1

The Dome of Heaven

You may have heard the music of Man but not the music of Earth. You may have heard the music of Earth but not the music of Heaven.

—Chuang Tzu

Had we never seen the stars, and the sun, and the heaven, none of the words which we have spoken about the universe would ever have been uttered. But now the sight of day and night, and the months and the revolutions of the years, have created number, and have given us a conception of time, and the power of enquiring about the nature of the universe; and from this source we have derived philosophy, than which no greater good ever was or will be given by the gods to mortal man.

—Plato

The skies of our ancestors hung low overhead. When the ancient Sumerian, Chinese, and Korean astronomers trudged up the steps of their squat stone ziggurats to study the stars, they had reason to assume that they obtained a better view that way, not, as we would say today, because they had surmounted a little dust and turbulent air, but because they had got themselves appreciably closer to the stars. The Egyptians regarded the sky as a kind of tent canopy, supported by the mountains that demarked the four corners of the earth, and as the mountains were not all that high, neither, presumably, were the heavens; the gigantic Egyptian constellations hovered close over humankind, as proximate as a mother bending to kiss a sleeping child. The Greek sun was so nearby that Icarus had achieved an altitude of only a few thousand feet when its heat melted the wax in his wings, sending the poor boy plunging into the uncaring Aegean. Nor were the Greek stars significantly more distant; when Phaethon lost control of the sun it veered into the stars as suddenly as a swerving chariot striking a signpost, then promptly rebounded to earth (toasting the Ethiopians black on its way down).

But if our forebears had little notion of the depths of space, they were reasonably well acquainted with the two-dimensional motions of the stars and planets against the sky, and it was by studying these motions that they were led, eventually, to consider the third dimension as well. Since the days of the ancient Sumerians and probably before, there had been students of the night sky willing to devote their evening hours to the lonely business of squinting and straining to take sightings over aligned rocks or along wooden quadrants or simply across their fingers and thumbs, patiently keeping records of what they saw. It was a lot of trouble. Why did they bother?

Part of the motive may have had to do with the inchoate longing, mysterious but persistent then as now, to express a sense of human involvement with the stars. As Copernicus noted, reverence for the stars runs so deep in human consciousness that it is embedded in the language itself. "What is nobler than the heavens," he wrote, "the heavens which contain all noble things? Their very names make this clear: *Caelum* (heavens) by naming that which is beautifully carved; and *Mundus* (world), purity and elegance."[1] Even Socrates, though personally indifferent toward astronomy, conceded that the soul "is purified and kindled afresh" by studying the sky.

There were obvious practical incentives as well. Navigation, for one: Mariners could estimate their latitude by measuring the elevation of the pole star, and could tell time by the positions of

the stars, and these advantages were sufficiently appreciated that seafaring peoples codified them in poetry and mythology long before the advent of the written word. When Homer says that the Bear never bathes, he is passing along the seafarer's knowledge that Ursa Major, the constellation that contains the Big Dipper, is circumpolar at Mediterranean latitudes—that is, that it never sinks beneath the ocean horizon.

Another practical motive was timekeeping. Early farmers learned to make a clock and a calendar of the moving sky, and consulted almanacs etched in wood or stone for astronomical guidance in deciding when to plant and harvest their crops. Hesiod, one of the first poets whose words were written down, emerges from the preliterate era full of advice on how to read the sky for clues to the seasons:

> When great Orion rises, set your slaves
> To winnowing Demeter's holy grain
> Upon the windy, well-worn threshing floor. . . .
> Then give your slaves a rest; unyoke your team.
> But when Orion and the Dog Star move
> Into the mid-sky, and Arcturus sees
> The rosy-fingered Dawn, then Perseus, pluck
> The clustered grapes, and bring your harvest home. . . .
> When great Orion sink, the time has come
> To plough; and fittingly, the old year dies.[2]

The hunter-gatherers who preceded the farmers also used the sky as a calendar. As a Cahuilla Indian in California told a researcher in the 1920s:

> The old men used to study the stars very carefully and in this way could tell when each season began. They would meet in the ceremonial house and argue about the time certain stars would appear, and would often gamble about it. This was a very important matter, for upon the appearance of certain stars depended the season of the crops. After several nights of careful watching, when a certain star finally appeared, the old men would rush out, cry and shout, and often dance. In the spring, this gaiety was especially pronounced, for . . . they could now find certain plants in the mountains. They never went to the mountains until they saw a certain star, for they knew they would not find food there previously.[3]

Stonehenge is one of thousands of old time-reckoning machines the moving parts of which were all in the sky. The Great Pyramid at Giza was aligned to the pole star, and it was possible to read the seasons from the position of the pyramid's shadow. The Mayans of ancient Yucatan inscribed stone monuments with formulae useful in predicting solar eclipses and the heliacal rising of Venus (i.e., its appearance westward of the sun, as a "morning star"). The stone medicine wheels of the Plains Indians of North America ticked off the rising points of brighter stars, informing their nomadic architects when the date had come to migrate to seasonal grazing lands. The twenty-eight poles of Cheyenne and Sioux medicine lodges are said to have been used to mark the days of the lunar month: "In setting up the sun dance lodge," said Black Elk, a priest of the Oglala Sioux, "we are really making the universe in a likeness."[4]

Political power presumably played a role in early efforts to identify periodic motions in the sky, inasmuch as what a man can predict he can pretend to control. Command of the calendar gave priests an edge in the hardball politics of the Mayans, and Christopher Columbus managed to cow the Indians of Hispaniola into providing food for his hungry crew by warning that the moon otherwise would "rise angry and inflamed to indicate the evil that God would inflict on them." Writes Columbus's son Ferdinand, in his journal entry for the night of February 29, 1504:

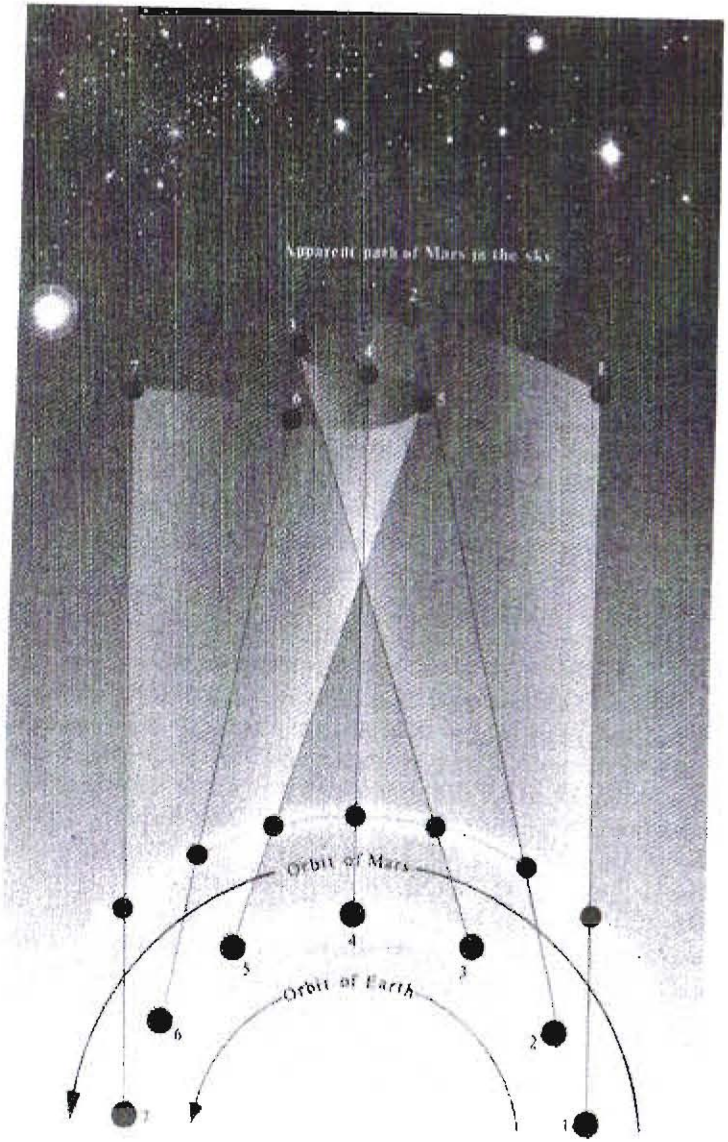
> At the rising of the moon the eclipse began, and the higher the moon rose the more the eclipse increased The Indians observed it, and were so frightened that with cries and lamentations they ran from every side to the ships, carrying provisions, and begged the Admiral by all means to intercede for them with God that he might not make them feel the effects of his wrath, and promised for the future, diligently to bring all he had need of. . . . From that time forward they always took care to provide us with all that was necessary, ever praising the God of the Christians.[5]

But the better acquainted the prehistoric astronomers became with the periodic motions they found in the night sky, the more complicated those motions proved to be. It was one thing to learn the simple periodicities—that the moon completes a circuit of the zodiacal constellations every 28 days, the sun in 365¼ days, the visible planets (from the Greek *planetes*, for "wanderers") at intervals ranging from 88 days for fleet-footed Mercury to 29½ years for plodding Saturn. It was another and more baffling matter to learn that the planets occasionally stop in their tracks and move backward—in "retrograde"—and that their paths are tilted relative to one another, like a set of ill-stacked dishes, and that the north celestial pole of the earth precesses, wobbling in a slow circle in the sky that takes fully 26,000 years to complete.*

The problem in deciphering these complexities, unrecognized at the time, was that the earth from which we view the planets is itself a planet in motion. It is because the earth orbits the sun while rotating on its tilted axis that there is a night-by-night shift in the time when any given star rises and sets at a given latitude. The earth's precessional wobble slowly alters the position of the north celestial pole. Retrograde motion results from the combined wanderings of the earth and the other planets; we overtake the outer planets like a runner on an inside track, and this makes each appear first to advance, then to balk and retreat across the sky as the earth passes them. Furthermore, since their orbits are tilted relative to one another, the planets meander north and south as well as east and west.

These complications, though they must have seemed a curse, were in the long run a blessing to the development of cosmology, the study of the universe at large. Had the celestial motions been simple, it might have been possible to explain them solely in terms of the simple, poetic tales that characterized the early cosmologies. Instead, they proved to be so intricate and subtle that they could not be predicted accurately without eventually coming to terms with the physical reality of how and where the sun, moon, and planets actually move, in real, three-dimensional space. The truth is beautiful, but the beautiful is not necessarily true: However aesthetically pleasing it may have been for the Sumerians to imagine that the stars and planets swim back from west to east each day

*This phenomenon, called the precession of the equinoxes, was known to the ancient Greeks and may have been discovered even earlier. Georgio de Santillana, in his book *Hamlet's Mill*, identifies it with the ancient myth of Amlodhi (later Hamlet), the owner of a giant salt grinder that sank to the bottom of the sea while being transported by ship. The mill has ground on ever since, creating a whirlpool that slowly twists the heavens. Whether or not it describes precession, the myth of Hamlet's mill certainly endures; I first heard it at the age of nine, in a rural schoolyard in Florida, from a little girl who was explaining why the ocean is salty.



Retrograde motion of Mars occurs when Earth overtakes the more slowly moving outer planet, making Mars appear to move backward in the sky.

via a subterranean river beneath a flat earth, such a conception was quite useless when it came to determining when Mars would go into retrograde or the moon occult Jupiter.

Consequently the idea slowly took hold that an adequate model of the universe not only should be internally consistent, like a song or a poem, but should also make accurate predictions that could be tested against the data of observation. The ascendency of this thesis marked the beginning of the end of our cosmological childhood. Like other rites of passage into adulthood, however, the effort to construct an accurate model of the universe was a bittersweet endeavor that called for hard work and uncertainty and deferred gratification, and its devotees initially were few.

One was Eudoxus. He enters the pages of history on a summer day in about 385 B.C., when he got off the boat from his home town of Cnidus in Asia Minor, left his meager baggage in cheap lodgings near the docks, and walked five miles down the dusty road to Plato's Academy in the northwestern suburbs of Athens. The Academy was a beautiful spot, set in a sacred stand of olive trees, the original "groves of academe," near Colonus, blind Oedipus' sanctuary, where the leaves of the white poplars turned shimmering silver in the wind and the nightingales sang day and night. Plato's mentor Socrates had favored the groves of academe, which even Aristophanes the slanderer of Socrates described lovingly as "all fragrant with woodbine and peaceful content."[6]

Beauty itself was the principal subject of study at the Academy, albeit beauty of a more abstract sort. LET NONE BUT GEOMETERS ENTER HERE, read the motto inscribed above the door, and great was the general enchantment with the elegance of geometrical forms. Geometry (*geo-metry*, "the measurement of the earth") had begun as a practical affair, the method employed by the Egyptian rope-stretchers in the annual surveys by which they reestablished the boundaries of farmlands flooded by the Nile. But in the hands of Plato and his pupils, geometry had been elevated to the status approaching that of a theology. For Plato, abstract geometrical forms *were* the universe, and physical objects but their imperfect shadows. As he was more interested in perfection than imperfection, Plato wrote encomiums to the stars but seldom went out at night to study them.

He backed this view with an imposing personal authority. Plato was not only smart, but rich—an aristocrat, one of the "guardians" of Greek society, descended on his mother's side from Solon the lawmaker and on his father's from the first kings of Athens—and physically impressive; *Plato*, meaning "broad-shouldered," was a nickname bestowed upon him by his gymnastics coach when as a youth he wrestled in the Isthmian Games. Eudoxus, we may assume, was suitably impressed. He was, however, a geometer in his own right—he was to help lay the foundations of Euclidean geometry and to define the "golden rectangle," an elegant proportion that turns up everywhere from the Parthenon to the paintings of Mondrian—and, unlike Plato, he combined his abstract mathematical reasonings with a passion for the physical facts. When he made his way to Egypt (a pilgrimage to the seat of geometrical wisdom that many Greek thinkers undertook, though Plato seems never quite to have got around to it), Eudoxus not only conducted research in geometry but applied it to the stars, building an astronomical observatory on the banks of the Nile and there mapping the sky. The observatory, though primitive, evinced his conviction that a theory of the universe must answer to the verdict, not only of timeless contemplation, but of the ceaselessly moving sky.

When the mature Eudoxus returned to the Academy, now as a renowned scholar with his own retinue of students, he set to work crafting a model of the cosmos that was meant to be both Platonically pleasing and empirically defensible. It envisioned the universe as composed of concentric spheres surrounding the earth, itself a sphere.* This in itself would have gratified Plato, who esteemed the sphere as "the most perfect" of the geometric solids, in that it has the minimum possible surface area relative to the volume of space it encloses. But the Eudoxian universe was also intended to better fit the observed phenomena, and this aspiration mandated complexity. To the simple, spherical cosmos that had been proposed by Parmenides a century earlier, Eudoxus added more spheres. The new spheres dragged and tugged at those of the sun, moon and planets, altering their paths and velocities, and by adjusting their rates of rotation and the inclination of their axes Eudoxus found that he could, more or less, account for retrograde motion and other intricacies of celestial motion. It took a total of twenty-

*By Eudoxus' day, all educated Greeks accepted that the earth was spherical, on the strength of such evidence as the shape of the shadow it casts on the moon during lunar eclipses.

seven spheres to do the job. This was more than Plato would have preferred, but it answered somewhat more closely to the data than had the preceding models. The hegemony of pure, abstract beauty had begun its slow retreat before the sullen but insistent onslaught of the material world.

But, ultimately, even so complex a cosmos as that of Eudoxus proved inadequate. The data base kept improving—with the conquest of Babylon by Alexander the Great in 330 B.C., the Greeks gained access to such Babylonian astronomical records as had previously eluded them, while continuing to make at least intermittent observations of their own—and Eudoxus' model failed to explain the subtleties revealed by this more ample and refined information. Thus began the phoenixlike cycle of the *science* of cosmology, where theories, however grand, are held hostage to empirical data that has the power to ruin them.

The next round fell, for better or worse, to Aristotle. Routinely described in the textbooks as an empiricist alternative to Plato, Aristotle was, indeed, relatively devoted to observation; he is said, for instance, to have spent his honeymoon collecting specimens of marine life. But he was also addicted to explanation and intolerant of ambiguity, qualities not salutary in science. A physician's son, he inherited a doctor's bedside habit of having a confident and reassuring answer to every anxious question. When pressed, this cast of mind made him credulous (women, he asserted, have fewer teeth than men) and propelled him to the extremities of empty categorizing, as when he observed that "animals are to be divided into three parts, one that by which food is taken in, one that by which excrement is discharged, and the third the region intermediate between them."[7] Aristotle wrote and lectured on logic, rhetoric, poetry, ethics, economics, politics, physics, metaphysics, natural history, anatomy, physiology, and the weather, and his thinking on many of these subjects was subtle as dewfall, but he was not a man to whose lips sprang readily the phrase, "I do not know." His mind was a killing jar; everything that he touched he both illuminated and anesthetized.

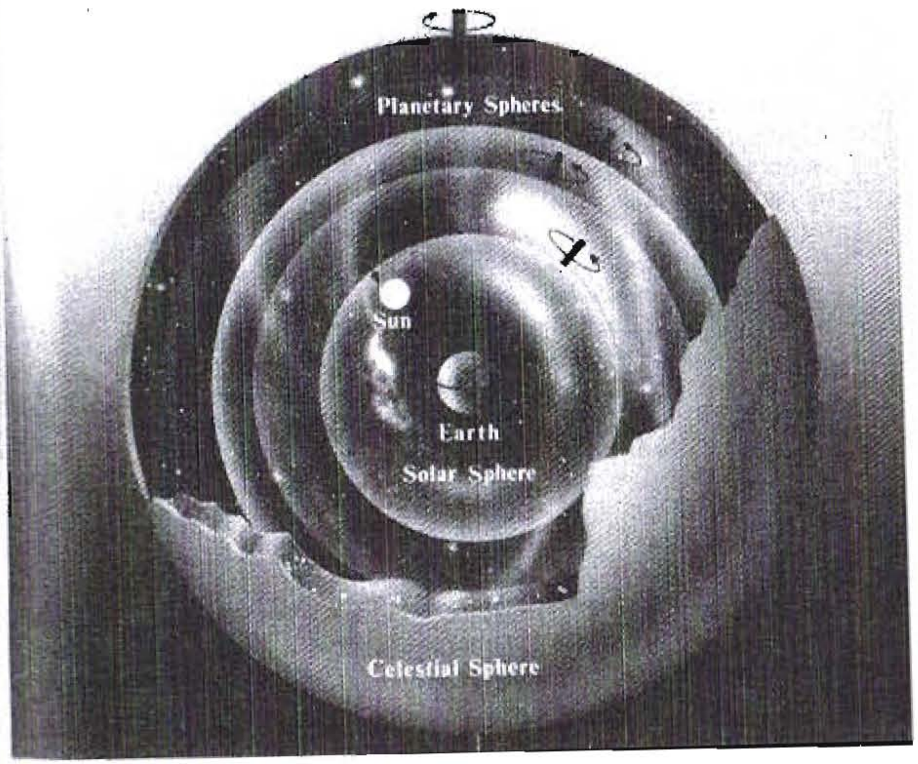
Nobody really likes a man who knows everything, and Aristotle became the first known victim of the world's first academic politics. Though he was an alumnus of the Academy and its most celebrated teacher, and clearly the man best qualified to succeed Plato as its director, he was twice passed over for the post. He then took the only satisfactory course open to a man of his stature, and stalked off to teach at another institution. As there *was* no other academic institution, he was obliged to found one; such was the origin of the Lyceum.

When it came time for Aristotle to declaim on the structure of the universe, he based his model on the heavenly spheres of Eudoxus, whom he had esteemed at the Academy for his moderate character as well as for his peerless accomplishments in astronomy. As his research assistant on the cosmology project Aristotle chose the astronomer Callippus, a native of Eudoxus' adopted home of Cyzicus. Together Aristotle and Callippus produced a model—consistent, symmetrical, expansive, and graceful to contemplate—that ranks among the most stirring of history's many errant cosmologies. Enshrined in Aristotle's book *De Caelo* (*On the Heavens*), it was to beguile and mislead the world for centuries to come.

Its details need not detain us; they consisted principally of adding spheres and adjusting their parameters, with the result that the universe now sported fully fifty-five glistening, translucent spheres. Beyond its outermost sphere, Aristotle argued on exquisite epistemological grounds, nothing could exist, not even space. At its center sat an immobile Earth, the model's shining diadem and its fatal flaw.

Confronted with an inevitable disparity between theory and observation, cosmologists who worked from the geocentric hypothesis had little choice but to keep making their models ever more complicated. And so cosmology was led into a maze of epicycles and eccentrics in which it would remain trapped for over a thousand years. The virtuoso of this exploration was Claudius Ptolemy.

He was born in the second century A.D. in Ptolemais on the Nile, and funding for his astronomical studies came from the Ptolemaic dynasty via the museum of Alexandria. Whatever his shortcomings—and many have been exposed, including evidence that he laundered some of his data—he was a hardworking astronomer and no armchair theorist. He charted the stars from an observatory at Canopus, a city named for a star, situated fifteen miles east of Alexandria, and was acquainted with atmospheric refraction and extinction and many of the other tribulations that bedevil the careful observer. He titled his principal cosmological work *Mathematical Syntaxis*, meaning "the mathematical composition," but it



Aristotle's universe consisted of spheres nested within spheres, their axes and directions of rotation adjusted to approximate the observed motions of the sun, moon, and stars across the sky. (Not to scale.)

has come down to us *Almagest*, Arabic for "the greatest." What it did so splendidly was predict the motions of the sun, moon, and stars more accurately than had its predecessors.

The epicycles and eccentrics by which Ptolemy sought to reconcile theory and observation had been introduced by the geometer Apollonius of Perga and refined by the astronomer Hipparchus. Epicycles were little circular orbits imposed upon the orbits of the planets: If a planet for Aristotle circled the earth like an elephant on a tether, the same planet for Ptolemy described the path of a stone whirled on a string by the elephant's rider. Eccentrics further improved the fit between the inky page and the night sky, by moving the presumptive center of the various heavenly spheres to one side of the center of the universe. To these motions Ptolemy added another, circular motion pursued by the center of the planetary spheres: The elephant's tether pole itself now orbited the center of the universe, hauling the whole system of spheres and epicycles back and forth so that planets could first approach the earth and then recede from it.

The system was ungainly—it had lost nearly all the symmetry that had commended celestial spheres to the aesthetics of Aristotle—but it worked, more or less. Wheeling and whirring in Rube Goldberg fashion, the Ptolemaic universe could be tuned to predict almost any observed planetary motion—and when it failed, Ptolemy fudged the data to make it fit. In its elaboration, and in the greater elaborations that later astronomers were obliged to add, it made predictions accurate enough to maintain its reputation as "the greatest" guide to heavenly motion from Ptolemy's day down to the Renaissance.

The price Ptolemy's followers paid for such precision as his model acquired was to forsake the claim that it represented physical reality. The Ptolemaic system came to be regarded, not as a mechanical model of the universe, but as a useful mathematical fiction. All those wheels within wheels were not actually out there in space—any more than, say, the geometrical boundary lines recorded in the Alexandrian land office represented real lines drawn across the silted farmland along the Nile. As the fifth-century Neoplatonist Proclus noted, "These circles exist only in thought. . . . They account for natural movements by means of things which have no existence in nature."[8] Ptolemy himself took the position that the complexities of the model simply reflected those found in the sky; if the solution was inelegant, he noted, so was the problem:

> So long as we attend to these models which we have put together, we find the composition and succession of the various motions awkward. To set them up in such a way that each motion can freely be accomplished hardly seems feasible. But when we study what happens in the sky, we are not at all disturbed by such a mixture of motions.[9]

The aim of the theory, then, was not to depict the actual machinery of the universe, but merely to "save the appearances." Much fun has been made of this outlook, and much of it at Ptolemy's expense, but science today has frequent recourse to intangible abstractions

of its own. The "space-time continuum" depicted by the general theory of relativity is such a concept, and so is the quantum number called "isospin," yet both have been highly successful in predicting and accounting for events in the observed world. It should be said in Ptolemy's defense that he at least had the courage to admit to the limitations of his theory.

The phrase to "save the appearances" is Plato's, and its ascension via the Ptolemaic universe marked a victory for Platonic idealism and a defeat for empirical induction. Plato shared with his teacher Socrates a deep skepticism about the ability of the human mind to comprehend nature by studying objects and events. As Socrates told his friend Phaedrus while they strolled along the Ilissus, "I can't as yet 'know myself,' as the inscription at Delphi enjoins, and so long as that ignorance remains it seems to me ridiculous to inquire into extraneous matters."[10] Among these "extraneous matters" was the question of the structure of the universe.

Aristotle loved Plato, who seems not entirely to have returned his devotion; their differences went beyond philosophy, and sounded to the depths of style. Plato dressed plainly, while Aristotle wore tailored robes and gold rings and expensive haircuts. Aristotle cherished books; Plato was wary of men who were too bookish.* With a touch of irony that has survived the centuries, Plato called Aristotle "the brain."

Aristotle, for all his empirical leanings, never lost his attachment to the beauty of Plato's immortal geometrical forms. His universe of lucid spheres was a kind of heaven on earth, where his spirit and Plato's might live together in peace. Neither science nor philosophy has yet succeeded where Aristotle failed. Consequently his ghost and Plato's continue to contend, on the pages of the philosophical and scientific journals and in a thousand laboratories and schoolrooms. When philosophers of science today wrestle with

*In Plato's *Phaedrus*, Socrates recounts an old story of how the legendary King Thamus of Egypt had declined the god Theuth's offer to teach his subjects how to write. "What you have discovered is a recipe not for memory, but for reminder," says King Thamus. "And it is no true wisdom that you offer your disciples, but only its semblance, for by telling them of many things without teaching them you will make them seem to know much, while for the most part they know nothing, and as men filled, not with wisdom, but with the conceit of wisdom, they will be a burden to their fellows." This remains one of the most prophetic denunciations of the perils of literacy ever enunciated—although, of course, it is thanks to the written word that we know of it.

such questions as whether subatomic particles behave deterministically, or whether ten-dimensional space-time represents the genuine architecture of the early universe or is instead but an interpretive device, they are in a sense still trying to make peace between old broadshoulders and his bright brash student, "the brain."

Coming of Age in the Milky Way

Timothy Ferris

Anchor Books
DOUBLEDAY
NEW YORK LONDON TORONTO SYDNEY AUCKLAND