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INTRODUCTION

> For as long as there been humans we have searched for our place in the cosmos.
>
> — *Carl Sagan, 1980*

1.1 My Brief History

I am an astronomer, and as such my professional interest is focused on the study of light emitted by objects in the sky. However, unlike many astronomers, my interest in the night sky didn't begin until later in my life, well into my college education. I don't have childhood memories of stargazing, I never thought to ask for a telescope for Christmas, I didn't have a moon-phase calendar on my wall, and I never owned a single book about astronomy until I was twenty-one years old. As a child, my closest approach to the subject of astronomy was a poster of the Space Shuttle that hung next to my bed, but my interest was piqued more by the intricate mechanical details of the spacecraft rather than where it traveled.

Looking back, I suppose the primary reason for my ignorance of astronomy was because I grew up in a metropolitan area, in the North County of St. Louis, Missouri. The skies are often cloudy in the winter when the nights are longest, the evenings are bright with light pollution from the city even when the clouds are absent, and the air is humid and mosquito-filled in the summer.[1] Another important factor is that from age six until twelve I spent a good fraction of my time in my room building with Legos. From early on I seemed destined to be an engineer rather than the astrophysics professor I am today.

It wasn't until I attended a small engineering college in the town of Rolla, Missouri (pronounced locally as Rah-lah, Mizz-ur-ah) that I had my first memorable experience with the night sky (the school is now known as the Missouri University of Science & Technology). The town of Rolla boasts a population of about 20,000, but only during the academic year; once the students leave for summer break, the population dips below 12,000. One hot summer evening in August 1997, just before the start of the fall semester, I was sitting in my room playing computer games over our homemade local area network when my roommate Jason convinced me to go out that night to see the Perseids meteor shower. Jason had learned about the shower from a public service announcement from the student radio station, KMNR, where we both worked as deejays. With nothing much better to do before classes started, we and several friends drove out to a farmer's field just outside of town, threw out a few blankets and waited for the shooting stars.

As we watched the meteors of various sizes streak across the night sky, I noticed a swath of faint, splotchy light and I asked if anyone else saw it, too. It turned out that we were

[1] But how 'bout them Cardinals?!

seeing the Milky Way—our own galaxy as viewed from the inside—along with many of the summer constellations. It was that event, at the age of twenty-one, that sparked my interest in the grander Cosmos.

From that night on I started looking up to notice twinkling stars of various subtle hues, the phases of the Moon, and the sky in general. One night later that year I saw a remarkably bright star that I hadn't noticed previously. A few weeks later I asked one of my physics professors, Dr. Schmitt, about the mysterious star expecting to hear about some component of a constellation with a Latin name or some boring numerical designation. I explained about how much brighter it was than the surrounding stars, and how it seemed to stand out so much clearer than everything else in the sky. He smiled and told me that I wasn't seeing a star at all. Rather, I was seeing the planet Jupiter. Thinking back to that moment now, I suppose that was when I had just "discovered" my first planet! The discovery may have been thousands if not millions of years old and therefore hardly new to humanity. But it was new to me and it further sparked my interest in the subject of astronomy.

1.2 The Human Activity of Watching the Sky

Throughout history humans have taken inventory of the night sky, its stars, planets and other luminous bodies. Given many more nights staring up, rather than down at my textbooks or across at my computer screen, I would have noticed other bright planets in addition to Jupiter, including Mercury, Venus, Mars and Saturn. If I had paid careful enough attention, as my ancestors had thousands of years ago, I would have noticed that the planets did not always appear in the same place month after month with respect to the surrounding stars. Compared to the relatively static background of the constellations, the planets wander at their own pace, and sometimes move in a direction opposite of the stars. The activity of measuring the positions of astronomical objects relative to the background of relatively static stars is known as *astrometry*. The history of exoplanets starts with humans conducting astrometric measurements of the planets, and the story of the discovery of the nature of the Solar System planets marks the dawn of science as we know it.

While the word *planet*, meaning "wandering star," originates with the Greeks, astrometric measurements of planets were first recorded by the Babylonians, who started recording the positions of Venus sometime in the seventeenth century B.C.E. We know this based on the ancient Venus Tablets, on which these earlier astrometric observations were later reproduced and preserved. These tablets date back to the seventh century B.C.E., and the original observations were most likely made in relation to religious customs and beliefs, with the times of maximum separation from the Sun associated with various omens. Later Babylonian texts noted the positions of other planets, along with the Sun and the Moon, and noted the periodic nature of these objects' motion in the sky.

The Babylonian tabulations of planetary positions are the earliest written records of humans tracking the positions of night-sky objects. However, while various aspects of planetary motion were noted to be periodic and therefore predictable, ancient astronomers had no proper system of motion attributed to the planets and stars. With the advent of geometry, the Greeks later devised the first mathematical description of the movements of objects in the sky. They posited that the Earth was a sphere—they were aware that the Earth is not flat—and around the central sphere rotated a larger sphere containing the stars and planets. This "two-sphere" model was advanced by the most prominent philosophers of the time, notably Socrates, Aristotle and Ptolemy, and later adopted by Christian theologians through the sixteenth century B.C.E. (Kuhn, 1957).

The preference for the two-sphere model was not necessarily based on its ability to make accurate physical explanations of observed phenomena, but were instead based on assertions about nature that had aesthetic, rather than scientific appeal as we would demand today. According to the ideas of the early Greek philosophers, later expanded upon by Ptolemy, the basic elements of the Universe had preferred locations and behaviors. For example, in a Ptolemaic Universe, the Earth and its constituents—earth, water, air and fire—were changing and imperfect. Further, things that are of the Earth tend toward its center, which provides an explanation for why objects are pulled to the Earth. While things of the Earth are subject to change, objects in the heavens were created perfect and immutable. Rather than falling toward the Earth, the outer sphere(s) containing the celestial bodies moved in circular motion, eternally cycling back on itself with no beginning and no end.

The two-sphere model held sway for nearly two millennia, and as a result there was little progress in the physical understanding of how the Universe works. The perfection and constancy of the model, with celestial objects cycling along eternal circular tracks, made it appealing to Ptolemaic and later Christian sensibilities. But beyond the visual appeal of the heavens, the stars in the night sky were otherwise largely uninteresting. The stars, Moon, Sun and planets existed above the Earth, and the rules that govern change on the Earth were simply presumed to be invalid for the heavens. This meant that finding detailed explanations for astronomical phenomena wasn't particularly compelling to most people in the centuries leading up to the time of Copernicus (1473–1543), other than the impact that planetary positions had on keeping track of time, aiding in navigation, and the connection between human fate and the precepts of astrology. Questions were restricted to when astronomical phenomena would occur, and only because it was presumed that those phenomena impacted human affairs. Asking *why* the heavens move as they do, or ascertaining their origins, was not the province of educated philosophers who were concerned with the nature of humans rather than the nature of stars, planets and the Universe.

If the night sky were populated only with stars, then the two-sphere model might have continued for centuries longer than it did. However, then as today, planets captured the attention of early philosophers, scientists and tinkerers. While stars execute their uniform, circular motion about the Earth, the planets are the iconoclasts, breaking the rule of immutability. Venus and Mercury don't use the entire night sky as their playing field, but rather appear to the naked eye only close to when the Sun is setting or rising, swapping positions from one side of the Sun to the other. Venus in particular grabs people's attention to this day, appearing bright and bold just before and during sunset on some days, and around sunrise on other days, hence its designation as the evening star or morning star, respectively. Mars, Jupiter and Saturn are also extremely bright, yet they move across the entire night sky drifting across the background field of stars at their own paces.

Even more curiously, Mars, Jupiter and Saturn—along with the other outer planets, which are not visible to the naked eye—occasionally halt and then reverse course for weeks to months, from night to night moving from west to east, counter to their more typical east-to-west motion. From our vantage point of modern science, this *retrograde* motion, coupled with the restricted movement of Venus and Mercury, are evidence against an Earth-centered Solar System. Venus and Mercury never stray far from the Sun because the Earth is orbiting exterior to them and we are looking in toward their smaller, Sun-centered orbits. Meanwhile, Mars, Jupiter and Saturn orbit the Sun exterior to the Earth, so we can see them in their larger orbits that range over our entire night sky, often far from the Sun's position. Furthermore, the orbit of the Earth can "overtake" the orbits of the outer planets, causing them to appear to move backward on our sky as we pass them.

However, the prevailing way of thinking about the Universe before the sixteenth century compelled people to double down on the preference for perfect circular motion. Ptolemy built on the concepts of circular motion that were originally proposed by Hipparchus and Apollonius of Perga. Instead of traveling solely along giant circles centered on the Earth, the planets also moved along smaller circles centered on a point along the larger orbital circle, known as *epicycles*. This circle-on-a-circle concept allowed the planets to move from east to west on the sky most of the time, but the rotation of the epicycle allowed them to occasionally reverse direction. The epicyclic modification of Ptolemy was the dominant model of the Solar System for more than a millennium, from the second century A.D. up until the time of Copernicus in the sixteenth century.

1.3 Asking Why the Planets Move as They Do

For much of his life, Nicolaus Copernicus was employed variously as a politician, theologian, and physician. However, his true passion was astronomy and he was well-versed in the astronomical philosophy of Ptolemy, with its spheres and epicycles. However, the use of epicycles required not just small circles atop larger circles, but the model required other modifications such as offsets between the Earth and the center of the different planetary motions to reproduce, for example, the varying brightnesses and speeds of the planets throughout the year.

Copernicus found that circular planetary orbits could be accommodated by a Sun-centered (heliocentric) model (Sobel, 2011). Copernicus shared the Greek admiration for circles because an object on a circular path has eternal motion, which reflects the eternal perfection of the heavens. As an additional benefit, the arbitrary mechanism of epicycles was no longer needed to explain retrograde motion. He first proposed his heliocentric model in a short treatise entitled *Commentariolus* ("short commentary"). In this short work he laid out a set of assumptions, notably that there was no single center in the Solar System, but instead several rotation points; the Moon orbits the Earth; the objects other than the Moon orbit the Sun; the stars are fixed and at a great distance from the Solar System; and the apparent retrograde motion of the outer planets is related to the Earth's motion on a sphere interior to those planets' spheres. These assumptions formed the basis for his later work, *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Heavenly Spheres), which described his heliocentric model more fully.

It should be noted that Copernicus' motivations for a heliocentric Solar System weren't particularly compelling as viewed from a modern scientific standpoint. Because of his insistence on circular motion, which we now know is not generally true of planetary motion, he proposed placing the Sun near the center of his system based on another aesthetic motivation: light tends to emanate from a central location, like light from a candle in an otherwise dark room. So he proposed to place the Sun at the center of the Solar System—the center of the room, so to speak—with the planets, including the Earth, revolving around the central light. Copernicus' reasoning for a heliocentric universe provided a simpler explanation than an Earth-centered model with epicycles. But more important, the heliocentric model later found overwhelming and compelling support in direct observational evidence.

His motivations aside, Copernicus' idea proved revolutionary because it provided an entirely new way of observing and interpreting the Universe. Kuhn astutely notes that the Copernican Revolution ushered in a new paradigm of scientific thinking.[2]

A scientific paradigm is a system of thought that forms a starting point for working out scientific problems. For example, before the modern germ theory of disease, illness was thought to be due to poor air quality, or "miasma." Today, our understanding of bacteria, parasites and viruses provides a much more effective framework for treating and preventing diseases that would be unrecognizable to medical practitioners of, say, the eighteenth century.

Similarly, the assumption that the Earth does not occupy a special place in the Universe provides a common starting point for working out modern astronomy problems, and this approach was largerly unheard of before Copernicus' revolutionary idea. Because of Copernicus' paradigm shift the assumptions under which scientists interpreted the world around them were fundamentally changed. With the Sun moved to the center of the planets' orbits, the Earth was no longer the center of the entire Universe. With the new model, there was at last a system of planetary motion around the Sun; there was now a Solar *System*, a logical, universal mechanism for explaining the motion of planets. Later observations and reasoning revealed the Sun to be one of myriad stars in a Universe

[2]Owen Gingerich once told me the story of Thomas Kuhn, who extended the definition of paradigm to the scientific realm. Thomas was one day walking near Harvard Square, whereupon he was asked by a beggar if he could 'pare a dime. I love a good pun!

that was much larger than just the Earth and its immediate environs.

Contrary to popular belief, the church initially took a rather pragmatic stance toward Copernicus' new idea. His heliocentric model provided a much easier method of computing predictions for the positions of the planets, and was therefore quite a bit more useful than previous astrometric methods. Copernicus was also a part of the church hierarchy, and he was very careful to follow proper rules and etiquette when publishing his ideas, going so far as to dedicate *De Revolutionibus* to the pope (Pogge, 2005). Immediately following the publication of *Commentariolus*, some religious leaders, both Catholic and Protestant, expressed disdain at the removal of the Earth from the center of God's creation. But there was not an organized, church-led suppression of Copernican thinking until several decades later. Copernicus was nonetheless sensitive to potential religious objections to his theory, which is one reason he waited until late in his life to publish *De Revolutionibus*.

Another obstacle to the widespread acceptance of the heliocentric model is the requirement of a moving Earth. A static Earth at the center of the Solar System fit into the existing philosophical beliefs that the elements associated with the Earth tend to fall toward its center. However, this tendency is distinct from the modern notion of gravity, and many scoffed at the notion of a moving Earth because it was felt that things resting on the Earth's surface, as well as the atmosphere and the Moon, would fly away if the Earth moved around the Sun. After all, if a horse-drawn cart laden with supplies turns a corner too quickly, the cargo will fly over the edge. Shouldn't the same hold true for the Earth and its "cargo"? Another objection was related to the firmly held belief that there could be only one center of motion, and having the Earth orbit the Sun as one center while serving as the center of the Moon's motion seemed absurd.

Copernicus' heliocentric model provided an adequate match to existing observations, but so did the prevailing Earth-centred (geocentric) model. To Copernicus, moving the Sun to the center of the planetary orbits provided a simpler, more mathematically elegant construct, but the tension between new and old theories would only be settled using the force of new observational evidence. If a model says astronomical objects—or the entire Universe, for that matter—should behave in a certain way, there are usually consequences that can be observed if that model is true. New observations of the Universe often provide tests of key aspects of theoretical models. Should the new theory pass the observational tests, then it can be adopted as a viable means of understanding the Universe, especially if the competing model cannot pass the same tests. Sadly, Copernicus died within a year of his theory's publication and therefore never saw the tests that led to the widespread acceptance of his hypothesis.

At the time of Copernicus, astronomical instruments were no more than basic surveyor's tools—means of measuring positions, angles and times in order to chart the motion of objects visible to the naked eye. Tycho Brahe (1546–1601) combined the latest versions of these tools with meticulous attention to detail to make marked improvements to past astrometric measurements of the planets. While Tycho strongly opposed Copernicus' heliocentric model, his collaborator Johannes Kepler inherited—or stole, depending on one's perspective—Tycho's data after he died, and used the highly precise data to refine Copernicus' model. Rather than uniform circular motion around the Sun, Kepler found that a modified law of motion could account for all aspects of planetary motion as manifest in Tycho's astrometric data.

The first of Kepler's laws states that planets move along ellipses rather than circular paths, with the Sun at one of the two foci. The second states that the closer a planet is to the Sun along its orbital path, the faster it moves, and vice versa, such that equal areas inside of each orbital ellipse are swept out in equal intervals of time. Today, we understand this through the lens of the conservation of both energy and angular momentum. The smaller the distance d between a planet and the Sun, at *perihelion*, the more negative the potential energy: gravitational potential energy goes as $-1/d^2$. In order to reduce its potential energy (note the negative sign) while conserving its total energy, the planet must increase its kinetic energy by speeding up. The opposite happens at *aphelion*, or the maximum orbital separation along the ellipse.

Kepler's third law is perhaps most familiar to physics students. It states that size of a planet's orbit, given by its semimajor axis a, is proportional to its orbital period, P, such that

$$P^2 \propto a^3 \qquad (1.1)$$

Kepler's third law provided a unified mathematical framework for understanding the motion of the planets within

Copernicus' heliocentric model. The Universe containing the Earth, Sun, Moon and five naked-eye-visible planets was no longer an ad hoc collection of mechanisms, but rather a self-consistent system. However, lingering concerns about a moving Earth remained until the Solar System bodies could be inspected much more closely than was possible with the naked eye.

In the early 1600s, Dutch glass workers developed the first telescopes, which used systems of lenses to improve upon the eye's light-gathering ability and spatial resolution. These original telescopes were used for, e.g., spotting distant ships out at sea. A few years after the construction of the first telescopes, Galileo Galilei, an Italian polymath cut from the same cloth as Copernicus, started building his own telescopes and improved on the original Dutch designs. Rather than looking horizontally at objects on the Earth's surface, Galileo turned his improved telescope upward to the night sky. What he found from his newfound vantage point would have astounded the ancient Greek philosophers and surely warmed Copernicus' heart had he been alive to share the view.

Galileo's observations of the brightest object in the night sky, the Moon, revealed a crumpled, cratered landscape that stood in stark contrast to the supposed perfectly reflecting surface of a body made of ether, a perfect substance through which heavenly bodies moved and were constructed. The dark patches, rather than reflecting the imperfections of the Earth, were intrinsic to the Moon. Similarly, the projected image of the Sun's surface showed dark patches (sunspots) that changed in both size and location on timescales of days. Neither the Sun nor the Moon was perfect and immutable.

His close inspections of the planets were equally surprising. Venus was observed to exhibit phases during its orbit, similar to the Moon throughout the month. This showed convincing evidence for at least one planet orbiting the Sun rather than the Earth. The resolved image of Saturn showed that it was not perfectly circular, but rather had elongations on either side that change throughout the year. These elongations are known to be Saturn's characteristic ring system, but their variability was another knock against the unchangeable nature of the heavenly bodies.

The surprises kept on coming when Galileo examined Jupiter. Unlike Saturn, Jupiter resolved into a seemingly solid disk with no rings. But Galileo had a finely tuned attention to detail, and he noticed several "stars" that lay in a straight line that passes through Jupiter's center and always appear near Jupiter on the sky. Night after night, these attendant points of light would move from side to side and appear to change in number as one or two would disappear only to show up again in a new location the following night. Remarkably, from this apparently random jumping about on a two-dimensional surface, and despite interruptions due to poor weather, Galileo was able to infer that the points of light were executing three-dimensional orbital motion around Jupiter. This was profound because Jupiter suddenly became another center in the Universe, around which other bodies orbited. And since Jupiter orbits the Sun, it was evidence that the Earth could move through the Solar System without losing its Moon, atmosphere and human inhabitants.

1.4 Exoplanets and Completing the Copernican Revolution

More than four centuries after Copernicus' revolutionary idea we now live in an era of astronomy marked by another paradigm shift thanks to the discovery of planets around stars other than the Sun. The study of exoplanets—from their initial discovery to their physical characterization—is known as exoplanetary science.[3] The new knowledge flowing from this rapidly growing field is revolutionizing how we think of the origins of the Solar System specifically, and the formation and evolution of planetary systems throughout the Galaxy more generally.

Before the discovery of exoplanets our concepts of planetary systems were shaped and guided by a sample of one: our own Solar System. The downside of this sample-of-one approach should be fairly obvious. Focusing on our Solar System alone is like doing sociology based on solely investigating one's own life history. An approach to understanding humans by considering only oneself may be preferred by most children, but eventually we all grow up and realize that we cannot understand ourselves and our society without studying other humans. Similarly, we cannot hope to understand our own planet's origins, and the formation of planetary systems in general, without a large sample of planets other than those in the Solar System.

[3] Planets orbiting other stars were initially called extrasolar planets. However, Virginia Trimble noted that she had never heard of a planet residing *inside* of the Sun. While some might blanch at the mash-up of Greek and Latin, the more commonly used word today is "exoplanet."

The dominant view of planets that existed before the discovery of exoplanets is worth examining. Black (1995) provided a comprehensive yet pessimistic review of planetary science in an article entitled "Continuing the Copernican Revolution." Some of the noteworthy features of the Solar System that informed the dominant paradigm circa 1995 include:

1. The planets all lie more or less in the same orbital plane, with mutual inclinations less than 4 degrees. The exception is the innermost planet, Mercury.
2. The average angular momentum vector of the planets is nearly parallel to that of the spin angular momentum of the Sun.
3. The planets have nearly circular orbits, again with the exception of Mercury.
4. All of the planets orbit in the same direction, and with the exceptions of Venus and Uranus, they all spin in the same direction as their orbital motion and in the same direction as the Sun's spin.

Many of these features were noted hundreds of years earlier, around 1755, by Immanuel Kant. Based on the features of the Solar System, he proposed that the planets all trace a common origin to a flattened, rotating distribution of gas—a nebula.[4] This *nebular hypothesis* was expanded upon by Pierre-Simon Laplace, who envisioned

[4]Kant also correctly reasoned that the Milky Way galaxy is a flattened disklike distribution of stars orbiting a common center.

the nebula cooling and contracting to form successively larger rings moving away from the newly formed central Sun. These rings then collapsed to form the planets.

While the nebular hypothesis of Laplace and Kant ran into speed bumps between the eighteenth century and mid-twentieth century, by the time of Black's review article the notion of planets forming out of a flattened distribution of gas and dust surrounding a newly formed star was the dominant model of planet formation. Indeed, it still is. We think that the process of planet formation is a by-product of the process of star formation. In the interstellar medium—the collection of gas and dust that roams in the vast expanses of the Galaxy between stars—there exist large clouds containing relatively dense, cool pockets of molecular gas. These molecular clouds experience compression, perhaps due to the shock fronts emanating from supernovae explosions from nearby star formation regions, and as a result start to contract under the pull of their own self-gravity. If the force of gravity cannot be counterbalanced by the internal thermal support of the molecular cloud, the cloud begins to collapse in on itself.

Molecular cloud collapse leads to one or many central concentrations that become stars. As the molecular cloud material condenses toward the central star, the conservation of angular momentum leads to the formation of a flattened, spinning disk containing gas and dust; material can compress along the spin axis of the natal star/disk. Turbulence, viscosity and magnetic fields help transport the inflowing gas through the disk and onto the central star, while stellar winds and irradiation push disk material back out into the interstellar medium. The leftover dregs of the star-formation process go into forming larger and larger collections of solid material that form the seeds of planet formation.

The planet formation process is brief compared to the lifetime of the central star. Stars like the Sun have lifetimes of roughly 10 billion years. However, the planet-formation epoch lasts only 10 million to 100 million years, or a period several orders of magnitude shorter than the life of the eventual system containing planets and the host star. Before the diversity of exoplanetary systems was observed, the Solar System was generally assumed to represent a static "fossil record" of the planet-formation process. Small planets formed close to the star, where the density of gas was smaller than in the outer regions, and where the temperatures were too hot for the condensation of volatiles such as water ice. However, beyond the so-called snow line, the disk temperatures dropped to the point at which ices could condense and solid planetary cores could form more easily. Together with the increased density of gas the giant planets were able to form more efficiently, hence Jupiter and the other gas giants at large orbital distances.

The discovery of exoplanets immediately challenged this picture of gas-disk-to-planet fossil preservation. Exoplanet architectures provide strong evidence of post-disk gravitational jostling among planets. For example, gas-giant planets around other stars are often discovered in orbits much smaller than the 5.2 astronomical units (AU) that separate the Sun and Jupiter. Also, gas-giant exoplanets are often in eccentric orbits, and sometimes the orbits are significantly tilted with respect to other planets in the system, and with respect to the stellar spin axis. The prevalence of eccentric, tilted, close-in planets has led to the invocation of gravitational interactions between planets and their disks, between planets and their stars, and among planets. With a sample of one, it would be difficult to make a strong argument for such radical gravitational interactions and inward orbital migration. But with the view afforded by thousands of alien planetary systems, we can now see that the orderly architecture of the Solar System may be an exception rather than the rule throughout the Galaxy.

An analogy for our view of planetary systems before and after the discovery of exoplanets is the story of a Victorian house in the middle of an urban area such as Manhattan.[5] Imagine growing up in such a house, but never having the opportunity to look outside, and therefore never seeing other dwellings where other people live. Then, one day at the age of twelve you are afforded the opportunity to step outside and look around. The high-rise apartment complexes, townhouses and condominiums would look nothing like the house you spent your whole life in. Any theories of how other people live would be radically changed, and instantaneously so. At the same time, your mind would be flooded with basic but perplexing questions such as, How do people get up into their dwellings from the ground level? How were these towering complexes built and who built them? Do people collectively own the entire building, or do they own only parts of the building?

[5] Here, I'm envisioning the house in one of my favorite children's books, *The Little House*, by Virginia Lee Burton.

All of these basic questions have fairly basic answers, but those answers would be far from obvious on the first few days outside of the little Victorian house. Similarly, the large number and variety of planetary systems that we have found elsewhere in the Galaxy are causing us to confront similarly basic yet perplexing questions. Having "grown up" in a Solar System with a system of small, rocky planets close to the Sun (Mercury, Venus, Earth and Mars), and a system of gas giants further out (Jupiter, Saturn, Uranus and Neptune), how do we understand the existence of hot Jupiters: gas-giant planets orbiting right next to their host stars with orbital periods of days rather than years (Schilling, 1996)? How do we explain the formation of planetary systems containing three to seven sub-Neptune-sized planets all packed into regions smaller than the Sun–Mercury separation (Mayor et al., 2009; Lissauer et al., 2011; Swift et al., 2013)? What context do we have for Saturn-sized planets that orbit not one, but two stars—circumbinary planets from which one would see vistas similar to that of Luke Skywalker standing on Tatooine, the fictional double-Sun planet in the movie *Star Wars* (Doyle et al., 2011; Orosz et al., 2012)?

Our models of planet formation, which had for decades been informed by and tuned to explain our own Solar System and its architecture, must now undergo radical revision. Describing the Solar System is no longer the only challenge facing planet-formation theorists. Indeed, as of only 2014 we now know that our Solar System is not even a typical planetary system in the Galaxy. Tiny red dwarf stars outnumber stars like the Sun by a ratio of about ten to one, and there are one to three planets per red dwarf (Dressing & Charbonneau, 2013; Morton & Swift, 2014). Just as with Copernicus' radical theory, in which the Earth was dethroned from its central position in the Solar System, thanks to the discovery of exoplanets the entire Solar System has been moved from its position of primacy in our thinking about planetary systems in general. The birth and rapid rise of exoplanetary science has fundamentally and radically changed our paradigm for understanding the existence, origin and evolution of planets on a galactic scale.