes. The first three chapters cover the three most basic characteristics of minor planets. We see these objects because they reflect or emit light, they all have distinct orbits around the Sun, and they are all composed primarily of minerals that can be studied on Earth using meteorites.

The remaining chapters expand on these basic characteristics to discuss how we study minor planets. The fourth chapter covers reflectance spectroscopy and asteroid taxonomy, since the mineralogies of asteroids are primarily determined by how they reflect light. The fifth chapter covers asteroid families and the physical properties (e.g., diameters, masses, densities, distributions) of asteroids. The sixth chapter primarily covers outer Solar System bodies such as comets, Trojan asteroids, and trans-Neptunian objects and the spacecraft missions to these bodies. The seventh chapter covers near-Earth asteroids, cratering, and the impact threat. The eighth chapter covers past, current, and future spacecraft missions to asteroids and how these missions help us understand the geological histories of these bodies.

Equations are written so that the units balance so as to make them more understandable to new researchers not previously familiar with the formulas. However, this means that the equations may be written in a slightly different way than how they are usually given. As much as possible, different symbols are used for different quantities.

At the end of each chapter, practice questions are given. These questions will reinforce topics that were learned from the chapter. The questions range from short answer to calculations.

The book was written for a 13-week class. The course should cover approximately a different chapter every week and a half. During the last few weeks of the class, the students should do short presentations on *Nature* or *Science* articles on minor planets, cratering, or meteorites to apply what they learned throughout the semester. Papers in these journals are chosen because these articles are relatively short and are usually very scientifically important discoveries.

The book is ambitious because it tries to cover as much as possible about asteroids. I always feel it is better to shoot for the Moon with any project than to keep both feet on the ground. I have tried to make it as understandable as possible to an audience unfamiliar with asteroids. I have learned so much writing this book and I hope the reader will too.

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Variables, Constants, and Unit Abbreviations

a	largest axis of triaxial ellipsoid
a	semi-major axis
A	Bond albedo
Å	angstrom
A_1	constant used for scattering function 1
A_2	constant used for scattering function 2
a_J	semi-major axis of Jupiter (5.2 AU)
a_p	proper semi-major axis
AU	astronomical unit
A_v	visual Bond albedo
b	constant in phase function
b	intermediate axis of triaxial ellipsoid
b	power law exponent
b	y-intercept
B_1	constant used for scattering function 1
B_2	constant used for scattering function 2
BAR	Band Area Ratio
$B(g)$	backscatter function
BI Center	Band I center
BII Center	Band II center
B_0	amplitude of opposition effect
$B(\lambda,T)$	Planck function for isotropically emitted radiation
$B_\lambda(\lambda,T)$	Planck function per unit solid angle
c	constant in phase function
c	number density of craters when the crater diameter is 1 km
c	smallest axis of triaxial ellipsoid
c	speed of light (3×10^8 m/s)

C	specific heat capacity
C_{i}	counts in the *i*th pixel
cm	centimeter
C_{sky}	average count in a background sky pixel
d	distance between two bodies
d	distance metric
D	diameter
d_1	distance of Body 1 to the Sun
d_2	distance of Body 2 to the Sun
d_{cut}	cutoff distance
dF_a	differential absorbed flux
dF_i	differential incident flux
D_{frag}	diameter of a sphere with a volume equivalent to all the fragments
D_i	number of atoms of a nonradiogenic stable isotope of the daughter atom
d_j	average effective particle size for mineral
D_{LM}	diameter of largest member
D_0	original amount of daughter atoms
D_{PB}	diameter of original parent body
dS	differential surface area
$D(t)$	amount of daughter atoms at time t
$\frac{dx}{dt}$	change in *x* divided by change in time
$\frac{dy}{dt}$	change in *y* divided by change in time
$\frac{dz}{dt}$	change in *z* divided by change in time
e	eccentricity
e	emission angle
E	energy
E_1	energy of body 1
E_2	energy of body 2
En	enstatite content
e_p	proper eccentricity
F	flux
$\mathrm{F_a}$	fayalite content
F_a	absorbed flux
f_B	background frequency
F_c	centripetal force

F_g	gravitational force
F_e	emitted flux
F_{ir}	infrared flux
Fo	forsterite content
F_{ref}	reference flux
Fs	ferrosilite content
f_{0,λ_i}	observed flux at a particular wavelength scaled to a phase angle of 0°
f_{λ_i}	observed flux at a particular wavelength
F_{λ_i}	theoretical flux at a particular wavelength
F_λ (object)	flux at a particular wavelength for an object
F_λ (star)	flux at a particular wavelength for a star
F_λ (Sun)	flux at a particular wavelength for the Sun
g	phase angle
G	gravitational constant (6.67384×10^{-11} m^3 kg^{-1} s^{-2})
G	slope parameter
Ga	billion years
$g(x)$	Gaussian distribution for variable x
h	Planck's constant (6.626×10^{-34} J s)
H	absolute magnitude
hr	hour
$H(x)$	Chandrasekhar H function
Hz	hertz
$H(\alpha)$	reduced visual magnitude at phase angle α
i	incident angle
i	inclination
i	counting variable
I	radiance
I	observed intensity
I_o	original intensity
i_p	proper inclination
j	counting variable
J	irradiance
J	joule
k	Boltzmann constant
k	extinction coefficient
K	kelvin
K	K filter
km	kilometer

kT	kiloton of TNT
m	meter
m	magnitude
m	mass
m	slope
M	mass
M	mean anomaly at epoch
m_1	mass of the primary body
m_1	magnitude of Body 1
m_2	mass of the secondary body
m_2	magnitude of Body 2
magnitude	measurement of brightness
m_{inst}	instrumental magnitude
M_j	mass fraction for each mineral
m_{ref}	reference magnitude
Ma	million years
mm	millimeter
MT	Megaton of TNT
n	mean motion
n	neutron
n	number
n	real part of the complex index of refraction
$\underline{n}$	complex index of refraction
$N_{cum}(\geq D)$	cumulative number of craters equal to or larger than a particular diameter
N_i	number of molecules for each molecular species
nm	nanometer
N_o	original amount of parent atoms
$N(t)$	number of parent atoms at time t
offset	arbitrary constant
ol	olivine content
opx	orthopyroxene content
p	geometric albedo
p	differential slope index
p	orbital period
p	proton
P	Palermo Scale value
P	power
P_A	absorbed power

P_E	extincted power
$p(g)$	single particle phase function
p_i	impact probability
P_S	scattered power
p_v	visual geometric albedo
pyx	pyroxene content
q	perihelion
q	phase integral
Q	aphelion
Q_A	absorption efficiency
QE	quantum efficiency
Q_E	extinction efficiency
Q_i	production rate for each molecular species
Q_S	scattering efficiency
r	distance
r	heliocentric distance in AU
r	orbital distance of the center of a moon to the center of the mass of the system
R	radius
R	reflectance
R_b	reflectance at band center
R_c	reflectance of the continuum at the band center wavelength
r_0	variable in Chandrasekhar H function
R_λ	reflectance at a particular wavelength
$r_\lambda(i,e,g)$	bidirectional reflectance
s	second
s	strength of band
S_0	solar constant (1366 W/m^2)
sr	steradian
t	time
T	orbital period
T	rotation period
T	temperature
$t_{1/2}$	half-life
T_J	Tisserand parameter with respect to Jupiter
T_{SS}	subsolar temperature
$T(\theta)$	surface temperature distribution versus angle
v	velocity
V	volume

V_b	bulk volume
v_e	escape velocity
V_g	grain volume
$V_{obs}(\alpha)$	observed visual magnitude at phase angle α
w	single scattering albedo
W	watt
Wo	wollastonite content
x	x position
y	y position
yrs	years
z	z position
α	absorption coefficient
α	phase angle
α	right ascension
β	mean phase coefficient
γ	variable in Chandrasekhar H function
Γ	thermal inertia
δ	declination
Δ	geocentric distance in AU
δa_p	change in proper semi-major axis
ΔE	change in energy
Δm	amplitude
Δt	change in time
$\Delta\lambda$	change in wavelength
$\delta^{17}O$	deviation in parts per thousand of ^{17}O
$\delta^{18}O$	deviation in parts per thousand of ^{18}O
$\Delta^{17}O$	offset from terrestrial fractionation line
ε	emissivity
η	beaming factor
θ	angle between the incident flux and the normal direction of the surface element
κ	thermal conductivity
λ	wavelength
λ_d	decay constant
λ_{EC}	electron capture decay constant for ^{40}Ar
λ_i	individual wavelength
λ_{max}	maximum wavelength
λ_0	original wavelength
λ_T	total decay constant for ^{40}K

λ_{87}	decay constant for ^{87}Rb
λ_{235}	decay constant for ^{235}U
λ_{238}	decay constant for ^{238}U
μ	center of the band in energy
μ	cosine of emission angle
μ	planetary discriminant
μ_0	cosine of incident angle
μm	micron
ν	frequency
π	pi
ρ	density
ρ_b	bulk density
ρ_g	grain density
ρ_j	single particle density for each mineral
σ	geometrical cross section
σ	standard deviation
σ	width of the band given as a standard deviation
σ	Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
σ_A	absorption cross section
σ_E	extinction cross section
σ_i	standard deviation of the *i*th measurement
σ_S	scattering cross section
τ_i	mean lifetime of the molecular species
$\Phi_1(\alpha)$	function 1 that describes scattering off a surface
$\Phi_2(\alpha)$	function 2 that describes scattering off a surface
υ	true anomaly
χ^2	chi-square value
ω	argument of periapsis
Ω	longitude of the ascending node
′	arcminute
″	arcsecond
°	degrees