20 Longitude and Latitude plus Two Greek Mapmakers

[The Lord] telleth the number of the stars; he calleth them all by their names.

—Psalm 147:4, Hebrew Bible (King James Version)

The stars about the lovely Moon hide their shining forms when it lights up the Earth at its fullest.

—Sappho (lived sixth century B.C.E.), Greek poet, *Fragment 4* ("Some say there are nine Muses, but they are wrong. Look at Sappho of Lesbos; she makes ten," wrote Plato.)

Hipparchus did a bold thing, that would be rash even for a god, namely to number the stars for his successors and to check off the constellations by name. For this he invented instruments by which...it could easily be discovered not only whether stars perish and are born, but also whether any of them change their positions or are moved and also whether they increase or decrease in magnitude. He left the heavens as a legacy to all humankind, if anyone be found who could claim that inheritance.

—Pliny the Elder (ca. 23–ca. 79 C.E.), Roman statesman and scholar, *Natural History*

It's easy to measure the Earth. Well, it did take tens of thousands of years to get it right—and satellites helped a lot—but Earth is made for mapping. It's punctuated with rivers and mountains and oceans and coastlines that are points of reference; they put things in place.

Mapping the night sky is something else. All you have are points of light—stars, mostly. That didn't stop Eudoxus (yoo-DAHK-sus) of Cnidus, another of those persistent Greeks, who, about 350 B.C.E., decided to map the sky. He realized that the heavens needed markers in order to create regions. So he put the northern polestar (which was Kochab back then, not Polaris—see page 62) in the middle of his map and drew imaginary lines fanning out from it, like

SKYLINES

This sky map (below), from a German encyclopedia called *Bilderatlas* (1860), uses celestial coordinates similar to those that Eudoxos created. At the center sits the north celestial pole, an imaginary North Pole in the sky. The North Pole on Earth is at 90°N latitude; its sky-high counterpart is at 90° declination (a term for celestial latitude). The first ring of declination is 80°; the second is 70°; and so on down to 0° declination, the biggest ring. That's the celestial equator, an imaginary circle above Earth's equator. Declinations south of 0° use negative numbers: –10°, –20°, etc.

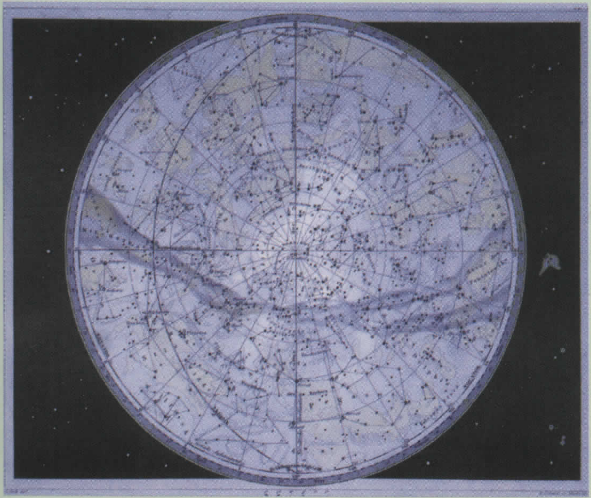
The lines radiating from the celestial pole like spokes of a wheel are called right ascensions. Count them (below left). Like longitude lines, there are 24—one for each hour of the day. That's how they're labeled: 1 hour (h), 2 hour, etc., with spaces in between marked in minutes (m).

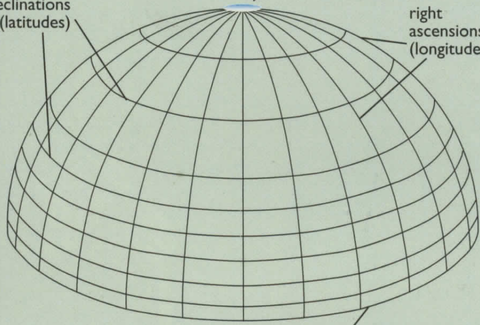
Using a spoke and a ring, you get a celestial coordinate—the point where the two lines meet. Here's a popular one:

Right ascension: $6^{h}45^{m}$

Declination: –16°43′ (the foot symbol stands for minutes)

That's where you'll find Sirius ("the Dog Star"), the brightest star in the sky.





spokes of a wheel. Then, going back to the polestar and using it as a bull's eye, he drew concentric circles around it. The circles crossed the spoke lines to make a grid with coordinates (places where the lines meet). Those celestial spokes, which started as points and became fat and wide at the ends, would come to be called lines of longitude. The circles, evenly spaced, were lines of latitude, similar to those on a globe. Now on this imaginary sky grid, Eudoxus could pinpoint stars almost exactly. He thought he was fixing the heavens on his map and that the stars would stay in place forever.

About 200 years later, another determined Greek, Hipparchus (hi-PAR-kuhs), looked heavenward and saw a

Hipparchus is using a cross-staff to measure the altitude of the polestar, which is the same as the degree of latitude. (At 45°N latitude, the polestar is 45° above the horizon.) Later, astronomers figured out how to use the noon Sun to determine latitude—a trickier calculation, since the Sun's position changes over the course of a year.

bright star he had never seen before. It wasn't on Eudoxus's grid. Something was wrong. The stars were supposed to be unchanging. Where had this one come from? Perhaps it had just been missed in the past. But Hipparchus didn't really think so. He decided to remap the heavens, then if another star made a surprise appearance, he would be prepared and know if it was new. So he made a star map using Eudoxus's lines of latitude and longitude. Hipparchus placed close to 1,000 stars on his map.

He divided the stars into classes according to brightness (later called magnitude). The 20 brightest were of the first magnitude; stars of the second magnitude were slightly dimmer, and so on to the sixth magnitude, which is barely visible to the naked eye. With some modifications, we use that classification today.

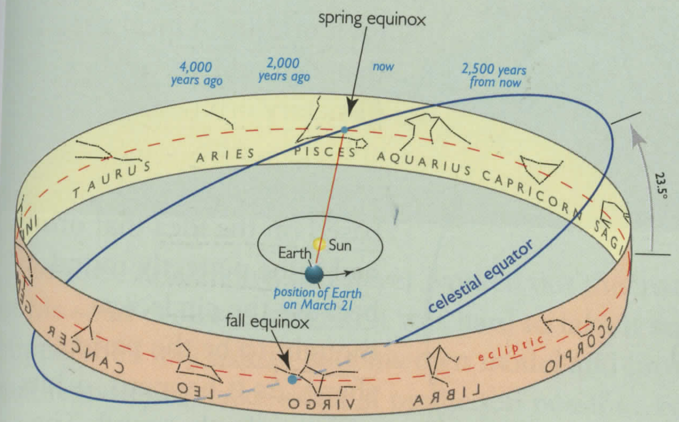
In making his star map, Hipparchus compared the locations of stars he could see with those recorded by Eudoxus and earlier astronomers. He discovered that although, night after night, the stars appear to be fixed in position, over time they actually shift from west to east. But the shift is so slow, no one sees it during a normal lifetime; it takes about 100 years for the change to be

WHY DOES EVERY EQUINOX LOOK A LITTLE DIFFERENT?

Here's why: The Earth revolves around the Sun *a tad less* than once a year. Each March 21 (or thereabouts), our planet reaches the place in its orbit that is the vernal (spring) equinox. And each year, that place is a little bit short of last year's spot. Because Earth is in a different spot, the stars look as if they're in a different spot, too. It takes a century or so for someone standing on Earth to notice this tiny change, but given a thousand or more years, the yearly shortfalls seriously add up.

Four thousand years ago, on the day of the spring equinox, Earth was opposite the constellation Aries, the ram. For Hipparchus, some 2,000 years ago, the opposing constellation was Pisces, the fish. Now it's about to become Aquarius, the water carrier. (There's a hit song from the musical play *Hair* about the "dawning of the Age of Aquarius." Now you know what that catchy lyric means.)

If you know your zodiac, you realize that the constellations are going backward in relation to the calendar. The rate is about one constellation every 2,160 years. Because there are 12 zodiac constellations, it takes about 26,000 years for the Earth to end up in the same equinox position.



The 12 zodiac constellations don't really circle our solar system. Their stars aren't even grouped in a pattern—they're spread light years apart. It just looks that way to us. So this diagram isn't a map of space, and it's definitely not to scale. Think of it as a useful tool to picture why the stars appear to us as they do.

Plant yourself on the Earth. It's the spring equinox, March 21. If you're on the side of Earth facing away from the Sun, it's night; you see the constellation Virgo fixed among the stars. If you're on the side facing the Sun, it's daytime; you can't see any stars. Hidden from view, directly behind the Sun, lurks the constellation Pisces.

noticeable. Hipparchus didn't realize it, but at the rate that the stars shift, they complete a huge circle in our sky about every 26,700 years.

Other things change slowly, too. The equinox (the day when light and dark are equal) arrives a few seconds earlier each year. It's called the precession of the equinoxes (see above). More than 16 centuries after Hipparchus, a Polish stargazer named Copernicus would discover that this precession is caused by a slight wobble of the Earth on its axis.

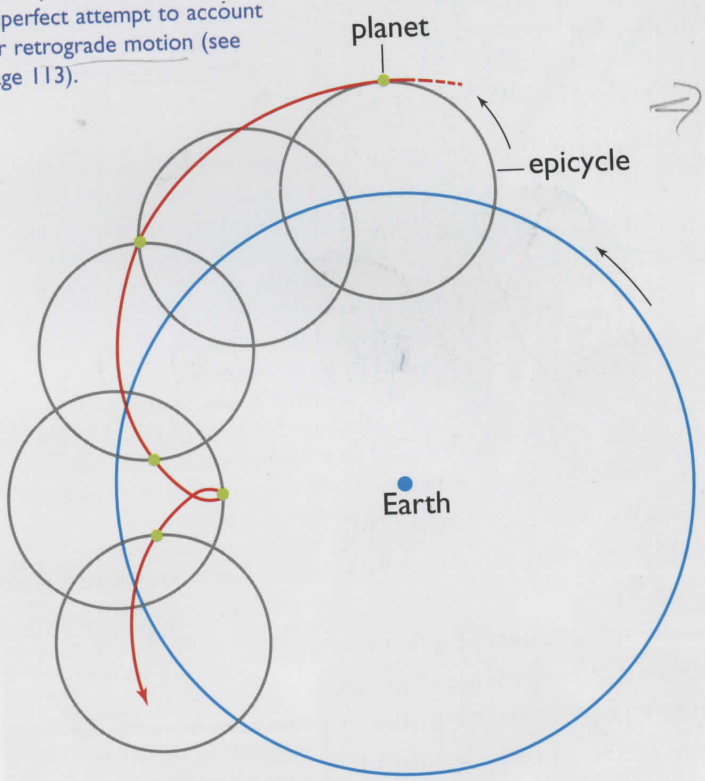
Hipparchus, who is said to be the greatest of the Greek

***Precede* means "to go before" in Latin, so PRECESSION, the noun form of that verb, means "the act of going before."**

An OBSERVATORY is a place with instruments for making science observations—of the stars, the weather, pollution levels, and so on. A planetarium isn't an observatory. It's a model, or copy, of the night sky.

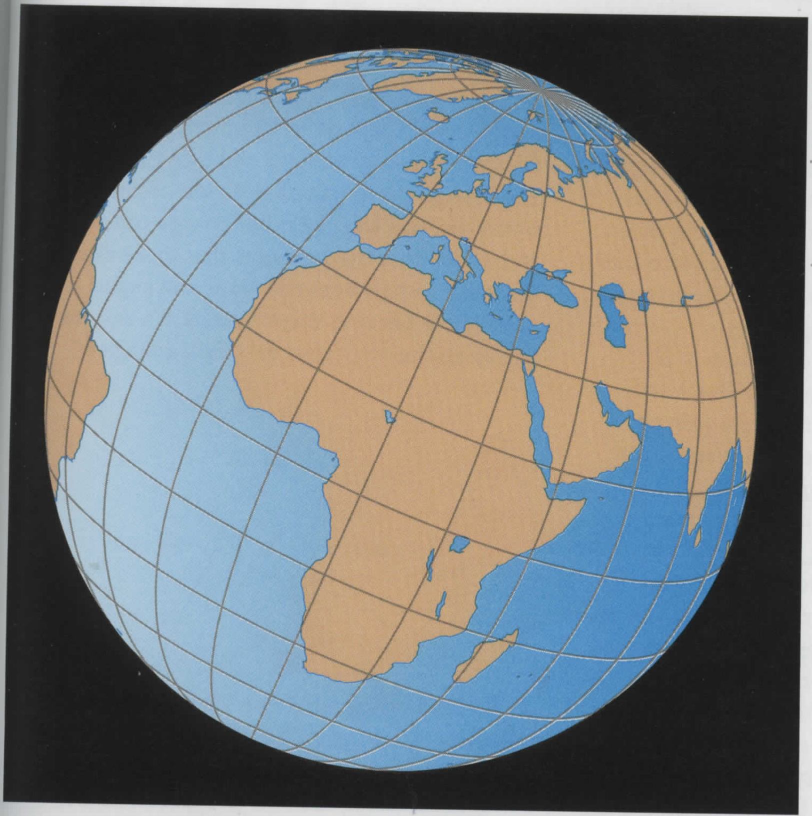
astronomers, set up an observatory on the island of Rhodes in the Aegean Sea; there he invented stargazing instruments that would be used by sky watchers for centuries to come. But his most ambitious achievement came when he worked out a complex scheme to explain the movements of the stars and, especially, of the planets. Remember, Aristotle had 54 layered transparent spheres holding the stars as they all moved in the same direction around a stationary Earth. But Aristotle never came up with a good explanation of the wandering movement of the planets.

Knowing what you know about the solar system, you might think this drawing of a planetary orbit looks really goofy. Yet if you are standing on Earth, these epicycles—loops within loops—provide a reasonable explanation of why planets sometimes move across the sky in an erratic path. Specifically, they are an imperfect attempt to account for retrograde motion (see page 113).



Hipparchus accepted Aristotle's basic idea but reduced the number of large spheres to seven. To handle the planets, Hipparchus had each orbiting a focal center that also orbited Earth. These planetary orbits were called epicycles. This very complicated scheme was based on the idea that orbits had to be perfectly round because the circle was thought to be the perfect shape. As it happens, orbits aren't perfectly round. The idea was wrong, but it would take a long, long time to figure that out.

Hipparchus knew that Aristarchus, who had taught and worked at Alexandria about 130 years before his time, had believed the universe was heliocentric (Sun-centered). The motion of the planets and Earth could be easily explained without epicycles, said Aristarchus, if they all moved around the Sun. But if that was true, Earth had to be moving, and that must have seemed bizarre to Hipparchus. It did to almost everyone else.



Lines of longitude on Earth meet at the North Pole—and at the South Pole too. Lines of latitude, looking like belts around the Earth—are parallel. They never meet. The equator is 0° latitude, and the North and South Poles are 90° latitude. Compare this Earth-bound mapping system to the celestial coordinate system on page 175.

Besides, Aristarchus had never worked out the mathematics of his solar-centered idea, so it was hard to take it seriously. Hipparchus was able to take his own model and provide the mathematics to make celestial prediction possible. For a long time it all seemed to work.

That's not all Hipparchus did. He is sometimes called the Father of Trigonometry. Trigonometry is about measuring the angles and sides of triangles (see page 180). Imagine you're at sea and lost, and then you sight a familiar star. By setting up an imaginary triangle from ship to star and comparing it with a known triangle from land to that same star, you can usually figure out your location.

Hipparchus did even more for those of us who want to know where we are. He took the lines of latitude and longitude from Eudoxus's sky maps and put them on a map of the land. That was around 129 B.C.E. We've been using those lines on Earth maps ever since.

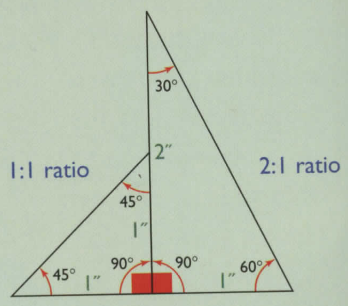
WITH TRIGONOMETRY, YOU CAN KNOW IT ALL

There's more than one way to measure a triangle, but you already know that. Thales made a little triangle with the same angles as a huge one in order to find the distance of a ship (see page 43). Pythagoras did his bit with the three sides of a right triangle (see page 79). Hero said that if you know the three sides of any triangle, you can find its area (see page 132).

With trigonometry, you can know it all. (Well, all about triangles, anyway.) The word *trigonometry* means "three (*tri*) angle (*gōnia*) measure (*metron*)," and it's the ultimate math for measuring triangles of any size or shape.

Jacques Ozanam, a seventeenth-century mathematician, wrote in his book *Cours de Mathématiques* that he couldn't live without it: "'tis by Trigonometry only that the Courses of the Phenomena and Changes which happen in the Universe can, with any certainty, be discovered... nor can anyone arrive at the knowledge of the Motions of the Celestial Bodies, but by that of the most simple Figures, which are Triangles.... The Usefulness of Trigonometry is so great, that it is in a manner impossible to live without it."

Trigonometry works because, as Ozanam points out, triangles are "the most simple Figures"—just three sides and three angles. If you change the length of one side or the size of one angle, you can't help but change other sides and angles too. The beauty is that these changes, the relationships between sides and angles, are predictable because they're ratios. It's easy to see by comparing these two right triangles:



All I did was double one side of the second triangle—a 2:1 ratio. The 90° angle stayed the same, but the other two angles went from being equal (a 1:1 ratio at 45° apiece) to 60° and 30°—another 2:1 ratio. This 2:1 business is no accident. It's trigonometry. In any right triangle with two short legs in a 2:1 ratio, the other two angles will be 60° and 30°. It doesn't matter how tiny or gigantic the triangle is. The ratio stays the same.

Trigonometry fans have brewed up table after table of these useful ratios. You just need to know one side and any other two pieces of a triangle; trigonometry will fill in the rest. In other words, you'll know it all.

In this German woodcut (ca. 1530), surveyors show how to use cross-staffs and trigonometry to measure the distance between any objects, in the sky or on land—a technique called triangulation.

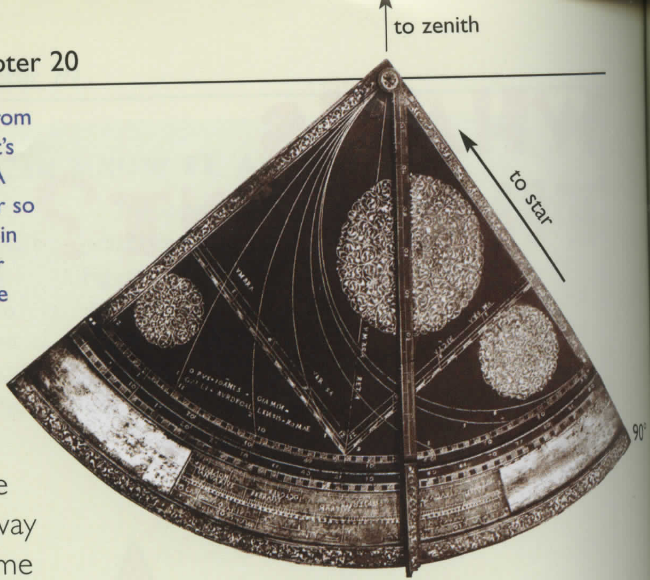
WHAT'S THE POINT?

A **point of reference** is any landmark that you use to judge the distance, direction, or location of a place. Street signs are obvious markers, but lots of familiar sights help you get around town.

If you're in the Northern Hemisphere, the Big Dipper is like the corner store—you can't miss it. It's a point of reference that looms large, night after dependable night. Its two end stars are always pointing at Polaris, the polestar (see page 63). The problem is, unlike a store, the Big Dipper takes a spin around the sky once every night. So, while you can tell where stars are in relation to each other, you need another way to describe an exact position in the sky. That's especially true for the Moon and planets, which pop up in lots of spots.

To locate a spot in a city, you can usually just say, "It's at the corner of This Street and That Street." Likewise, to pinpoint a star or

Any chance they could get, navigators hopped ashore to take their celestial measurements. On flat ground, gravity kept a plumb line (the string with the bob) at right angles to the horizon. A rolling, pitching ship made the line (and the navigator) sway.



A quadrant is a quarter circle marked with degrees from 0 to 90. Its point of reference isn't the horizon (0°); it's the zenith, the point directly overhead, which is 90°. A quadrant is easy to use: Dangle the tool at the corner so that the free-swinging stick is vertical. The stick stays in position while you adjust the quarter circle with your other hand so that the right edge points to a star. The stick marks the star's degree of altitude.

planet, you need two "streets"—two points of reference. One point tells you altitude—how high in the sky it is above the horizon. The other tells you which way to look—north, east, south, west, or some spot in between. Another word for that is azimuth, which comes from the Arabic for "the way."

Over the millennia, astronomers, like Eudoxus, have mapped stars using a bunch of different coordinate systems. (Coordinates are overlapping points on a grid.) In case you're curious, here's the royal road (the easy way) to geometric star charting (below and opposite page).

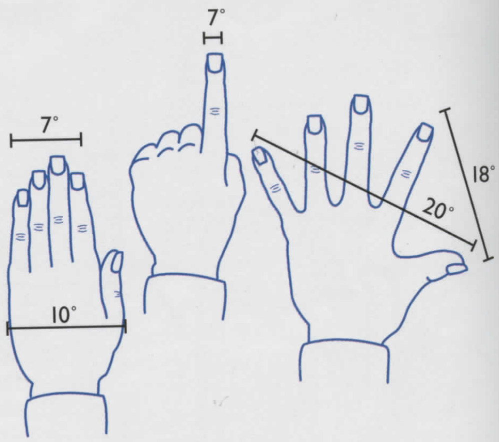
ALTITUDE: 90° OF SEPARATION

No matter where you're standing on Earth, no matter which way you're facing, there's an imaginary point directly above your head. It's called a zenith, and it's at right angles, 90°, to your horizon. Everything that you can see in the sky is somewhere between the horizon, call it 0°, and the zenith. All you have to do is measure its altitude in degrees. It's easy, if you just want a rough idea. Hold your hand at arm's length and follow the guide at right.

Of course, there are big hands and little hands, long arms and short arms. To take a better reading, you need an instrument with degree markings. On paper, that instrument would be a compass or a protractor, each with a degree marker shaped like a semicircle. An astrolabe is just a protractor for the sky (see photo, opposite page).

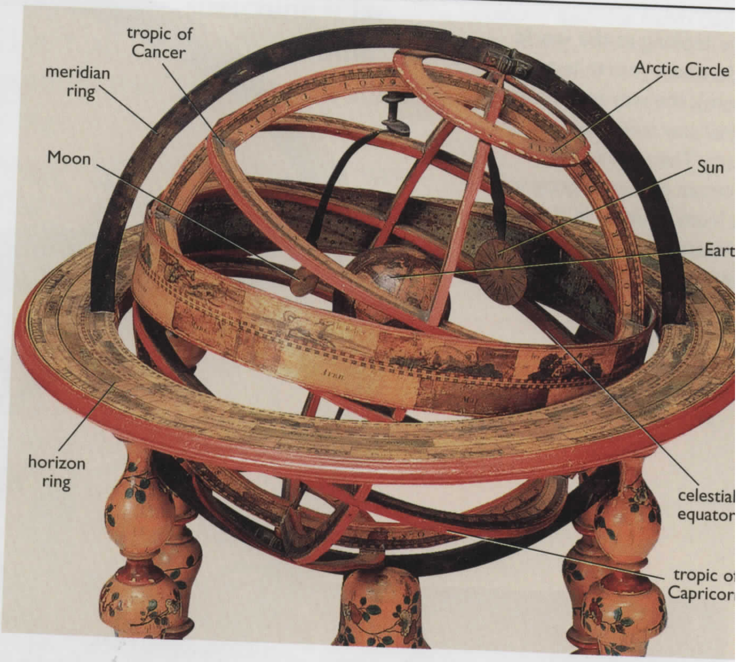
There's another little hitch: Altitude changes with latitude. The farther north you are, the higher Polaris is in the sky. So your measurement, no matter how accurate, only works for your latitude.

To have a universal coordinate system, you can't use the horizon as your base. You need a plane of reference that works for everyone—like the equator or the ecliptic (the Sun's path in the sky). That's where the math gets sticky, but if you're still curious, look up "equatorial coordinates" on the Internet or in an astronomy book.



astronomy of his day.

This Ptolemy was not an emperor or a general, as were the Ptolemys who ruled Egypt. We hardly know anything about his personal life. We do know that he was born in North Africa and was part of the Greek-speaking Hellenistic world. Most authorities believe that he was Greek, but a few think he may have been Egyptian. He lived and studied in Alexandria a century or so after Strabo and more than three centuries after Eratosthenes.



An armillary sphere is a see-through celestial sphere, a model of the sky as it appear from Earth. The tilted Earth i caged in the middle, while rings carrying the Sun and Moon rotate around it. The planets are missing because Ptolemaic (Earth-centered) spheres can't model their erratic paths across our sky. In the sixteenth century, Copernican (Sun-centered) armillary spheres with planets began to appear in Europe.

When he considered the heavens, Ptolemy rejected those thinkers. He looked to Hipparchus, who studied at Alexandria in the second century B.C.E. Hipparchus had followed and improved Aristotle. All three (Aristotle, Hipparchus, Ptolemy) came to the conclusion that a round Earth is at the center of the universe and that it stands stone-still while everything else in the heavens revolve around it.

Remember, Aristarchus had figured out that Earth goes around the Sun. But that idea—of a heliocentric universe—was never very popular. The Earth whirling about in space? That seemed absurd. Ptolemy rejected the notion and followed where Hipparchus and Aristotle had led.

He based his great work on their geocentric mistake. That wasn't Ptolemy's only mistake. He also believed that Earth is mostly dry land rather than ocean. (That was another idea that went back to Aristotle.) He thought the stars and planets orbited in perfect circles. (That was Plato's perfection idea.) And he thought Earth much smaller than it actually is. When Ptolemy calculated, Earth came out 30 percent smaller than what Eratosthenes had figured it to be—and what it really is.

You're looking at the world upside down (north is at the bottom), the way mapmaker al-Idrisi saw it in the twelfth century. The well-traveled Moroccan gathered geographic data from sources in the East and West, both new and ancient (including Ptolemy).

Seeing Stars (and Planets Too)

The ancients could see five planets with the naked eye: Mercury, Venus, Mars, Jupiter, and Saturn. They could see thousands of stars, perhaps as many as 9,000. Naming them and marking their coordinates on a grid was painstaking but to dedicated scholars, very worthwhile.

By the third century B.C.E., Chinese astronomers had cataloged more than 800 stars. About 100 years later, Hipparchus, a Greek astronomer, cataloged 850 stars and set up his 6-point scale for magnitude (apparent brightness). In the second century C.E., Ptolemy added more than 170 stars to that list. He also named 48 constellations, which still appear on star maps today.

What the Greeks Saw

Magnitude 1 (brightest):	20 stars
Magnitude 2:	50 stars
Magnitude 3:	150 stars
Magnitude 4:	450 stars
Magnitude 5:	1,350 stars
Magnitude 6 (barely visible):	4,000 or so stars

The telescope, which came along in the seventeenth century, changed everything. Stargazers could now begin to glimpse the vastness of the universe. They saw tens of thousands more stars, although no one had an idea that there are a multitude of galaxies and that we are not the center of it all. In 1781, another planet, Uranus, emerged from the darkness, followed by Neptune in 1846.

In the last half of the nineteenth century, photography began to allow us to take pictures of the sky and study it in detail. The images revealed a multitude of moons, distant nebulae (gas clouds), and other galaxies. At the Harvard College Observatory, a team of women called "computers" glued their eyes to photographic plates, counting dense fields of stars. As they called out facts and figures, "recorders" added each star to a growing list, later named the *Henry Draper Catalogue*. (Henry Draper, a physician and amateur

Besides that, Ptolemy made Asia huge, stretching it far beyond where it actually is. Later, all those errors would make Christopher Columbus think that Asia was just across an ocean that wasn't terribly big.

Remember (it's in the previous chapter, so you don't have to go far) the Hipparchus/Aristotle model of the cosmos? Earth, in the center of the universe, is circled by transparent moving spheres that have planets and stars attached to them. It was an ingenious way to explain the fixed movement of the stars across the sky. It also seemed to explain why the stars don't fall from the heavens.

When it came to the problem of the wandering planets, Hipparchus had come up with a complicated system of epicycles (see page 178) to explain their motion. Ptolemy

Ptolemy said the Earth couldn't be moving, because if it were, people would be tossed around and birds would fall from the trees. A ball thrown in the air would come down in a different place than it went up. It wasn't a foolish observation. Think about it: If Earth does move, why *can't* we feel it? More than 14 centuries after Ptolemy, a scientist named Galileo would finally answer that.

photographer, is said to have taken the first picture of a star's spectrum. Those nineteenth-century women got little credit for their work.)

We now believe that our galaxy, the Milky Way, has 200 to 400 *billion* stars—maybe more. And the Hubble space telescope and other powerful eyes in the sky have found many, many more galaxies. "Computing" stars has just begun.

Among the thousands of stars visible since ancient times, a handful have become celebrities. The North Star, a favorite among mariners, is famous. But when it comes to starring in art, mythology, and astronomical maps, it's hard to top the 12 zodiac constellations. Above, they're featured players in a ceiling fresco by Italian artist Taddeo Zuccaro (1529–1566). A Catholic cardinal—Alessandro Farnese—chose this starry theme for his palace. You'll also find zodiac art in churches and public buildings throughout Europe.

Ptolemy's influence on mapmaking stretched well into the fifteenth century. A German map published in 1486 echoes his *Geographia*, including the idea that most of the globe is covered by land. Today, we know the opposite is true: oceans occupy more than two-thirds of the planet's surface.

worked hard to improve and refine Hipparchus's work. It seemed the best explanation there was, so most people thought it correct. (It wasn't.) Knowledge is a step-by-step process. A step may have rotten boards that seem to be sound. Eventually, those boards get found and replaced, but sometimes they provide support before they fall apart. Ptolemy's steps seemed to make sense. They stood in place for about 1500 years, and they were essential to the development of science.

Ptolemy wasn't much of an original theorist, but he was a solid thinker who compiled and organized and extended the work of the past and left a base for future scientific study. His great contribution was in explaining the world mathematically. Those who followed would be compelled to do the same thing.

Ptolemy wrote massive volumes on science, geography, and mathematics. And his ideas seemed to work. With his model and his mathematics, you could predict the motions of the Sun, stars, and planets. You'd be close enough so that farmers, sailors, and teachers could use the results—which they did. Today we're apt to look back at Ptolemy and forget how important he was for centuries and centuries and centuries. Those who turned to Ptolemy were rejecting superstition and magic and using a solid work of scholarship.

His monumental book was called *Megale mathematike syntaxis* ("*Great Mathematical Composition*"). Sometimes it was just called *Megiste* ("*The Greatest*"). It mapped and charted the visible stars, going still further than Hipparchus. Ptolemy's star charts became enormously helpful to anyone trying to navigate a ship at sea. As to his writings on mathematics, math historian Carl B. Boyer calls them "by far the most influential and significant trigonometric work of all antiquity." Today, no one is sure how much of it was Hipparchus's work and how much was Ptolemy's.

Measuring the altitude of stars above the horizon to find latitude was easy (see page 182). Finding longitude in a ship at sea was close to impossible without an accurate clock. Ships' motion made all the known timepieces inaccurate. Read the book *Longitude* by Dava Sobel for details.

But don't think of Ptolemy as a copycat. He was a corrector and improver. Yes, he got most of his ideas from others, but he worked hard to extend them. When he wrote an atlas, the *Geographia*, he did follow Hipparchus by putting grids with lines of latitude and longitude on its 27 maps. Then he introduced many previously unknown places using information from sailors' reports. In China, cartographers, who had no idea the world was round, also developed a grid system for maps. The Chinese maps showed details far better than maps made in the West, but they were limited by the flat-world idea.

This illustration, a copy from a tenth-century Arabic manuscript called *Treatise on the Fixed Stars,* by al-Sufi, combines two constellations derived from Ptolemy. The constellation Sagittarius, in the form of a centaur (half man, half horse), battles Leo, a lionlike beast.

By the time Ptolemy finished writing his books, things were in turmoil in the world centered at Alexandria. Rome was now dominant, and the Romans weren't terribly interested in pursuing scholarly ideas. They never even translated Ptolemy's books into their Latin language.

Arab scholars were interested. They translated most of his books into Arabic. They took the *Megiste*, put the Arabic "*al*" in front of it (it means "the") and got *al-majusti* , which comes to us as *Almagest*, meaning "the greatest." And for a long, long time, that's what scientific thinkers thought it was. The Arabs probably saved Ptolemy from being lost forever. Although, for a while, hardly anyone in Europe seemed to care.

That's because Ptolemy and Aristotle and the rest of Greek science were going into a deep freeze. And question asking? It would soon be just about out of style.