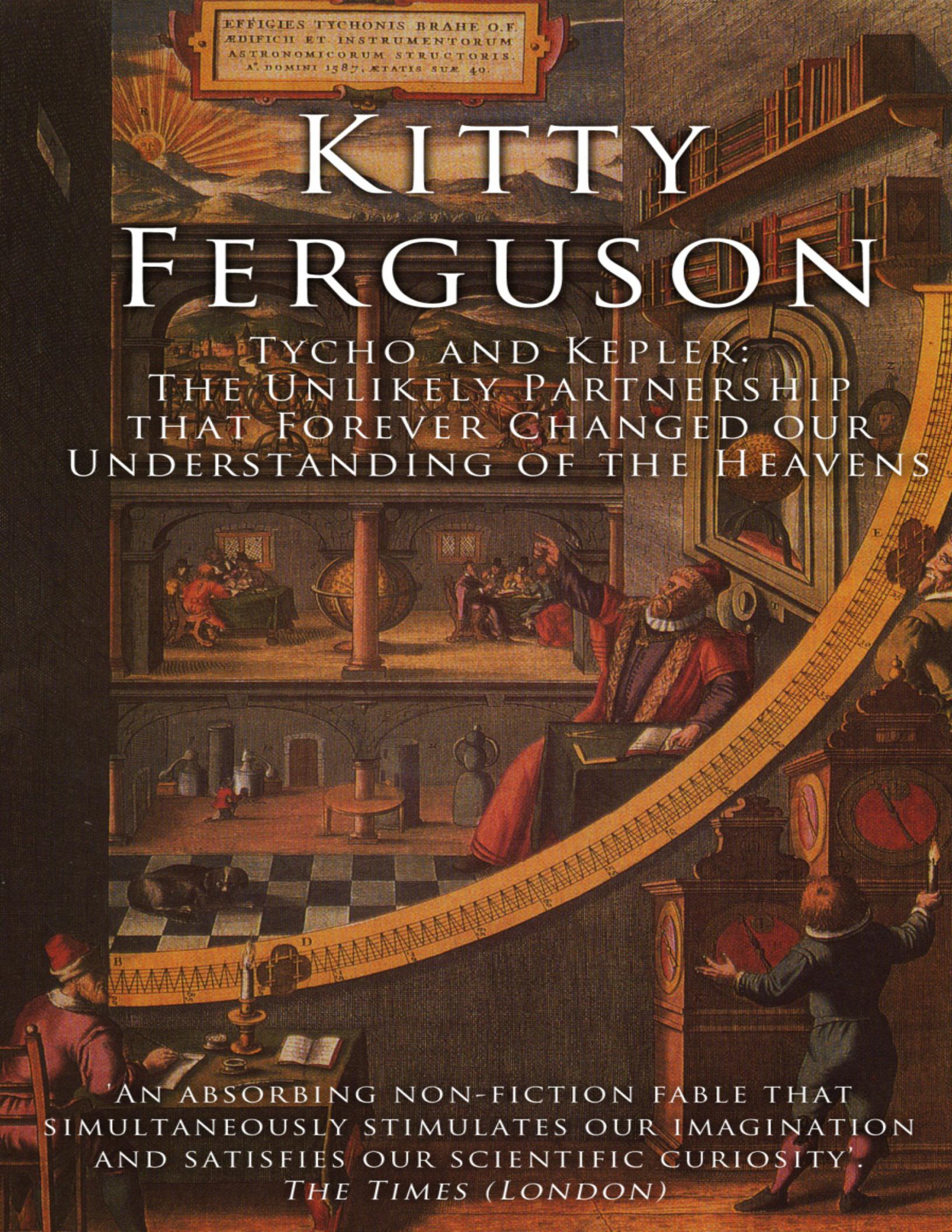




EFFIGIES TYCHONIS BRAHE O.F.
ÆDIFICII ET INSTRUMENTORUM
ASTRONOMICORUM STRUCTORIS.
A. DOMINI 1587. ÆTATIS SUÆ 40.

KITTY FERGUSON

TYCHO AND KEPLER:
THE UNLIKELY PARTNERSHIP
THAT FOREVER CHANGED OUR
UNDERSTANDING OF THE HEAVENS

'AN ABSORBING NON-FICTION FABLE THAT
SIMULTANEOUSLY STIMULATES OUR IMAGINATION
AND SATISFIES OUR SCIENTIFIC CURIOSITY'.
THE TIMES (LONDON)

About the Book

The extraordinary, unlikely tale of Tycho Brahe and Johannes Kepler and their enormous contribution to astronomy and understanding of the cosmos is one of the strangest stories in the history of science.

Kepler was a poor, devoutly religious teacher with a genius for mathematics. Brahe was an arrogant, extravagant aristocrat who possessed the finest astronomical instruments and observations of the time, before the telescope. Both espoused theories that seem off-the-wall to modern minds, but their fateful meeting in Prague in 1600 was to change the future of science.

Set in one of the most turbulent and colourful eras in European history, when medieval was giving way to modern, Tycho and Kepler is a double biography of these two remarkable men.

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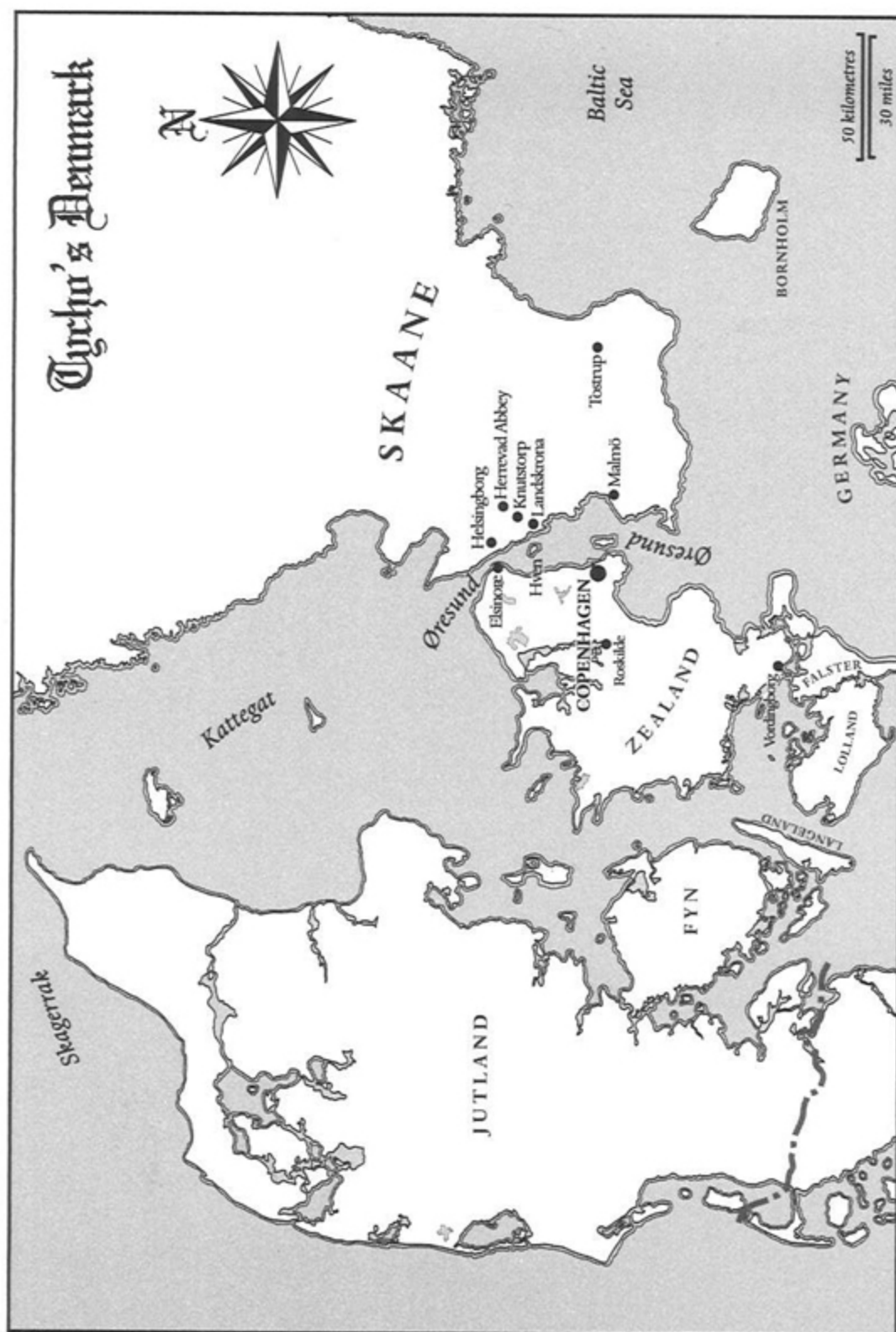
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TYCHO & KEPLER

*The Unlikely Partnership That Forever
Changed Our Understanding of the
Heavens*

KITTY FERGUSON

To my sister, Virginia





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PROLOGUE

ON JANUARY 11, 1600, the carriage of Johann Friedrich Hoffmann, baron of Grünbüchel and Strechau, rumbled out of Graz and took the road north. The baron was a man of great wealth and culture, a member of an elite circle of advisers to Emperor Rudolph II of the Holy Roman Empire. Having fulfilled, for the time being, his occasional duties as a member of the Styrian Diet in the Austrian provincial capital, he was returning to court in Prague, the glittering hub of European political and intellectual life.

Among Hoffmann's acquaintances in Graz was a man considerably beneath his own station in society, an earnest young schoolmaster and mathematician named Johannes Kepler. Hoffmann was impressed by Kepler's intense interest in astronomy, an interest he shared, and was aware that Kepler's talents far surpassed those of an obscure provincial teacher. He also knew that Kepler's present situation as a Protestant in Graz was precarious, for the Counter-Reformation was raging there. Only Kepler's position as district mathematician and the expertise he brought to composing annual astrological calendars that predicted everything from crops to wars had prevented his being expelled from the city in 1598 along with other Protestant teachers and ministers. Hoffmann, for all his lofty status, was a thoughtful, kindly man. It had occurred to him that he might do his youthful friend a service by offering him a ride to Prague in his carriage at no cost to Kepler, who could ill afford such a journey, and an

introduction to a far more experienced and distinguished astronomer who had recently arrived there—whose nose was made of gold and silver.

The magnificent Tycho Brahe, the man with the extraordinary nose, was reputedly a difficult person. He had fallen foul of the Danish king and nobility and fled south as a princely refugee with his common-law wife, their six children, wagonloads of fabulous astronomical and alchemy equipment, and three thousand books. Hoffmann's own library was his passion. He was the sort of man to be drawn to an intellect such as Tycho's and also to admire the brilliant networking that had brought Tycho to Emperor Rudolph. In Prague, Tycho Brahe had flowed through the court like fine honey. Rudolph, an eccentric collector of all manner of curiosities, had welcomed him and promised to support him and his learned pursuits in munificent style.

Hoffmann's invitation to ride in his carriage to Prague was a godsend to Johannes Kepler. There was no man in the world whom he so longed to meet as Tycho Brahe. Kepler had already made inept but not entirely fruitless overtures to him. Tycho had had kind, if condescending, words to say about Kepler's first book and had hinted that he would welcome Kepler to join his coterie of assistants. Alas, Tycho Brahe had been too far away in northern Europe and the journey prohibitively expensive. Suddenly, by the grace of God (Kepler had no doubt that God had a direct hand in such matters), Tycho had moved closer, and Kepler had a free ride to Prague. Never mind that it was a one-way ticket, that he had to leave his wife and stepdaughter behind, that Tycho might not be as eager to meet him as he was to meet Tycho, that there was no guarantee a paying job would result. When the baron's carriage drove out of Graz on January 11 and the driver set the horses to the road north, young Kepler was on board.

The journey took ten days, and Tycho Brahe was not in the city when they arrived. He was at Benátky nad Jizerou,

a clifftop castle several miles to the northeast. Kepler stayed for a few days as a guest in Hoffmann's palace, considering how best to approach Tycho. Then on January 26, a letter arrived from the great man himself, who had heard that Kepler was in Prague. "You will come¹ not so much as guest," Kepler read, "but as very welcome friend and highly desirable participant and companion in our observations of the heavens." Kepler was apparently not to be just one additional beginner assistant.

Nine days later, on February 4, carrying a glowing letter of introduction from Baron Hoffmann, Kepler rode out of Prague, this time in Tycho Brahe's own carriage with Tycho's son, also named Tycho, and an elegant young man named Franz Tengnagel. They crossed the Labe River at Brandeis, where the emperor had a luxurious hunting lodge, and continued through wooded countryside. The trees, except for the numerous pines, were bare. It wasn't until the next day, February 5, that they reached the first significant change in the landscape, the bluff above the Jizerou River. Poised on top, near the cliff edge, was a square three-story structure of generous but pleasing proportions. It was not the formidable, gloomy fortress some castles were. Perhaps Kepler saw—for it had either been completed then or was in the process of creation—a wonderful fresco covering one entire exterior wall, showing hunting scenes with Emperor Rudolph prominently featured.

Kepler counted among his acquaintances several men such as Hoffmann who were of much greater social stature and wealth than himself. Nevertheless, the lord of Benatky whom he met that day came from a world almost completely outside his previous realm of experience and, in spite of their shared scholarly interests, largely beyond his understanding. Kepler was a well-educated but poorly paid schoolmaster who had spent his childhood in an impoverished, dysfunctional family in small towns on the

edge of the Black Forest. By his own description he resembled a little house dog, overeager to please—only occasionally attempting to assert himself by growling or barking and, when he did, succeeding only in causing people to avoid him. Tycho Brahe was renowned throughout Europe as a prince among astronomers and an astronomer among princes; he was supremely well aware of his own superior intellect and status; and he regarded lesser men as just that: lesser men, some of whom he liked and treated well, others not. At the time he met Kepler, he was feeling his age, fifty-three years. Bruised by recent defeats at the hands of enemies in Denmark, he was discouraged about the present state of his work. Nevertheless, he was on his feet again in a different court, lord of an imperial castle, with a promised income from the Holy Roman Emperor that was greater than that drawn by any other man at court. His current public image in Prague was as an elegant and extrovert luminary. Some who had encountered him in different contexts knew he could also be an overbearing, combative, paranoid, and even somewhat malevolent figure.

Though Kepler may have been becoming aware of his own genius, he was still a modest, pious, unassuming, ill-at-ease twenty-eight-year-old in the thrall of a glamorous, formidable, somewhat jaded world figure. Yet in Kepler the mighty Tycho met his match. If Tycho was the dragon of fairy tales, coiled on a fabulous golden hoard—the astronomical observations that he had spent years and a fortune making and now would let almost no one see—then Kepler was the unpromising folklore antihero who was nevertheless endowed with the power to wrest that treasure from him and, from it, forge a new astronomy.

Modern scientists and historians, with hindsight, know this is precisely who Johannes Kepler was. The kindly Hoffmann didn't know; nor did Tycho's son, or Tegnagel.

No one at Benatky Castle suspected . . . with the possible exception of Tycho Brahe himself.

Aware only of what Tycho and Kepler had accomplished before that February day when they met, one would not be likely to identify either of them as a prime candidate for immortality. Both men were engaged in developing theories that to modern eyes seem hopelessly misguided. Yet Johannes Kepler and Tycho Brahe would turn out to be two of a mere handful of men who would precipitate humanity into the modern era of scientific inquiry and discovery. When Kepler's exceptional gifts of imagination and inventiveness, his insistence on mathematical rigor and reasonable physical explanations, and his belief that God had created a universe in which harmony and logic prevail came to grips with Tycho's superb, unyielding observational data, the result would be the revelation of profound laws that govern how the heavenly bodies move. Kepler's struggle to find those laws would itself become a prototype for what science would *be* from that time forward. Sir Isaac Newton was referring to Copernicus, Tycho Brahe, Kepler, and Galileo when he said he had stood "on the shoulders of giants."

The colorful, dangerous world in which Tycho and Kepler lived and worked—the courts, universities, cities, palaces, and hovels of Renaissance Europe—afforded them little peace. Against this background, shaped by it and often at its mercy, they nevertheless stood as towering figures not really conformed to any age or time. Nor was their genius the only thing that set them apart. On a more superficial level, they were truly eccentric personalities. Either man, if encountered in a novel, would seem a fantastic or even absurd invention. The same can be said of many of their acquaintances: the unabashedly villainous Nicolaus Bär, the reclusive emperor Rudolph with his largely imaginary royal treasury, the rascal Rosenkrantz

who sparked Shakespeare's interest, Kepler's mother Katharina, who was tried for witchcraft. . . .

In this setting and among these people, all manner of events conspired to foil Tycho's and Kepler's loftiest and best-considered plans, destroy their happiness, and distract them from their science. However, this same chain of events brought them together and thus secured for them an immortality that they probably would not have achieved otherwise. No wonder Kepler concluded that the benevolent will of God led men along desperately unwanted paths that only later could be recognized as the right ones.

If invisible cords drew Tycho Brahe and Johannes Kepler over the passage of many years to their crucial encounter, and to the brief, strife-torn, amazingly fruitful relationship that followed it, those strands seem to have been moving almost from the moments of their births.

1

LEGACIES

1546-1561

THE ORIGIN OF the Danish castle Knutstorps Borg—in what was once part of Denmark but is now southwest Sweden—pre-dates written and even oral records. One ancient section of wall in the cellar comes from an eleventh-century structure, but no one knows who lived there then or what the building looked like, secluded among gentle folds of meadow and woodland. There are records from the fourteenth century of an inhabited stone keep. It was probably surrounded by the small lake that appears in sixteenth-century drawings. By that time the keep had become a substantial castle home, the ancestral seat of the noble Brahe family. The lake served as a defensive moat with a causeway and drawbridge.

Here, on December 14, 1546, more than half a century before Johannes Kepler's winter journey to Prague and Benatky, Beate Bille, wife of the Danish knight Otte Brahe, gave birth to twin sons. Only one of them lived, and he was christened Tyge (pronounced "Teeguh"), probably in the small stone parish church of the manor at Kågeröd. Tyge, who would later Latinize his name to Tycho, was Otte and Beate's first son and second living child. His parents did not tell him that he had been a twin.

He was also kept ill-informed about an unusual episode in his early childhood. When Tyge was two years old, his young uncle and aunt, Jørgen Brahe and Inger Oxe, abducted him from his parents' castle and carried him to their own stronghold at Tostrup. As far as records show, and as Tycho Brahe understood this bizarre incident when he was older, there was no outraged protest from his mother or father, no family schism, no scandal, and no attempt to recover him. Otte and Beate by then had a second son, Steen, and were expecting another baby. Tycho would later write simply that his uncle Jørgen "without the knowledge¹ of my parents took me away with him while I was in my earliest youth." It seems that was all Tycho knew.

Short of being a member of the royal family, it was impossible to be higher born than young Tyge.^{fn1} His ancestors and his relatives had for generations been powerful leaders who served the Danish kings with consummate skill and loyalty, who knew how to maintain a position of influence amid shifting factions at court and how to regain that position if it happened through some stroke of misfortune to be temporarily lost. On the Brahe side the men were warrior knights, at home in the heavy-drinking military circles of the Danish court and ably commanding and administering royal fiefs. Tyge's great-uncle Axel had been one of the first Danish aristocrats to reject Catholicism, so effectively supporting the Lutheran king Christian III during the Reformation in Denmark in the 1530s that he was chosen to carry the scepter at the coronation in 1537. Tyge's father Otte and his uncle and foster-father Jørgen honed their courtly and military skills during that same period of political and religious upheaval. In 1540, six years before Tyge's birth, the king granted them the joint fiefdom of Storekøbing, a step toward increasingly strategic fiefdoms. Otte would eventually become governor of Helsingborg Castle, the fortress that

guarded the Øresund—the crucial strait that led from the North Sea to the Baltic ([see map, Tycho's Denmark](#)). He would also hold a seat in the Rigsraad, a body of twenty nobles whose responsibility it was to seat kings, appoint regents, declare war, make treaties, and work with the king on a daily basis in affairs of state.

Tyge's forebears on his mother Beate Bille's side of the family had combined that same kind of secular service to the king with high ecclesiastical positions, and these connections had allowed considerable wealth to be channeled to family members who did not enter the church. When the Reformation came in the 1530s, no fewer than six Billes were in the Rigsraad, and most commanded important castles in Denmark and Norway. Less fortunately, seven of the eight Catholic bishops of Denmark were blood relations, linking the family embarrassingly with what turned out to be the losing side. However, by the time of Tyge's birth the Billes were rapidly repairing their fortunes. The marriage of Beate Bille to Otte Brahe was part of that recovery.

Neither the Billes nor the Brahes were scholars. However, Tyge's childhood abduction had made him the intellectual heir to a third line, the Oxes, the ancestors of his aunt and foster mother Inger. The Oxe family was traditionally more learned and cultivated than most of the Danish nobility. The family had arrived from France at the end of the fourteenth century, and hence their roots did not go back as far in Denmark as the Brahes and Billes. Nevertheless, they had produced four members of the Rigsraad before losing their position in civil upheavals at the time of the Reformation. A decade later, at the time of Tyge's birth, the Oxes' political fortunes were soaring again, thanks to Inger's brilliant eldest brother, Peder Oxe. Inger shared something of Peder's intellectual interests and abilities. She was a woman of great charm, intelligence, and social grace. One of her correspondents and closest

friends was the sister of Denmark's King Frederick, Princess Anne, herself a scholar who, despite the time-consuming burden of royal duties and the unlikeliness of the role for a woman of the time, was a skilled alchemist.

Young Tyge was certain to be brought up in a princely fashion, whether he lived with his parents or his uncle and aunt. Having two families gave him an added advantage. He had the attention of an only child in Jørgen's and Inger's castle and would have the support of four younger brothers in Otte's and Beate's family if he later chose to compete in the power politics of the adult world. Most significantly, thanks to the tradition of Inger Oxe's family, Tyge grew up with a somewhat unorthodox view of the world and of the educational and career choices available to him.

There is little record of Tyge's childhood and early youth. Presumably he spent considerable time at his uncle Jørgen's ancestral seat, Tostrup, which was on the side of the province of Skåne that is nearest the Baltic Sea, well to the east of Knutstorp and the Øresund. He also must have visited his parents and his brothers and sisters (seven eventually survived to adulthood) at Knutstorps Borg.

The duties of a Danish knight took Jørgen and almost certainly Inger and their nephew Tyge elsewhere as well. Administering royal fiefs meant periodically spending time in residence, assuring that the buildings and armaments were in a state of repair and ready for defense. However, a nobleman also had to protect his interests at court, networking and second-guessing royal whim. New royal fiefs did not fall one's way if one was continuously absent administering distant royal fiefs, and yet distant royal fiefs did not stay in good enough shape to satisfy the king if one was continually at court. It was a balancing act that required an ambitious vassal to be frequently on the move, and Jørgen clearly carried it off well. Tyge also may have accompanied Inger when she traveled with her own retainers to administer her large share of the Oxe family's

domain. When it came to taking an extensive aristocratic household on the road without ever appearing to be a nomad, a young Danish nobleman such as Tyge had plenty of early experience.

In 1552 Jørgen was promoted to the command of Vordingborg Castle, an enormous medieval stronghold on the south coast of Zealand (Sjælland). Tyge was about six, old enough to participate in some of the pomp and lavish ceremonial entertaining that were part of the life at such an important castle. Vordingborg stood guard over the principal travel route between Copenhagen and the Continent. Duke Ulrich of Mecklenburg and his court rode through the gates in 1556. Princess Elizabeth of Saxony stopped there in 1557 with an escort of no fewer than sixty knights, on the way to visit her grandparents in Denmark. King Christian III himself visited from time to time. Young Tyge was soon no stranger in the company of kings and princes.

Beginning soon after the time of the move to Vordingborg, Tyge began formal schooling. He wrote later that he “was sent to grammar school² in [his] seventh year,” and he continued elementary studies until about the age of twelve. Tyge’s was probably a cathedral school near the castle. At such establishments, sons of the nobility studied side by side with lower-class schoolboys. The curriculum was mostly Latin grammar and religion, with some music and theater, and perhaps Greek and elementary mathematics. Tyge’s father thought Latin was a waste of time, but his uncle Jørgen disagreed and insisted Tyge learn it.

When a nobleman’s son attended grammar school, he usually lodged in the household of a bishop or other highly placed clergyman so that he could continue to develop, as much as possible outside the castle, the niceties of a gentleman. The days when bishops in Denmark were Catholic aristocrats had ended with the Reformation. In

Tyge's school days they were Lutherans of middle-class background, often with large families of their own and not wealthy enough to support luxurious establishments. Nearly all these men had studied at Wittenberg in Germany, and their households emulated those where they had boarded with professors like Martin Luther and Philipp Melanchthon.

Family, boarding students, guests, and colleagues gathered for meals at long tables in a wood-paneled room. Tyge wouldn't have found that too different from mealtimes at the castle except for the conversation. In the household where he lodged, he probably heard for the first time the lively, wide-ranging, intellectual mealtime discussions that traditionally went on around a scholar's table. Mealtime conversation at his uncle's castle, by contrast, would more likely have dealt with warfare, politics, and court gossip.

Tyge Brahe went farther from home to continue his education at the University of Copenhagen when he was twelve—which was not an early age to begin university in those days. He may actually have matriculated, for he recorded the date he began, April 19, 1559. Matriculation was an unusual step for a nobleman's son, because young aristocrats didn't need university degrees as credentials. It was more common for them only to attend selected series of lectures as part of a course of study set by the professor under whose supervision they lived and worked, with no more formal arrangement.

University students lodged with professors rather than bishops or clergymen. Living conditions were comfortable, at least by sixteenth-century standards, because a university appointment, though it did not make a man a member of the nobility, paid fairly well. The professor who provided the lodging also supervised his students' reading and lecture attendance and arranged tutoring with older students residing in the same household. On a smaller,

more personal scale, such a household was not unlike a college at Cambridge or Oxford.

The University of Copenhagen was one of the premier universities of Europe. King Christian III, at whose coronation Tyge's great-uncle had carried the scepter, had set the university on a sound financial footing, and Frederick II, the present king, had enlarged its endowment, ensuring an income from landed estates, tithes, and church properties. Among other benefits, the university had the curious right to every eighth swine grazing in the university forests, which perhaps helped to supply the long tables in the professors' households.

The quality of a student's education depended heavily on whose household he belonged to, and there is no record of where Tyge lodged.³ His uncle and aunt may have placed him in the household of Nicolaus Scavenius, a professor of mathematics, for Tyge's mathematical interests began early, and Scavenius was a client of the Oxe family. On the other hand, he may have lodged in the establishment of Niels Hemmingsen, a renowned professor of theology who would play an interesting walk-on role later in Tycho's life. Anders Sørensen Vedel, who would accompany Tyge on educational journeys abroad, lodged there. Tyge studied Greek and possibly some Hebrew and acquired a classical education with skills in logic, rhetoric, debate, and public speaking, all traditionally considered useful for a young man who intended to follow his forebears into the ranks of the ruling elite.

However, education at Lutheran universities such as Copenhagen went beyond these subjects, largely thanks to Martin Luther's influential follower and friend Philipp Melanchthon. Melanchthon believed that the church could succeed in its mission to teach the path to salvation only if it made education a priority and produced a clergy of scholars strongly grounded in the "liberal arts":⁴ In order to understand the Scriptures and the writings of the church

fathers, one had to have Latin, Greek, and Hebrew. Knowledge of literature and history lent authority to preaching, which benefited even more directly from mastery of rhetoric and dialectic. Thorough comprehension of both the secular and sacred realms called for arithmetic and geometry. Besides their practical applications, these also helped one understand astronomy, which was considered to be the most heavenly of the sciences. Every Lutheran university had at least one professorial chair in these mathematical disciplines. Astronomy established the calendar of the church and opened one to the inspiration of nature and the mind of the Creator, but it also had its practical use as a basis for astrology. The two subjects were in fact not separate then, and one of the primary motives for practicing astronomy and training astronomers was to improve horoscopes. Though his mentor Martin Luther scoffed at such ideas, Melanchthon, along with many other educated people, thought the fate of human beings was closely linked to the stars and planets. Most significantly for Tycho Brahe and, twenty-five years later, for Johannes Kepler, the Philippist university curriculum promulgated by Philipp Melanchthon also embodied the humanist ideal that one could not truly comprehend and master any part of all this knowledge unless one comprehended and mastered the whole of it.

It was in the atmosphere of such broad intellectual ambitions that Tyge's interest in astronomy took shape. An eclipse of the Moon on August 21, 1560, that he either witnessed or heard about when he was thirteen years old, set fire to his already considerable fascination with the subject.^{[fn2](#)}

A surviving list of books Tyge purchased provides some information about the astronomy he studied. The books included Johannes de Sacrobosco's *On the Spheres*, the preeminent introductory astronomy text of the Middle Ages, which Professor Scavenius used in his lectures; Peter

Apian's *Cosmography*, a more advanced book; Johann Regiomontanus's *Trigonometry*; and an ephemeris (a table showing the positions of heavenly bodies on a number of dates in a regular sequence) from Stadius. Tyge inscribed his name and the date of purchase, "Anno 1561," in the Apian *Cosmography*, using a Latinized form of Tyge—Tycho. Tycho spelled the name sometimes with *ij*, sometimes with *ÿ*, never as Taecho, indicating that he intended it to be pronounced Teeko, or (closer to the Danish pronunciation) as though the *y* were a German *ü*.



ASTRONOMERS IN THE ERA when Tycho lived thought of their subject as being separated into two parts, described as the *primum* and *secundum mobile*. The *primum* dealt with the way the celestial sphere as a whole “rose” and “set” every night, and the fact that the particular portion of that celestial sphere visible at night changes throughout the year in a regular annual cycle. One needed trigonometry, the most advanced form of mathematics then known, to understand these phenomena in detail, so classroom discussions usually took place on a more general, qualitative level. The *secundum mobile*, involving planetary positions and motions, did require trigonometry.

Typical study of the *secundum mobile* began with Euclid's *Geometry*, a work that had endured since around 300 B.C. (Euclidean geometry is still taught in basic geometry classes.) From there the course went on to trigonometry and planetary theory. In Tycho's university years, planetary theory still meant theory according to Ptolemaic astronomy.

When Greek and Alexandrian scholars such as Aristotle, Hipparchus, and Claudius Ptolemaeus (known as Ptolemy) peered at the night sky, they saw virtually the same panorama that is visible with the naked eye on a clear night

now, far enough away from city light. Thirteen centuries after Ptolemy, Copernicus and Tycho Brahe also had no other view than that, for they too lived before the advent of the telescope. Ancient sky-watchers, by scrutinizing the sky with care over long periods of time, had discovered that the motions of the heavenly bodies are not random. Stellar and planetary movement is intricate, but it was possible to calculate well in advance what paths these objects would take and where they would be at a future time. Close observers knew early on that though change, chance, and whim seem to be the rule on Earth, the heavens perform a complex but predictable dance. That dichotomy became a key part of the ancient and medieval worldview.

The best way to describe and explain what one observed in the skies with the naked eye was to think of Earth as the center, with everything else moving around it. That concept still works admirably for purposes of navigation. In fact, to think that things might operate differently demands a leap of fancy that would seem ludicrous to anyone not steeped since childhood in Sun-centered astronomy.

Early astronomers knew, however, that there are phenomena that one observes looking at the sky with greater care over a period of time that seem at odds with a system in which Earth is the center and everything else is in motion around it. Rather than decide that these glitches were significant and stubborn enough to require one to discard the Earth-centered view of the universe entirely and look for another, they chose to attempt to explain the glitches, if they could, *within* an Earth-centered system. Ptolemy's success in doing so was one of the most impressive intellectual achievements in history.

Ptolemy did not begin with a tabula rasa in the second century A.D. by gazing up at the night sky as it appeared to him from near the mouth of the Nile at Alexandria. Instead, he drew together the results of centuries of previous speculation and observation and pondered all of this afresh,

applying his own superb mathematical talents. The result, set down in his *Almagest* and other works, was a cohesive explanation of the cosmos that endured and dominated Islamic and, later, Western thinking for fourteen centuries. Finally, even as it was rejected, it provided the springboard for Copernican astronomy and all that has followed from that.

Part of the intellectual worldview of the era in which Ptolemy lived was that the actual appearance of things had to be taken into account in trying to figure out what constitutes “reality.” To be plausible, an explanation had to “save the appearances,” not contradict them. Though in the early seventeenth century, after Tycho’s death, some Ptolemaic astronomers refused to look through Galileo’s telescope when it seemed to reveal things that contradicted Ptolemy, Ptolemy himself did not ignore “what can be seen up there” in favor of some mathematical fable. He would have looked through Galileo’s telescope. However, nothing about the appearance of the heavens, as Ptolemy and his predecessors were able to study them, forced them or him to reject the intellectual tradition that held that all heavenly movement occurred in perfect circles and spheres.

The “spheres” were not the planets themselves, but transparent glass spheres in which the planets traveled. Astronomers spoke of “crystalline” spheres, each having an inner and an outer wall, with space between the two walls for the planet to move. The spheres were nested one within the other, with each successive sphere just small enough to fit within the one outside it. They were tightly packed with no extra space left between them, but not so tightly as to prevent their moving, one against the other, with the outer surface of one sphere scraping against the inner surface of the next larger.

Sitting at the center of this system of nested crystalline spheres was Earth. The outermost sphere in the

arrangement was the sphere of the stars. The innermost sphere—nearest Earth—was the sphere in which the Moon moved. The others each contained a planet, except for the one that contained the Sun. Each body could move only between the outer and inner walls of its own sphere. Not all scholars agreed about the nature and mechanics of these spheres, but there was general agreement that a planet couldn't break through those walls and enter another planet's sphere. In fact, in this system, *no* heavenly body could break through the walls of a sphere. That would shatter it. This last restriction became significant for Tycho Brahe and Johannes Kepler.

One of the most stubborn problems for ancient astronomers was how to explain a phenomenon known as the “retrograde” movement of the planets. A planet normally moves from west to east against the background of stars. However, during a period known as its “opposition,” when it is on the opposite side of Earth from the Sun, a planet appears for a while to move from east to west. Scholars were faced with the problem of explaining this in a model that required uniform movement and perfect circles and spheres. The solution, devised before Ptolemy, was ingenious.

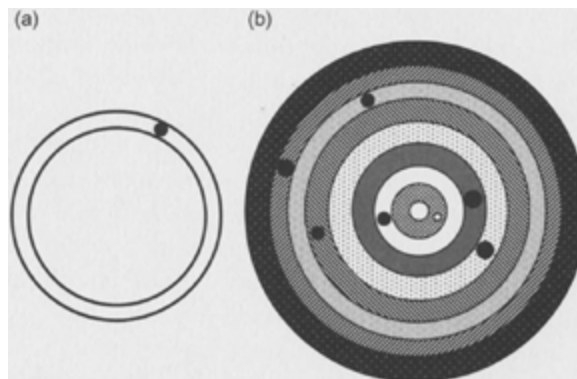


Figure 1.1: Early astronomers thought of the planets and the Sun and Moon as each moving in its own “crystalline” sphere (a), with these spheres nested one within the other and Earth at the center (b).

A carousel is a helpful analogy for understanding the idea: On the simplest carousel, the horses are bolted directly to the floor, which is a large, rotating disk. They circle, as the disk rotates, but they have no other motion. If the amusement park is dark and there is a light attached to the head of one horse, an observer, positioned at the center of the carousel in such way as not to move with the rotating disk, sees the light circle steadily. It will have no “retrograde motion”—never seem to back up.

Suppose instead that the observer does occasionally see the light stop, back up for a while, and then resume its former motion. This isn’t a random occurrence, as it might be if the light were on the cap of the ticket taker as he moves among the riders, or if a large firefly happened to venture into the carousel. The backing up happens regularly and predictably. The observer decides that the horse with the light on its head must not be bolted directly to the rotating disk. Instead, each horse is part of a minicarousel perched near the edge of that disk. Hence, in addition to their motion with the disk, the horses are moving around in smaller circles, chasing their tails.

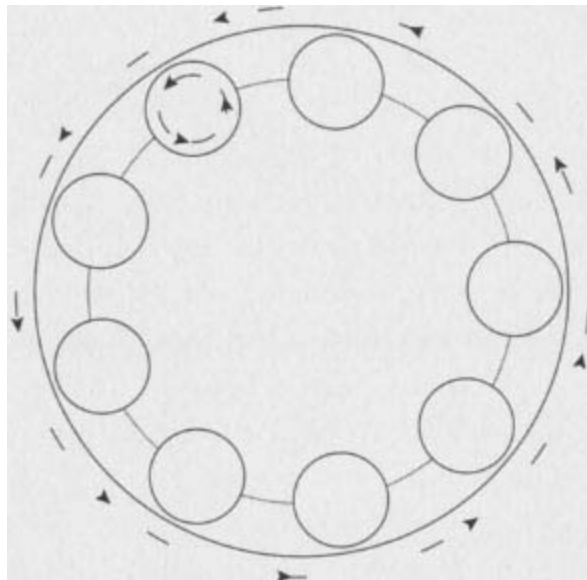


Figure 1.2: On this carousel the horses are attached to smaller rotating disks that ride on the perimeter of the large, rotating floor. As the carousel turns, the horses not only make their way all the way around the large circle but also move in smaller circles, chasing their tails.

By the same token, in a stroke of insight, ancient astronomers realized that if the planets moved continually in smaller circles centered on the rim of a larger circle centered on Earth, the result would be the regularly occurring retrograde motion they were observing.

The technical term in Ptolemaic astronomy for the small circle in which a planet moved was *epicycle*. The larger circle on which the epicycles turned (in [figure 1.2](#), the inner circle—the radius at which the minicarousels are bolted to the floor) was the *deferent*. By adjusting the size, direction, and speed of the epicycles, astronomers could explain many irregularities they observed in the way the planets, Sun, and Moon move. A planet traveling in its epicycle would sometimes be closer to Earth and sometimes farther away, which explained apparent variations in its brightness. In Ptolemaic astronomy a planet's sphere was just large enough for the planet to cartwheel along on its epicycles.

Tycho, Kepler, and their peers at university also learned the use of the *eccentric*. With an eccentric, the planet (perhaps simultaneously traveling in an epicycle) orbited Earth, but the orbit wasn't centered precisely on Earth. Its center was a point a small distance away from Earth.