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James A. Hall III

Moons of the Solar System

From Giant Ganymede to Dainty Dactyl

Springer

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This book is dedicated to all the people who
helped support me during my times of need;
Including my family and closest friends;
And to "the lovers, the dreamers and me."

Preface

Ever since the first thing that could be called "human" has first looked up at night, we have had a single eye-like orb looking back at us. However, it would take some of the greatest achievements of humankind to know what we now know about it. Hence Armstrong's famous line, "one small step for [a] man, one giant leap for mankind."

It was originally and long thought our moon was affixed to a sphere that orbited the Earth (which was naturally at the center of the universe). We now know that this is not true; current scientific thought dictates that the moon orbits the Earth, the Earth orbits the sun (Sol, by name), and that other natural objects orbiting the sun also have yet other natural objects orbiting them, under the catch-all title "satellites." Since our solar system has so many of these objects, one might want a book detailing a bit about them. Finding most such books incomplete or simply out-of-date, I found that I had to write my own book.

What Is a Moon, Anyway?

"Describe a moon." Sounds easy, doesn't it? (Fig. 1)

But some people may want a dictionary definition description, denotation only, for example, "a rock in space orbiting a planet." Others may be interested in the mythology and connotations, for example, "Pluto, named for the Roman god of the underworld, has a large moon, Charon, named for the boatman over the river Styx, which incidentally is the name of another of Pluto's moons." Others want a more elaborate description with data, for example, "the Saturnian, Gallic moon Erriapus has a mean argument of periapsis precession period of 219.9 years with a mean longitude of the ascending node precession period of 323.49 years." Here are the four elements this book prioritizes:

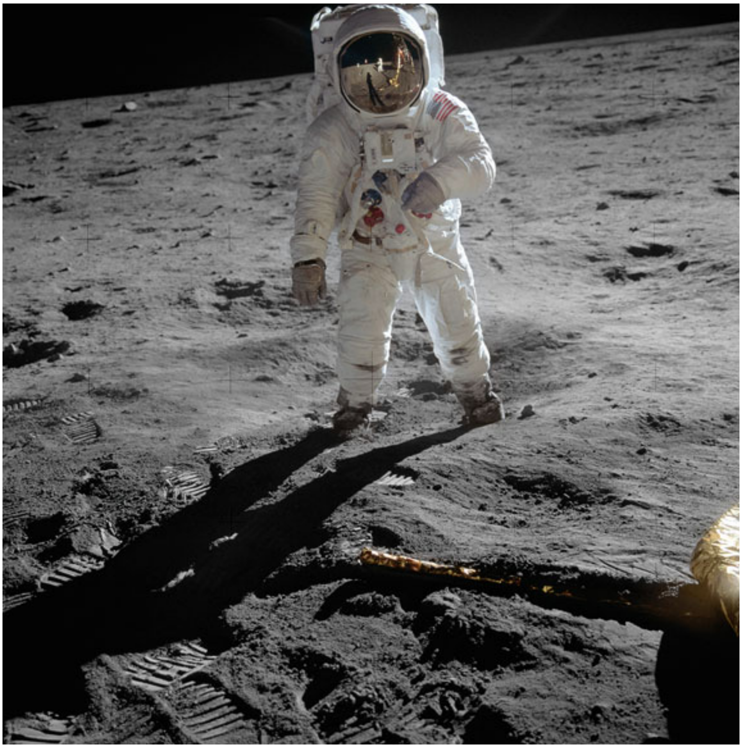

Fig. 1 Buzz Aldrin, Portrait Shot. In this picture, easily the most iconic of the space age, Edwin "Buzz" Aldrin, second man on the moon, poses for a photo op like none other, as Neil Armstrong, first man on the moon, takes his picture. In Buzz Aldrin's gold-colored visor the photographer, Armstrong, can be seen as well as the landing strut of the Eagle, the lander module of Apollo 6 (Credit: NASA)

1. Data. Pure, hard data, but about more commonplace things, such as distance, diameter, mass, and composition. Not about obscure items, such as the longitude of the ascending node, or argument of the periapsis.
2. Fresh, New Information. What do we know? And what don't we know?
3. Unusual Items. The extreme and superlative satellites are given extra attention due to what they can tell us about the behavior of the Solar System.
4. Pretty Pictures. Some of the objects within our little corner of the Galaxy are truly stunning and can be viewed in greater detail today than ever before.

What Data Is Included?

Data is ubiquitous online. Therefore I could omit that the eccentricity of Ganymede is 0.0013. But what if a reader wants to know that tidbit without going to JPL and/or NASA? Since no two people share identical interests, I tried to include a table that displays some (but not all) data in most cases. This covers the discoverer and the date of discovery, other names and designations used for the object, general orbital characteristics, physical characteristics, and atmospheric characteristics for major objects. For minor objects (such as Erriapus) less data if any will be included; 99 % of people have no clue what the argument of perihelion is or what the longitude of ascending node is, to say nothing of know-why it is important. For complete ephemeris data and information down to a dozen decimal places, JPL is really the best place to go. Only the most reliably known data is included in the book, or it is marked as unknown.

Spectral Classes

One important tool astronomers have is the spectrometer (with a telescope: spectroscope). Now, in case you do not know, a spectrometer is a tool designed to break apart light. When light from a moon or asteroid (specifically, reflected sunlight) is broken apart it creates a spectrum. Certain light types are not reflected—they are absorbed. These create absent lines in the spectra. This is called an absorption spectrum. (There are other types of spectroscopy, but these determine star properties, transiting exoplanet atmospheres, and other purposes beyond the scope of this work.) These spectra are then charted out (Figs. 2 and 3).

The dark lines in a spectroscope (like the above image of the spectrograph of our sun) are as unique as fingerprints. When what is being absorbed is known, then we can determine from that what elements are present and this gives us a clue to the moon's composition, or at least to the moon's surface composition. This can tell us about the possible origins (i.e., If XYZ has a spectrum a lot like Vesta, XYZ may be a captured asteroid of that family.)

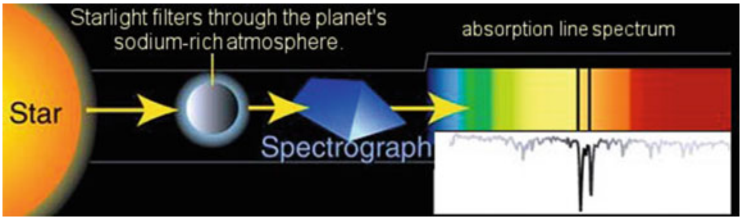

Fig. 2 Absorption spectroscope diagram (Credit: NASA/STSCI)

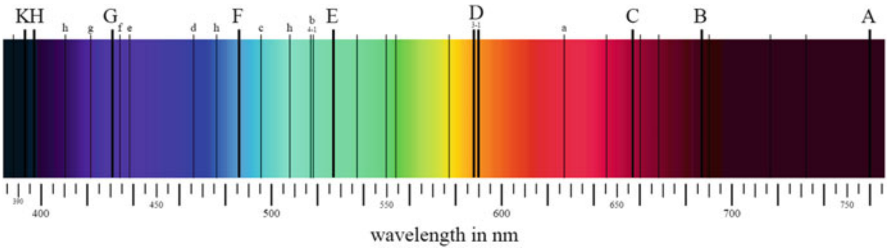

Fig. 3 Solar spectrum (Credit: Public Domain)

By using such spectroscopic techniques, we can also determine the composition of other moons (or at least their surface), by seeing what type of features shows up under spectroscopic analysis.

There are two main systems for classifying items. One is "Tholen" and the other is "SMASS."

Tholen

Tholen was defined by David J. Tholen in 1984. He designed this classification after analyzing 978 asteroids in the Eight Color Asteroid Survey (ECAS) from the 1980s. The measurements used for this survey were between 0.31 μm (microns or micrometers) and 1.06 μm.

The asteroids were then classified into 14 types (not including "U"), with three main groupings and a number of minor classes.

- C-group: These asteroids are dark (the albedo typically ranges from 0.03 up to 0.1) and carboniferous. These include the types B, C, F, and G. The C asteroids are similar to C meteorites (carbonaceous chondrites). There are few volatiles (such as hydrogen and helium), but are otherwise similar to the sun/solar nebula in composition. There are some water-containing (or hydrated) minerals. 324 Bamberga may be the most bright, but with its eccentric orbit it is hard to be certain (since it never gets close enough to Earth to get very bright). This class makes up about 75 % of all known asteroids. They absorb UV spectra in the range of 0.4–0.5 μm, but above that are mostly reddish. They also absorb light around 3 μm which indicates water.

- B-type: Similar to the C-type, however, the UV absorption below 0.5 μm is absent, and the spectrum is more bluish than reddish. Albedo is also higher. Surface minerals usually include anhydrous silicates, hydrated clay minerals, organic polymers, magnetite, and sulfides. 2 Pallas is the largest B-type asteroid.
- C-type: This is the textbook C-type, as above. It includes all C-group object types that are not B, F, or G-types. The largest is 10 Hygiea, although 1 Ceres could be a C-type asteroid (it could also be a G).
- F-type: These have spectra generally similar to those of the B-type asteroids, but the "water" absorption feature around 3 μm indicative of hydrated minerals is absent, and the ultraviolet spectrum feature is present, but below 0.4 μm. The largest is 704 Interamnia.
- G-type: Also similar to the C-type objects, but with a strong ultraviolet absorption feature below 0.5 μm. An absorption feature around 0.7 μm may also be present—this indicates phyllosilicate minerals such as clays or mica.

- S-group/type: A group and a type, these asteroids are bright (the albedo typically ranges from 0.1 up to 0.22) and siliceous. The S asteroids are similar to S meteorites (stony). The materials are mostly iron and magnesium silicates. 7 Iris is an S-type and unusually reflective, making it the second brightest of any asteroid (the brightest being 4 Vesta). They have a steep spectrum shorter than 0.7 μm and have a weak absorption feature around 1 and 2 μm. 1 μm indicates silicates. A broad shallow absorption feature at 0.63 μm is often present. 15 Eunomia and 3 Juno are both S-types.

- X-group: These asteroids are usually metallic. These include the types E, M, and P, but otherwise have little in common.
  - E-type: These asteroids have a high albedo and are siliceous. The albedos are typically at least 0.3. The S asteroids are similar to S meteorites (stony). The materials are mostly Enstatite ($MgSiO_3$) achondrites. They have a rather featureless, flat red spectrum. E-types are tiny—in fact only three are known to have diameter in excess of 50 km (44 Nysa, 55 Pandora, and 64 Angelina). The Hungaria asteroids are E-type (see Chap. 3)
  - M-type: These asteroids are not very bright; the albedo typically ranges from 0.1 up to 0.2. Some are nickel-iron and give rise to iron meteorites. Others have unknown compositions (such as 22 Kalliope). They have a rather flat red spectrum. Subtle absorption feature(s) longward of 0.75 μm and shortward of 0.55 μm are sometimes present. 16 Psyche is M-type.
  - P-type: These objects are very dark objects, with albedos not exceeding 0.1. They are similar in composition to a mix between the M-type and C-type. They are redder than S-types, and show no spectral features.
- Minor Classes: There are a number of classes that do not fit into the C, S of X group:
  - A-type: These have a strong, broad 1 μm feature that indicates Olivine feature (a common magnesium-iron silicate with the formula $(Mg^{2+}, Fe^{2+})_2SiO_4$) and a very reddish spectrum shortwards of 0.7 μm. Their origin is likely the completely differentiated mantle of an asteroid. These asteroids are rare. As of 2015, there are 17 asteroids known to be A-type, the largest of which is 246 Asporina.
  - D-type: These objects have a very low albedo and have a featureless reddish electromagnetic spectrum. The composition is a mixture between silicates, carbon, and anhydrous silicates. Water ice may also be common. 152 Atala and 944 Hidalgo are D-type; the Jupiter Trojan 624 Hektor (which we know has a moon) is the largest D-type asteroid known. Many Trojans may in fact be D-type.
  - Q-type: These are uncommon objects with strong, broad Olivine ($(Mg^{2+}, Fe^{2+})_2SiO_4$) and Pyroxene features (Pyroxene is

a mixture of |Ca, Na, Fe^{2+}, Mg, Zn, Mn, or Li||Cr, Al, Fe^{3+}, Mg, Mn, Sc, Ti, V, or Fe^{2+}|$(Si,Al)_2O_6$). (Olivine and Pyroxene together comprise most of the upper mantle of Earth—they are very common.) A steep slope indicates the presence of metal. There are absorption features shortwards and longwards of 0.7 μm. It is similar to S-types and V-types.

– R-type: These objects are moderately bright and relatively uncommon. They bridge the gap between A-type and V-types. There are Olivine and Pyroxene features at 1 and 2 μm. There is a possibility of Plagioclase as well (a feldspar of $NaAlSi_3O_8$ or $CaAl_2Si_2O_8$). Shortwards of 0.7 μm the spectrum is very reddish. 4 Vesta was the prototype R-type but it has been reclassified as a V-type, and indeed is now the prototype (and progenitor) of that class. 349 Dembowska is recognized as being type R when all wavelengths are taken into account.
– T-type: These are rare objects of unknown composition with dark, featureless and moderately red spectra. There is a moderate absorption feature shortwards of 0.85 μm. They may be related to D or P-types, or possibly a modified C-type. Samples are 96 Aegle, or 114 Kassandra.
– U-type: Miscellaneous (these items do not fit neatly into any category. U is almost universally assigned with another letter (see below).)
– V-type: These are moderately bright and similar to the more common S-type. These are stony irons and ordinary chondrites. These are rare and contain more Pyroxene than the S-type. The electromagnetic spectrum has a very strong absorption feature longward of 0.75 μm, another feature around 1 μm and is very red shortwards of 0.7 μm. 4 Vesta is the prototype.

Many items are a mixture of one or more of the above (i.e., 53 Kalypso is an "XC" with features of both, 273 Atropos is SCTU, and 343 Ostara is CSGU).

SMASS

SMASS is a newer system. SMASS was defined by Schelte J. Bus and Richard P. Binzel in 2002. They designed this classification after analyzing 1447 asteroids in the Small Main-belt Asteroid

Spectroscopic Survey (the eponymous SMASS). The measurements used for this survey were between 0.44 and 0.92 μm. This different range of measurements revealed different data, which tended to lead to different results. The resolution was also much greater. They also ignored albedo which was a major part of determining the Tholen type.

The asteroids were then classified into 26 types; however, the scientists did attempt to keep the Tholen classification as much as possible, so they appear similar.

- C-group:
  - B-type: Tholen B-types and F-types
  - C-type: Tholen C-types
  - Cg-types and Cgh-types: Tholen G-types
  - Ch-types: C-types with an absorption feature around 0.7 μm
  - Cb-types: Objects between SMASS C and B-types
- S-group:
  - A-type: Tholen A-types
  - K-type: These asteroids were "featureless S-types" under Tholen classification. These objects have a particularly shallow 1 μm absorption feature, and lack a 2 μm absorption. These were found during studies of the Eos family of asteroids.
  - L-type: These asteroids were "featureless S-types" under Tholen classification. These objects have a strong reddish spectrum shortwards of 0.75 μm, and are flat longward of this.

    Ld-type: See below
  - Q-type: Tholen Q-types
  - R-type: Tholen R-types
  - S-type: "typical" Tholen S-types
  - Sa, Sk, Sl, Sq, Sr-types: Transitional objects between S and their respective classes.
- X-group:
  - X-type: "typical" Tholen X-types
  - Xc, Xe, and Xk-types: Transitional objects between X and their respective classes.

- Other classes:
  - T-type: Tholen T-type
  - D-type: Tholen D-type
  - Ld-type: This group has an L-like flat spectrum longwards of 0.75 μm, but even redder in visible wavelengths. Tholen called these D-types usually but some were also listed as A-type (i.e., 728 Leonis)
  - O-type: This is best defined as having a spectrum similar to the unusual asteroid 3628 Boznemcová. Their spectra have a deep absorption feature longward of 0.75 μm. This definition is due to the fact that until just recently, only one such asteroid has the O-type—the aforementioned 3628 Boznemcová! Now, there are seven listed in the JPL database.
  - T-type: Tholen T-types
  - V-type: Tholen V-types

How Many Moons?

The question of how many moons are in our Solar System has undergone a lot of flux. As an example, Venus has no conventional moons, but has a co-orbital body and two smaller bodies (asteroids) related to its orbit. And while no book could really detail these three objects, due to the small amount known about them, no book even mentions them in passing. Just like no book mentions that 4 of the 5000+ Jupiter Trojans are known to have moonlets, or that there must be 1000 or more that have moonlets that we are unaware of.

According to one source published in 1958 (a book which also clearly shows that Pluto is considerable larger than Mercury, almost the size of Mars), there were 31 moons in the Solar System (and since Pluto was bigger than Mercury, I think we can understand why it showed no moons around Pluto). A later source in 1963, which was revised in 1977, showed there were 34 moons. According to a 1993 book there were 61 for the giant planets, plus 3 for the Earth and Mars and 1 for Pluto (still a planet in 1993). Moving ahead to 2006, it was 163 (with pluses after Jupiter and Saturn), including little Dactyl (which orbits an asteroid), and minus 1 since Pluto was not a planet any more, but an ice dwarf planet/trans-Neptunian object, and Charon's definition was fuzzy too. In 2011, it was 7 major, 8 medium, and 166 as a mix of minor and very minor (a four-part distinction which will be used extensively throughout the organization of the book.)

Now it is 2015, so it is time for a new count. When the book was completed, 164 moons could be found around planets, 8 around dwarf planets in the asteroid belt, 96 around smaller asteroids, 3 as Venus co-orbitals, with an additional 4 Jupiter Trojans, 51 Near-earth objects, 20 Mars-crossing objects, and 87 TNO satellites. There are also 150 or more "possible" satellites in Saturn's rings (few of which are included in this volume due to minimal information about said objects). But be forewarned, this information changes practically on a day-to-day basis. However, through using Information Clearing House wikis, an exhaustive list of reputable sites can be found. One such list is an exhaustive list of asteroids with moon, and while it would not be practical to call the any such Earth-made list complete, it is exhaustive of what is currently known, even as that knowledge is continually being revised.

Finally, this book tends to concentrate mainly on this solar system, since there is no positive information on any moons outside of it (even though it can be safely assumed they exist).

How to Use This Book

The first part of the book starts with an introduction of the subject, covering the planets and their moons in increasing distance from the sun. The chapters are organized by planet or regions, starting with Mercury and Venus and moving outward. Only asteroids that stay within the asteroid belt are covered in their own chapter. More are described by the planet(s) that they seem most tied to, so that Jupiter Trojans are dealt with in Chap. 5, and Venus' co-orbitals in the Chap. 1 (although few are covered in any detail). This initial listing talks briefly about the objects, and the number and type of moons known to exist around each planet. Each major moon is highlighted with some spotlight information and photos.

The more significant the moon, the more that is said about it. The "major" moons (diameters to exceed 2400 km) are covered extensively, all of the moderate moons (diameters in excess of 1000 km) are discussed in somewhat less detail, and while not covering every one of the myriad minor moons (some with diameter of only about a km), their families are mentioned, as well as listing all of the notable/family-less ones.

The last part of the book focuses on projects targeted on moons and satellites. Some of these anybody with time and either a four-function calculator or lots of paper and a pencil and some extra free time can do; some require observing equipment; some require a solid mathematical background; and some require a moderately advanced knowledge of physics, math, and "how things work." I tried to keep most of them simple, everyman projects.

Above all, remember when reading this book…

Enjoy it.

Crystal River, FL, USA James A. Hall III

Acknowledgments

I would like to thank the use of some ideas from GoldenBooks *Skyguide* which, even though it is a basic book, is most useful for many common and a few obscure star names, and constellation border lines.

I would also thank the use of the venerable *Burnham's Celestial Handbook* which is really a seminal work from which I got the idea of how to incorporate the tables. Even 30 years after its 1977 revision, and 50 years after its 1963 initial edition, it is still a useful guide (and it has even the most obscure star names if there are any records known to exist). Readers of that book (whether you read the whole 2138 pages, thumbed through it as needed, or read about two volumes of it finishing through Orion like I did) I hope you will find this book to be a comfortable return to the familiarity of quality data, even if it does go out of date.

I would also like to thank *The Star Guide* for some up-close maps of the moon when Google could not find the item I was looking for, *NightWatch*, well, because it is *NightWatch*! (And if you have this book, you know why I do not need to say more than that. I would be hard pressed to try…)

I would also like to thank my magazine, but they insist that I not use anything I found in the magazine, so obviously I cannot thank them. It would be rude to name them now, so this is the last mention of them.

I also wanted to include some comics here and there to add visual interest to dry chapters, but when I saw how much money they wanted—well, now I know why they are called "syndicates."

Notes on the Text

The terms asteroids and minor planets are used interchangeably, especially by JPL whose data is used extensively in this book.

If a minor planet's orbit enters the parent planet's orbit from inside, but does not cross the orbit, it is an **inner-grazer**. If a minor planet's orbit enters the parent planet's from outside without crossing, it is then an **outer-grazer**. If the minor planet's orbit causes it to cross the orbit, it is a <**planet**>**-crossing** asteroid/minor-planet. If a minor planet orbits in the same orbit as its planet (and may share a 1:1 orbital resonance), then it becomes a **near** <**planet**> **object**. If an object crosses multiple gas giant planet orbits, it is a **centaur**.

If the object is either 60° ahead of or behind its planet's orbit in the L_4 or L_5 Lagrangian point (2 of the 5 points where gravity of various objects balance and cancel each other out and where (an) object(s) can be in a stable/semi-stable position), then it is a **Trojan**.

The last category is **co-orbital satellites**, and **quasi-satellites**, a subclass. Co-orbital satellites share some of the same orbital characteristics of another object and a variety of these exist including satellites that are similar, satellites that swap characteristics (including possibly position), and so on. Co-orbitals also include quasi-satellites—co-orbitals that share an orbit with their planet and near the same area (i.e., close to 0°) even though most such objects are unstable (unless also highly eccentric). These are not discussed in many cases unless it is a bona fide moon like Janus and Epimetheus, two of Saturn's satellites which are co-orbital and which swap orbit every few years. (There is little that can be said about a quasi-satellite that is barely a kilometer in diameter, except that it exists, and it has unusual orbital properties.)

Since I don't intend for anyone to use this book to launch space probes nor do any other type of highly technical work with my data, I have had to make a judgment call about how accurate the data should be. Some of my source data has 16 decimal places! Rather than say that something has an inclination of 32.6773542378542° (or 32°40′38.4757627512″), I think that 32.68° (or 32°40′48″) is more than sufficient, and as you can see the introduced error is only about 10 arc seconds! In all cases, I aimed for practicability.

For numerals, the books uses **e notation** (which is similar to scientific notation and based on it). Many computer programs and calculators use e notation to denote large and small number. For instance, if someone wanted to tell a calculator or programming language 6.02×10^{23}, they would tell the calculator 6.02E23, 6.02E23, or 6.02e23. Spreadsheets often will use 6.02E+23. I will use "e". In all such cases it means "$\times 10^{e}$" (i.e., 6.02e23 is actually 602,000,000,000,000,000,000,000.)

Lastly, the number of moons and what we know about them changes continually and will continue to do so; this book is accurate as of its writing, but the terrain is always changing.

About the Author

James A. Hall III is a substitute teacher (specializing in middle and high schools) living in Central Florida. In addition to writing "The Moons of the Solar System" for Springer, he has also written freelance since the late 1990s. He has volunteered in libraries and he interned at MOSI, the Museum of Science and Industry, in Tampa, at the Saunders Planetarium, rewriting their planetarium shows. He desires to get a permanent position at a library, museum, or school media center.

He holds an AA in Liberal Arts from Central Florida Community College (now Central Florida College), a BA in English in Creative Writing (and a minor in Theater) from the University of South Florida, and earned his MA in Library and Information Sciences (MLIS), as well as a Graduate Certificate in Museum Studies.

He is the author of, and has self-published, two novels; "The Distant Suns" and "The Yesterday with No Tomorrow" (available at Smashwords.com, its affiliates, and Amazon.com). He also intends to publish "The Flare Lance" and his epic series "Atlantis 2" when they are done being edited. He also wants to revise and update "The Moons of the Solar System," and write other books for Springer (if they are interested in his ideas).

He is also active in the American Library Association, Relay for Life, and occasional University Functions. His interests include astronomy, origami, wolves, tabletop role-playing games, computers, and writing.

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