An Earthling's Guide to the Solar System

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By

William H. Waller

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FOREWORD

What is it about the Solar System that is so alluring to us Earthlings? Perhaps it is that the Solar System offers up the most tangible piece of the cosmic puzzle, a place whose attractions we can actually visit, touch, see and smell! I fell in love with the Solar System when I studied the Saturn system using *Cassini* data. Years later, I continue to nurture a passionate and deep relationship with these wondrous planets, moons, comets and asteroids that co-orbit the Sun. This book provides a sublime homage to our home planet and its kindred realms. The way William Waller describes the salient features–while also including poems, anecdotes and even some mathematics–makes his paean to the Solar System truly come to life. I've studied the planets for many years, and so I found myself nodding in affirmation many times while reading, but also learning new things. Planetary science has been one of the most exciting areas of space science in recent years, starting with the *Venera* missions to Venus and progressing to the detection of exoplanets outside our Solar System. But even before these technological advances, humans have been fascinated with our Moon, the Sun, the panoply of visible planets and their diverse satellites–because at the end of the day, the Solar System is what we call home. Certainly, it is a special place because of planet Earth, and of our relationships with the living creatures that reside here. But the future potential for planetary science might well include astrobiology and the eternal search for life elsewhere. There is so much more to be discovered, and books like *An Earthling's Guide to the Solar System* will help us do just that.

Dr. Sheila Kanani, Honorary Researcher
Lancaster University, and
Education, Outreach & Diversity Officer
Royal Astronomical Society

Preface

To the ancients, the Solar System appeared as an itinerant troupe of gods, each luminary traipsing over the vault of heaven along a shared path but following its own unique cadence. The Sun ruled the daytime sky, while the shape-shifting Moon waxed and waned in both the daytime and nighttime skies according to its observed displacement from the Sun. Mercury and Venus shone most prominently in the Sun-kissed twilight sky, while Mars, Jupiter, and Saturn elegantly adorned both the twilight and deep night skies according to their annual rhythms.

It took the invention of the telescope in 1608 for us Earthlings to learn anything more about these celestial vagabonds. Telescopic views of the Sun revealed dark spots that were later recognized as knots of intense magnetism and sources of explosive flares. The Moon showed myriad craters that gave tangible testament to a history of violent impacts by other bodies. Mercury and Venus displayed phases like those of the Moon, while Mars sported polar ice caps that varied with the seasons on this ruddy planet. Jupiter dazzled with its striated bright zones, dark belts, Great Red Spot, and bevy of moons. Saturn had all that in more muted form plus a stunning system of rings. The telescope also led to the discovery of new planets–greenish blue Uranus in 1781 and similarly colored Neptune in 1846. Pluto was discovered in 1930 but has since been relegated to one of many minor, or dwarf, planets orbiting the Sun. Beginning in the 1960s, pioneering space missions have brought us ever closer to these worlds–revealing intimate insights to their physical constitution and dynamics.

Having written a prior book on introductory astronomy, (*Astronomy: A Beginner's Guide* [OneWorld Publications]), I came to realize that our current knowledge of the Solar System is far more intimate than what we know of other stars, star clusters, nebulae, galaxies, galaxy clusters, and the cosmic web. There is a reason for this deeper level of familiarity. Through our robotic probes, orbiters, landers, and rovers, we have vicariously visited many of the worlds that inhabit our Solar System. We have even set foot on the Moon and brought samples back to Earth for detailed investigations. In a few decades, we will be doing the same with Mars. These sorts of direct explorations have provided a wealth of information that was difficult to reconcile with the remotely sensed narrative offered in *Astronomy: A*

Beginner's Guide. Consequently, I was motivated to write this more focused book on the Solar System, itself.

To convey a complete accounting of our celestial family, I have borrowed and modified a few of the salient chapters in *Astronomy: A Beginner's Guide.* These include what are now "A Solar System Primer," "The Sun–Our Star," and "Birth of the Solar System." The remaining 9 chapters are unique to this book. You will notice that *An Earthling's Guide to the Solar System* also includes several "teachable moments" for sharing with students, friends, and family. Further information on these hands-on minds-on activities can be found in *Dr. Waller's Science Gazette* at https://sites.google.com/site/sciencegazette/home/teachable-moments-in-astronomy-astrophysics. Unlike *Astronomy: A Beginner's Guide*, this book is considerably more tentative in outlook. If there is one thing we have learned from our robotic and manned explorations, it is the surprising diversity of the worlds that we have encountered. We remain one space mission away from gaining startling new insights.

In this spirit, I welcome you to participate in the continually evolving explorations of our Solar System. One way for you to take part in this adventure is as a citizen scientist who helps carry out crowd-sourced projects through the online *Zooniverse* portal at https://www.zooniverse.org/. There are always new projects in space science being posted on the website, just waiting for your input.

As an astronomer and science communicator, I have benefited from the wisdom provided by many mentors, colleagues, students, and family. My mentors include Jim Cornell who gave me my first job as a science writer at the Harvard-Smithsonian Center for Astrophysics, Steve Strom and Sue Kleinman who advised me in my dissertation work at the University of Massachusetts, Paul Hodge who gave me my first lectureship position at the University of Washington, Bruce Woodgate who genially coached my postdoctoral fellowship at NASA's Goddard Space Flight Center, and lastly, Cary Sneider who provided a welcoming home at the Museum of Science in Boston for the *New England Space Science Initiative in Education (NESSIE)*–a NASA education and public outreach program that we co-ran together with Cathy Clemens of the Center for Astrophysics. Over the past four decades, I have enjoyed mentoring my own students --- at the University of Massachusetts, University of Washington, Tufts University, Endicott College, and Rockport High School. Their curious minds, infectious enthusiasm, and dauntless ways have been nothing less than inspirational. My family continues to encourage me in my writing endeavors–and supports me through thick and thin. I am honored to dedicate this book to them, especially.

The book you see today greatly benefited from the fine illustrative work of Leigh Slingluff, the editorial craftsmanship of the Cambridge Scholars team, and helpful input from expert reviewers. Any remaining glitches or errors of attribution remain mine to acknowledge and make amends.

Many people responded to my GoFundMe appeal for funding the costs of illustrations as well as permissions to use various copyrighted material (including my own!). These included Jerry Ackerman, Jenny Amory, Ted Blank, Jerry Bonnell, Linda Bosselman, Charles Carbonneau, Michael Deneen, Christopher DeRosa, Todd DiGeronimo, Christine Downing, Jeffrey Edmonds, Frank Fardy, Gary Gorczyca, Robert Grady, Paul Graveline, Laura Hallowell, Noorali Jiwaji, Claudine Kavanagh, Stephen Kolaczkowski, Ana Larson, Richard Luecke, Jamy Madeja, Kathleen Miller, Christiane Munkholm, Jane O'Maley, Stephen Ouellette, Joan Paille, Radha Pertaub, Rebecca Reynolds, John Ronan, Yves Simon, Lisa Smith, Cary Sneider, Ilya Taytslin & Lynn Breymer, David Tower, and Julian Waller. Of course, they are in no way responsible for any errors of fact or omission on my part. I remain deeply grateful to them for their support and encouragement.

SECTION I:

OUR CELESTIAL FAMILY

CHAPTER 1

A SOLAR SYSTEM PRIMER

> "Outside intelligences, exploring the solar system with true impartiality, would be quite likely to enter the sun in their records thus: Star X, spectral class G0, 4 planets plus debris."
> —Isaac Asimov, Essay 16, "By Jove!". In View from a Height, 1963 CE

If this book on the Solar System was apportioned by mass, every page would be full of information on the Sun, as it contains 99.86 percent of the Solar System's total mass. The planets, asteroids, plutoids, and sundry comets that make up the rest of our Solar System would all fit on the last few lines on the last page. Instead, I have given the Sun primacy of place, while devoting significant ink to the wondrous worlds that have grown up with the Sun and are still bound by its gravitational grip. As you will see, the dominant theme running through these chapters is the incredible *variety* manifested throughout the Solar System. This leaves open the question of what other stellar and planetary systems might look like. We have come to know that stars come in many colors, luminosities, masses, sizes, and ages– and that a major fraction of them are accompanied by planets. So, let's get to know our home system a little better–for its own sake, of course -- but also to prepare us for exploring what lies beyond.

Basic Plan

The overall layout of our Solar System can be visualized in a variety of ways. The most obvious is to create a scaled-down version that you could peruse on foot. Here is a scale model Solar System, wherein you can start with the Sun as a grapefruit and then pace-out upon a large playing field properly scaled-down versions of planets in the form of salt grains, poppy seeds, mustard seeds, peppercorns, an allspice seed, and one big blueberry. Feel free to substitute your favorite fruits, vegetables, and spices. The scaling is from 14 billion to one! Planetary distances refer to the Sun. In this model, both the planetary sizes and distances are to scale. Other model Solar Systems of various scaling can be found along the National Mall in

Washington, D.C., the Topsfield Linear Common in Massachusetts, Route 1 in Maine, and other well-traveled places.

Table 1-1: A 14 billion-to-one scaling of the Solar System showing both down-scaled sizes (D) and distances from the Sun (d).

Object	Diameter/Distance	Scale to	Model suggestion
Sun	$D = 1.4 \times 10^6$ km = 0.01 AU	10 cm	Grapefruit
Mercury	$D = 4.9 \times 10^3$ km $d = 58 \times 10^6$ km = 0.39 AU	0.35 mm 4.2 m	Salt grain Four big strides
Venus	$D = 12 \times 10^3$ km $d = 108 \times 10^6$ km = 0.72 AU	0.86 mm 7.7 m	Mustard seed Eight big strides
Earth	$D = 13 \times 10^3$ km $d = 150 \times 10^6$ km = 1.00 AU	0.91 mm 10.7 m	Mustard seed 11 big strides
Moon	$D = 3.5 \times 10^3$ km d (from Earth) = 3.8×10^5 km	0.25 mm 27 mm	Salt grain a thumb's width from Earth
Mars	$D = 6.8 \times 10^3$ km $d = 228 \times 10^6$ km = 1.52 AU	0.48 mm 16.3 m	Poppy seed 16 big strides (pitcher's mound to home plate in baseball)
Asteroid Belt	$d \sim 414 \times 10^6$ km ~ 2.8 AU Range is 2.1–3.3 AU	~30 m	30 big strides (1st to 2nd base in baseball)
Jupiter	$D = 143 \times 10^3$ km $d = 778 \times 10^6$ km = 5.20 AU	10.0 mm 55.6 m	Big blueberry or Kix 55 big strides (width of a football field)
Saturn	$D = 128 \times 10^3$ km $d = 1426 \times 10^6$ km = 9.54 AU	8.57 mm 102 m	Allspice or pea 100 big strides (100 meter dash or length of a football field)
Uranus	$D = 51 \times 10^3$ km $d = 2868 \times 10^6$ km = 19.2 AU	3.65 mm 205 m	Peppercorn 200 big strides (two football fields)
Neptune	$D = 45 \times 10^3$ km $d = 2868 \times 10^6$ km = 30.1 AU	3.55 mm 321 m	Peppercorn 320 big strides (Tiger Wood's golf drive)
Pluto (most famous "plutoid")	$D = 2.4 \times 10^3$ km $d = 5900 \times 10^6$ km = 39.4 AU	0.17 mm 421 m	Ground pepper Length of Boston Public Garden
Oort Cloud of Comets	$d = 7.5 \times 10^{12}$ km = 50,000 AU	536 km	Boston to Ottawa, ON
Alpha Centauri (nearest star)	$d = 4 \times 10^{13}$ km = 270,000 AU	2900 km	Grapefruit Boston to Denver, CO

If you tape or glue each scaled-down body to an index card, you can then give the cards to your buddies for pacing out on a large playing field. A big enough playing field should allow you to get out to the orbit of Neptune. Once all the "bodies" are distributed, the relative coziness of the inner rocky Solar System vs. the far-flung realm of the gas and ice giants will become obvious to all. (Using the online calculator at https://www.exploratorium.edu/ronh/solar_system/, you can pick your own scaling and find all the corresponding sizes and distances of your personal model Solar System).

This sort of "linear" visualization helps to highlight the vast spaces between the planets relative to their sizes. Another way to visualize the Solar System is to compress the distances logarithmically, so that you can more easily cope with the full range of distances that are traced by the planets and outer comets. This sort of rendering is shown in Fig. 1-1.

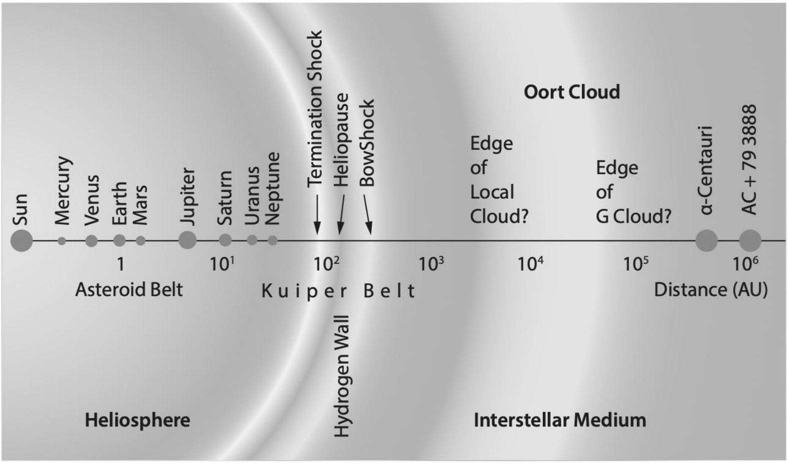

Fig. 1-1: Distribution of planetary and cometary orbits on a logarithmic scale of distances. (AU) refers to Astronomical Units, where the Sun-Earth distance equals one Astronomical Unit. The logarithmic scaling enables the enormous dynamic range of distances to be compressed into a single map. The rough doubling of planetary distances according to the Titius-Bode rule, is manifested here as equally-spaced intervals. The Asteroid Belt is most populated between the orbits of Mars and Jupiter. Beyond the Kuiper Belt of icy plutoids and comets, the Solar System extends to the Oort Cloud of comets halfway to the nearest star system (Alpha Centauri)! While Saturn is impressively 10 times farther from the Sun than Earth is, Oort's Cloud of comets is yet another 5,000 to 50,000 times farther away. (Credit: Wikipedia Commons).

Observing our Solar System

The sundry objects that make up our Solar System span an incredible range of distances and sizes. Much of what is out there defies ready reconnaissance. Yet there remains an awful lot that can be perceived by just looking up. Indeed, there is nothing like viewing these marvels for yourself–naked eye, through binoculars, or at the eyepiece of a small telescope.

The Sun can be viewed in a variety of ways. Here, safety is of paramount importance. The Sun's intense rays–even without optical amplification–can damage your eyes. One of the safest ways to view the Sun is through *projection.* Using a cardboard box, you can build a simple pin-hole camera that projects an image of the Sun onto one of the inner walls of the box. The trick is to cut a 2-inch (5 cm) hole out of the middle of one side of the box and to cover the hole with a piece of aluminum foil that has been pierced once by a pin. That hole, when pointed toward the Sun, will then project an image onto the opposite wall of the box.

If you don't mind spending a few dollars (about $370, or £248) you can purchase a Sunspotter (see https://www.enasco.com/p/The-Sunspotter%2BSB46150) which uses a lens to project a nice image of the Sun onto a surface at just the right distance from the lens. This is sufficient for you to see sunspots and to track their motion across the face of the Sun from day to day. From this tracking of sunspots, you can infer the Sun's spin period–a fundamental property of this nearest star.

Aluminized mylar filters allow you to directly view the Sun. You can purchase "solar shades" made of the proper material (see https://www.eclipseglasses.com/). These are often used during eclipses of the Sun. You can also top-off your telescopes with custom-fitted filters made of the same material. Finally, you can purchase a stand-alone solar telescope that filters out all light but a particular red emission produced by the Sun's stormy outer layer known as the chromosphere. These sorts of rigs can cost hundreds to thousands of dollars. However, the views they afford are spectacular, featuring fiery prominences that jut out from the solar limb along with sunspots full of roiling details. Amateur astronomy clubs often include members who have made the investment and are willing to share their views with students and the curious public. Establishing a good relationship with your local amateur astronomy club is definitely a good idea! The best part of observing the Sun is that you can do it in the daytime, when school is in session and your kids are awake. ☺

Mercury and Venus orbit the Sun interior to the Earth's orbit. Their closer relation to the Sun makes them appear in the twilight sky as "morning stars" or "evening stars." That means they are often found in the east just before sunrise or in the west just after sunset. The best time to view Mercury is when it is near its point of greatest elongation from the Sun. This amounts to no more than 28 degrees, so Mercury is always found in a significantly brightened sky. Venus has a far more forgiving maximum elongation from the Sun of 47 degrees, so it is possible to view this planet in a completely darkened sky. Through a small telescope, Mercury reveals very few of its secrets. One is even hard-pressed to perceive any asymmetries resulting from its particular state of solar illumination, i.e. its phase. Again, Venus is far more accommodating. I had the pleasure of once viewing Venus and the crescent Moon in the same part of the evening sky. Through my 8-inch diameter reflecting telescope, Venus showed the same phase as the Moon–a beautiful consequence of both orbs being mostly backlit by the Sun at the time.

Mars, Jupiter, and Saturn all orbit the Sun well-beyond the Earth's orbit. That means they are not limited in their elongations from the Sun as seen from Earth. Indeed, the best times to view these planets are when they are completely opposite the Sun, when they appear highest in the sky at local midnight. This state of *opposition* occurs roughly once every 2.1 Earth years (780 days) for Mars, every 399 days for Jupiter, and 378 days for Saturn. The angular sizes of the planets are largest during opposition, as the Earth and these planets are all on the same side of the Sun and so are closest to one another in their respective orbits. Naked-eye views of Mars can reveal a ruddy hue, while those of Jupiter are much whiter, with Saturn yielding a more tawny tone.

Binocular views of Mars provide a better rendering of its rusty color but not much more. Being half the size of Earth, Mars never appears large enough for any details to be resolved with binoculars. Even its two small moons remain below the threshold of detection. To do better, you need to gain access to a decent telescope. A properly focused refracting or reflecting telescope during times of opposition will typically show one or both of the polar ice caps along with some darkened features such as Syrtis Major. That is, unless a dust storm has completely enveloped the planet. Sometimes the use of colored filters at the eyepiece will help to bring out the contrast of the features. It takes the use of an observatory-class telescope to spy the tiny Martian moons Phobos and Deimos.

A well-aligned pair of binoculars will show Jupiter's substantial girth along with its four Galilean moons. These satellites will appear in a dynamically shifting lineup–with Io typically closest to Jupiter, followed by Europa, Ganymede, and Callisto. Amateur telescopes can literally bring Jupiter into fascinating focus. The giant planet's dark belts and bright zones can be resolved along with smaller features–including festoons, bright and dark spots, and the Great Red Spot itself. If you have the time, you can monitor Jupiter's rapidly rotating orb as it makes one rotation every 9.9 hours. You can also track the Galilean moons as they transit in front of or behind Jupiter. Sometimes you can catch one of these moons casting a shadow on Jupiter. If there happened to be any Jovians living beneath that shadow, they would be witness to a solar eclipse!

Being twice as far as Jupiter, Saturn reveals considerably less through binoculars. Its tallow color becomes more conspicuous, while its largest moon Titan should be evident. Some people will be able to see some asymmetries in Saturn itself, just as Galileo saw ear-like protuberances with his spyglass more than 400 years ago. It takes a good amateur telescope, however, to resolve these extensions into the exquisite ring system for which Saturn is justly famous. The Cassini Division between the A and B rings along with lesser divisions can be spotted during times of steady "seeing" through Earth's atmosphere. Some keen-eyed telescopic observers have discerned radial details in the broad inner B ring–what are known as "spokes." I regret to say that I'm not among these perceptive elites.

As Saturn sedately orbits the Sun, its ring system slowly changes its aspect with respect to the inner Solar System. Saturn's spin axis is tilted by 27.4 degrees with respect to its orbital axis, and so the planet experiences a similar sequence of seasons as does Earth. We therefore see Saturn appear to pirouette through configurations of maximal tilt toward us during one of its solstices followed by no tilt during one of its equinoxes. The ring system follows suit with the rings at maximum display during the solstice seasons and closest to disappearing during its equinoxes. Because a Saturnian year takes a full 29.4 Earth years, each Saturnian season spans the equivalent of 7.35 Earth years. Accordingly, Saturn's rings reached edge-on status in August 2009, attained maximal tilt toward us in May 2017, and will again diminish to edge-on insignificance in May 2025.

Uranus and Neptune are both beyond the reach of the unaided eye. High-quality binoculars and a good sky chart are sufficient to spot Uranus, but a telescope is required to sight Neptune. You will see no more than shimmering dots, with Uranus appearing greenish-blue and Neptune appearing slightly more blue. Considering that these major planets were completely unknown at the time of the American Revolution, you will likely cherish whatever views you get of them!

Comets spend most of their time in the outer Solar System. However, each decade or so we are witness to several comets that come close enough to the inner Solar System to put on magnificent displays. I personally treasure my naked-eye views of Comet Bennett in 1970, Comet IRAS-Araki-Alcock in 1983, Comet Halley in 1986, Comet Hale-Bopp in 1995, and Comet NeoWise in 2020. The most spectacular cometary apparitions feature a brilliant nucleus, from which a straight plasma tail and a curved dust tail emanate. Telescopes will enable you to zoom into the nucleus and surrounding coma, where you may see evidence of curving streamers. All this assumes that you have situated yourself well away from sources of light-pollution whose illumination of the sky will otherwise overwhelm these diffuse sights. Believe me, it will be worth the effort!

Epochal Explorations

As I write these chapters, robotic missions to sundry bodies in the Solar System are reaping ever-new insights into the structure, function, and history of our stellar and planetary home. More than 7 missions are currently deployed to study the Sun and its effects on the rest of the Solar System. The *Messenger* spacecraft mapped Mercury from 2011 to 2015 after a 40-year hiatus of robotic exploration. The surface of Venus was imaged by Soviet landers in the 1970s and radar-mapped by NASA's *Magellan* orbiter in the 1990s. The European Space Agency's *Venus Express* orbiter (launched in 2005) spent almost a decade studying the thick atmosphere of this hellish planet before it was commanded to descend through that same atmosphere in December 2014. Since 2015, *Akatsuki* (aka the *Venus Climate Orbiter*) has been swinging around Venus every ten days while taking fabulous pictures of the planet's dynamic atmosphere. Mars continues to draw our concerted attention with six orbital missions and three surface rovers currently operating–the SUV-size rover *Curiosity* rover that has been exploring since 2012, the *Perseverance* rover that landed successfully in 2021, and the Chinese *Zhurong* rover also landing in 2021. Complementing these rovers, the *InSight* lander sensed the planet's seismic activity between November 2018 and December 2022, retiring when the dust accumulation on its solar panels nixed any further operations.

Exploring beyond the terrestrial planets, the *Dawn* spacecraft began orbiting the large asteroid Vesta in August 2011 and encountered Ceres in 2015. In 2018, the *Hayabusa2* landed on the asteroid Ryugu, bringing back to Earth precious samples of the asteroid in 2020. The *OSIRIS-REx* spacecraft landed on Bennu in 2020 and successfully delivered its samples to Earth in 2023. Comet Halley was visited by six spacecraft during the comet's momentous passage through the inner Solar System in 1986. The dusty tail of Comet Wild-2 was sampled by the *Stardust* spacecraft in 2004. A capsule from the spacecraft returned a cache of comet dust back to Earth in 2006. *Stardust* was then directed toward Comet Tempel 1, where it imaged in 2011 the crater excavated 6 years prior by the *Deep Impact*