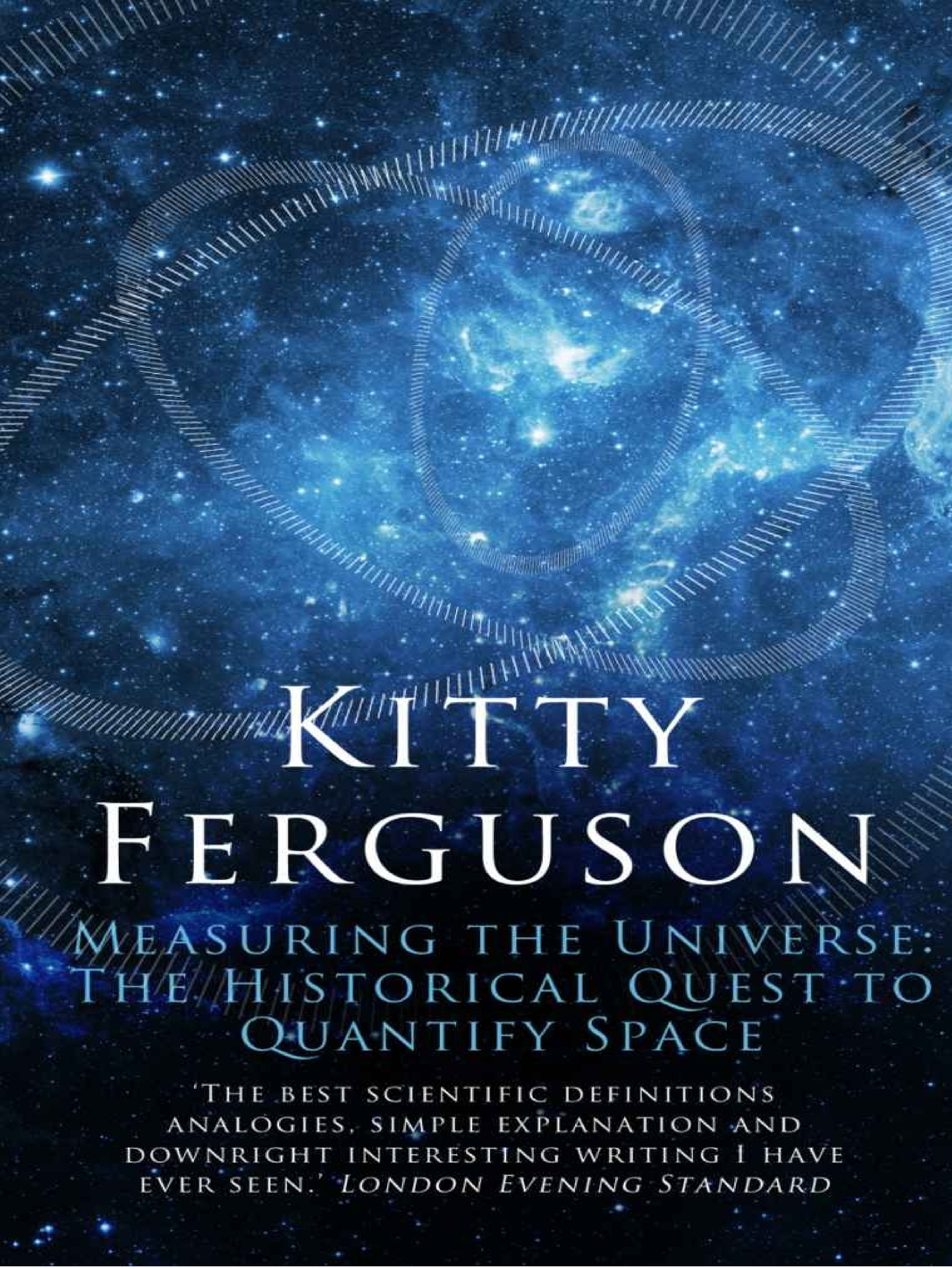
Kitty
Ferguson
Measuring the Universe:
The Historical Quest to
Quantify Space
'The best scientific definitions analogies, simple explanation and downright interesting writing I have ever seen.' London Evening Standard

About the Book

Suppose you and I still wondered whether all of the pinpoints of light in the night sky are the sam distance from us. Suppose none of our contemporaries could tell us whether the Sun orbits the Eart or vice versa, or even how large the Earth is. Suppose no one had guessed there are mathematical la underlying the motions of the heavens.

How would – how did – anyone begin to discover these numbers and these relationships witho leaving the Earth? What made anyone even think it was possible to find out “how far,” without goi there? In Measuring the Universe we join our ancestors and contemporary scientists as they tease th information out of a sky full of stars. Some of the questions have turned out to be loaded, and a gre deal besides mathematics and astronomy has gone into answering them. Politics, religion, philosop and personal ambition: all have played roles in this drama.

There are poignant personal stories, of people like Copernicus, Kepler, Newton, Herschel, and Hubbl Today scientists are attempting to determine the distance to objects near the borders of the observab universe, far beyond anything that can be seen with the naked eye in the night sky, and to measu time back to its origin. The numbers are too enormous to comprehend.

Nevertheless, generations of curious people have figured them out, one resourceful step at a tim Progress has owed as much to raw ingenuity as to technology, and frontier inventiveness is still n out of date.

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MEASURING *The* UNIVERSE

THE HISTORICAL QUEST TO QUANTIFY SPACE

KITTY FERGUSON

To my brother, David, who made himself ill as a child and caused a family crisis, worrying about th
size of the universe

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PROLOGUE

Tilting at Windmills 1951

WHEN I WAS nine years old, my father suggested one morning that he and my brother and I go out ar measure the height of the windmill on my grandparents' farm. My brother and I agreed that was a fir idea.

How would we do it? Climb the windmill, of course . . . at least my father would. My brother anc wouldn't be allowed to try anything so dangerous as that. When my father reached the top, the would still be the problem of how to measure the height. We didn't have a measuring tape that lon Would he take a yardstick and mark off the yards on the windmill as he climbed? Maybe he woul drop the end of a long rope from up there and cut it off, and we would stand clear while the cut-o piece fell, and then we would measure it. That must be the plan, for he'd said my brother and I wou help him.

My brother suggested that my father wouldn't need to climb the windmill at all. We could thro something over the top, just clearing it. Yes, I interrupted, attach a rope to the thing we threw, a rop with inches and feet marked on it, and then pull back on it gently so it would catch on the top of th windmill, and see what the measurement was to the ground! No, no, said my brother, who was tw years younger than I but already very mathematically minded, we would measure the curve the obje followed through the air. Good thinking, said my father, but, practically speaking, more difficult tha the original problem of measuring the height of the windmill.

I asked whether we might walk away from the windmill and measure how much smaller it looke as we got further away. More good thinking, said my father, but there was a better way.

He gave us a hint. He'd thought it was a wise idea to wait for a sunny day . . . and no one wou have to climb the windmill or take a walk or risk wrecking the windmill with a bad throw . . . and th only tools we'd need would be a yardstick and our eyes and brains and a pencil and paper to do son calculations. And although at this latitude it would be possible to measure the windmill precisely noon, it would be easier at another time of day.

Neither my brother nor I was clever enough to see where this was leading until my father sai 'The windmill does more than just pump water, you know. It casts a shadow, and so does a yardstick and then we began to understand how the trick could be done. We would stand the yardstick uprig and measure its shadow. Then we would measure the windmill's shadow. If a shadow *this* long we with a three-foot stick, then a shadow *that* long went with a windmill of thus-and-so height. M brother and I didn't know how to make the comparison. My father taught us how and then pointed o that there was actually a more primitive way to find the answer. Wait for the time of day when th three-foot yardstick cast a three-foot shadow. At that moment the length of the windmill's shado would be the same as the height of the windmill. We decided to use our newly acquired mathemati first, and then we checked our answer by sitting out in the Texas sun, watching the shadow of th yardstick creep along the ground.

That's how we measured the windmill, while above our heads the giant structure thrummed ar creaked with the watery, metallic sounds windmills in central Texas made in those days, doing i work, turning and pumping, adjusting its angle to catch a stronger breeze, not paying any attention the mental exertions of three little people below who had captured its shadow.

I was elated. It seemed we had outwitted the windmill without so much as touching it, and now w ~~knew a wondrous secret: Not the height of the windmill, but how to find it out. None of us thought~~ ask: why are we doing this? There was no need whatsoever for any of us three to know the height of windmill that wasn't even our own.

Measuring is one of the more practical uses for mathematics, but our ability and desire to measu isn't always wrapped up with the need to know useful answers. Going with numbers where we can't g in person – whether that's to the top of a windmill or to the origin and borders of the universe – ha been and still is one of humankind's favourite intellectual adventures. By the beginning of the twenty first century it had outrun our practical requirements by billions of light years.

Compared with the adventure of finding them out, the actual measurements often seem dry dust: The Sun is 149.5 million kilometres away (mean distance). The nearest star is 4.3 light year The 'Local Group' of galaxies covers an area about 3 million light years in diameter. The distance t the edge of the observable universe is 13.7 billion light years. We shake our heads at how large thes numbers are or admit their largeness makes them meaningless, remember them for a day or mayb long enough for a school exam . . . and then forget them. Science trivia.

Not trivial at all when you realize how hard-won these numbers are and what ingenuity it took an still takes to find them out. Can we even begin to imagine what it would be like if no one knew them The night sky sparkles with pinpricks of light. Are these all the same distance from us? Suppose w didn't know. Suppose none of our contemporaries knew whether the Sun orbits the Earth, or vic versa, or even how large the Earth is. Suppose no one had guessed there are mathematical law underlying the motion of the heavens. How would – how did – anyone begin to discover these numbe and these relationships without leaving the Earth? What made anyone even think it was possible find out 'how far'? Without going there. Without climbing the windmill.

In the pages to come we'll take many steps back, forget we know the measurements or how make them, and join our ancestors as they tease this information out of a sky full of stars. Th laboratory isn't a neat, sterile room where carefully controlled experiments take place. Events in th heavens happen in their own good time and not before, and they are often not repeatable. We hav learned to take what's on offer and make the best of it.

Our human point of view is sorely limited. Until recently we had no ground on which to stand an take our measurements, no possible viewing platform, other than here on Earth. In the twentie century we travelled to the Moon and looked back at our planet from space and sent probes out in the far reaches of our solar system. But by universal standards, by the standards of the distances we'v learned to measure and still hope to measure, how pitifully close to home that is.

This book is a chronicle of how men and women over the course of two and a half millennia hav built a ladder of measurement from our doorsteps to the borders of the known universe, and how th adventure has changed our ideas about the shape and nature of the universe and our place in it. It is n a history of all astronomy. There are fascinating discoveries, both in Western astronomy and in othe cultures, that I have had to remind myself have no direct bearing on our knowledge of distances, siz and shape. With regret, I have left them out, though the temptation to embark on long digressio from the main theme of the book has been almost irresistible.

We shall however broaden our focus in another direction to examine the context in which th discoveries have taken place, for this is a story inextricably bound up with the rest of social, politic and intellectual history. One of our tasks will be to look for reasons why a particular discovery o measurement happened when and where it did. What was it about that time and place, that societ that mindset or intellectual milieu, the available technology, the chain of previous discovery, the wa ~~some random occurrences fell out . . . perhaps most interesting of all, what was it about a specif~~ individual that precipitated this advance in knowledge?

The story of our wanting to know ‘how far’ – to make ridiculously out-of-reach measurements must surely have begun before the beginning of recorded history. The known story of our succe began some 2,200 years ago in north Africa near the mouth of the Nile with the measurement of th circumference of our own planet, long before anyone was able to circumnavigate it. The Hellenist librarian Eratosthenes didn’t need to know the circumference of the Earth. Nevertheless, he set abo measuring it and he did it in a remarkably simple way. We now call Eratosthenes the father of th science of Earth measurement, ‘geodesy’. The word has the sound of ‘odyssey’ in it.

We learn from Eratosthenes what I learned from my father . . . and we shall see it demonstrate repeatedly in this book: what can’t be measured directly – what it is unthinkable that we should ev measure directly – *can* be measured in roundabout, inventive ways. In the first decade of the twent first century we determined the distance to the borders of the observable universe, far beyond an pinprick of light we see with the naked eye in the night sky, and measured time back to the origin o the universe. The numbers are indeed too enormous to make sense to our little minds. Neverthele our little minds have figured them out, one resourceful step at a time, each step building upon the las It has been a history of astounding improvement in our technology, particularly in the twentie century, but more than that, a history of raw ingenuity. It still is. Frontier inventiveness is not out o date.

With the benefit of hindsight we may be tempted to exclaim, ‘Of course! Why . . . *I* could hav thought of that! The windmill has a shadow. Of course!’ for many of the methods we’ve devised t measure distances to out-of-reach places are simple enough for nearly everyone to understand – only little more complicated than measuring my grandfather’s windmill. But to figure these things out f the first time . . . how impossibly clever!

Kitty Ferguso
November 20

CHAPTER 1

A Sphere with a View
Third Century BC

The great mind, like the small, experiments with different alternatives, works out their consequenc for some distance, and thereupon guesses (much like a chess player) that one move will genera richer possibilities than the rest . . . It still remains to ask how the great mind comes to guess bett than another, and to make leaps that turn out to lead further and deeper than yours or mine. We do n know.

Jacob Bronows

ASK WHO ERATOSTHENES of Cyrene was, and unless you are talking to someone who specializes in t minutiae of Hellenistic culture, you are unlikely to hear that he was a man who attempted to fix t dates of the major literary and political events from the conquest of Troy until his own time in t third century BC, that he composed a treatise about theatres and theatrical apparatus and the works the best-known comic poets of the 'old comedy'; that he suggested a way of solving a problem th had tantalized mathematicians for two centuries – 'duplicating a cube'; that he let his voice be hea on the subject of moral philosophy and felt it essential to criticize those who were 'popularizin philosophy, accusing them of 'dressing it up in the gaudy apparel of loose women'. It is true f Eratosthenes, as it is for many celebrated figures, that the strokes of genius for which he is rever were only a minuscule part of a lifetime of achievement, and not necessarily the part he judged mo important.

Nothing on the list above won Eratosthenes his place in the history books. Two addition accomplishments did: the invention of 'the sieve of Eratosthenes' – a method for sifting through a the numbers to find which are prime numbers; and his remarkably accurate measurement of t circumference of the Earth.

Dismiss any thought that before Columbus no one knew the Earth was round. Admittedly, t shape of the Earth probably wasn't of much daily practical interest to most people in the ancie world. However, long before even Eratosthenes, those few who were wondering about it at all were n seriously suggesting that the Earth was flat or, indeed, any shape but spherical. The Pythagoreans, school of thinkers with particular genius for mathematics and music, had decided as early as the six and fifth centuries BC that the Earth is a sphere. Plato, still a century before Eratosthenes, pictured cosmos made up of spheres within spheres, nested one within another, with a spherical Earth at t centre. Aristotle, only a little later than Plato, vigorously subscribed to the idea of a spherical Eart and his defence proved convincing not only to the ancient world but also to the Middle Ages. The id that scholars of the Middle Ages believed the world was flat is, in fact, a myth created in mode times.

Aristotle used a number of arguments. During an eclipse of the Moon, the shadow cast by t Earth on the Moon is always curved. When we on the Earth move from north to south or vice versa notice what appears to be a change in the position of the stars in relation to ourselves. In Aristotle words:

> There is much change, I mean, in the stars which are overhead, and the stars seen are different,

> as one moves northward or southward. Indeed there are some stars seen in Egypt and in the ~~neighborhood of Cyprus which are not seen in the northerly regions; and stars which in the~~ north are never beyond the range of observation, in those regions rise and set. All of which goes to show not only that the Earth is circular in shape, but also that it is a sphere of no great size: for otherwise the effect of so slight a change of place would not be so quickly apparent.

Aristotle speculated that the oceans of the extreme west and the extreme east of the known wor might be ‘one’, and he reported with some sympathy the arguments of those who had noticed th elephants appeared in regions to the extreme east and the extreme west, and who thought therefo that those regions might be ‘continuous’.

These reasons for belief in a spherical Earth came from observation, but Aristotle also argued o the basis of his philosophy. In that philosophy, five elements, earth, air, water, fire and aether, eac have a natural place in the universe. The natural place for the element earth is at the centre of th universe, and for that reason earth (the element) has a natural tendency to move towards that centr where it must inevitably arrange itself in a symmetrical fashion around the centre point, forming th sphere we call *the* Earth. Aristotle reported that mathematicians had estimated the Earth circumference to be 400,000 stades; that is, about 39,000 miles or 63,000 kilometres (more than ha again as large as the modern measurement). No record survives of the method they used to arrive that number.

When Aristotle died in 322 BC at the age of 62, the military campaigns of his most high achieving pupil, Alexander the Great, had just ended with the death of Alexander. Though there is tendency to speak of ‘the Greeks’ and toss names like Eratosthenes into that file, the civilization ar the culture we are dealing with after Alexander was much larger both in territory and concept tha what is implied in the word ‘Greek’. Alexander’s campaigns had carried Greek knowledge, languag and culture throughout Asia Minor and Mesopotamia as far east as present-day Afghanistan ar Pakistan, all the way to the Indus River, as well as to Palestine and Egypt. Vastly widened intellectu horizons were part of his extraordinary legacy. The culture of Greece and its colonies and the culture of the conquered peoples began to mix and marvellously enrich one another. This was the dawn of th Hellen*istic* era, as opposed to the Hellenic era. That is, Greek*ish*, as opposed to Greek.

At the time of Alexander’s and Aristotle’s deaths, within a year of one another, Athens was sti the undisputed centre of the intellectual world. That pre-eminence was not to last. Alexander generals divided his empire, and Ptolemy’s portion was Egypt and Palestine. He made Alexandri near the mouth of the Nile, his capital. This already prospering city began to grow in size ar splendour, and Ptolemy and his successors, reputedly ruthless in their exploitation of the lands und their control, amassed a surplus of wealth, some of which they chose to spend on literature, the art mathematics and science. Scholars are divided as to which Ptolemy should get the credit (Ptolemy successors were also named Ptolemy), but either the first or the second of them, and perhaps it too both, decided to extend the royal patronage to found a library and museum. This was not an institutio of the sort we call ‘museum’ today. As that name suggests, it was a temple to the muses, which mear both a religious shrine and a centre of learning.

Meanwhile the old, justly famous schools across the sea in Athens – schools founded by Plat Aristotle, Epicureus and the Stoics – were no longer producing vibrant new ideas to quite the exte they had once done, though they were still the places a young man of Eratosthenes’s time would hav wished to go for his education. Alexandria began to rival and eventually supplanted Athens as th focal point of the intellectual world, and the museum and library there became *the* premier researc institution. The library grew large, containing by one ancient estimate nearly 500,000 roll ~~Eratosthenes was its director or librarian at the end of the third century BC, with a salary provide~~ from the royal coffers.

Most of us have heard that one of the devastating tragedies in the history of humankind was th burning of the contents of the library at Alexandria. The story (now thought to be apocryphal) is th all those rolls were burned to heat the public baths for six months in the seventh century AD. Toda there is a campaign underway to raise funds to rebuild the structure, but that effort seems rather pitif and beside the point, in view of what can never be retrieved – the assembled knowledge of o ancestors in antiquity, hard-won over many centuries. We sense that something dreadful happened t us with the loss of all those rolls, whether it occurred quickly and calamitously in the seventh centu or, more likely, gradually through neglect and the many political, military and religious turns fortune that affected the city of Alexandria prior to that. Perhaps its loss was the symbol and sympto of a greater tragedy: the increasing lack of any widespread perception that such intellectu achievement was valuable. By the seventh century, there was probably little left to burn. It too centuries for humanity in the Western world to reach again an intellectual level on a par with th civilization that had produced that lost collection. But when Eratosthenes was librarian (235–195 B that was all in the future. He knew the Alexandria library in its heyday.

Scholars in the Hellenic and Hellenistic worlds would have been mystified by our present-da concept of 'science' as a distinct category of knowledge and pursuit of knowledge. They had sever different words for what we call 'science'. Some modern words have evolved from these terms, b the modern words don't have precisely the same meaning these had in ancient Athens and Alexandri Some examples are: *peri physeos historia* (inquiry having to do with nature); *philosophia* (love wisdom, philosophy); *theoria* (speculation); and *episteme* (knowledge). Hellenistic scholars thought 'physics' as one of three branches of philosophy. The other branches were 'logic' and 'ethics'.

The financial support of the Ptolemys and their efforts to outbid all competitors when it came collecting the masterpieces of Greek literature and encouraging distinguished scholars to flock Alexandria were motivated by desire for prestige – to add to the lustre and apparent power of th dynasty. They were also far from displeased when research could be applied to problems connecte with weaponry. However, a key difference between the ancient way of thinking and ours is th although Hellenic and Hellenistic scholars didn't ignore the possibility that their study might serv practical purposes, they were much more inclined to justify their work on the grounds that contributed to wisdom, or improved one's character, or led to a greater appreciation of the beauty the universe and understanding of its creator. It seemed not to occur to these men and women th their efforts might hold the key to material progress. The work was its own reward, an end in itsel not a means to an end. The life of a scholar, the life of 'contemplation', was considered to be a exquisitely happy one. Doctors, whose efforts were intended to have more everyday practical valu were apt to differentiate themselves entirely from the 'philosophers'.

Related to this mindset that sees intellectual exercise as an end in itself is a perspective in whic *how* to solve a problem is equally as interesting as actually solving it, often more so. This attitu arose partly out of necessity, for Greek and Hellenistic scholars were avidly interested in question that they lacked the technology to answer definitively. Perhaps we can best acclimatize ourselves the ancient way of thinking by recalling doing mathematics in school. Presented with the problem ' you ride your bicycle at an average of 30 miles per hour, and it takes you 10 minutes to get to schoo how far is school?' you do not immediately start quibbling that 30 miles per hour is not an accura measurement of the speed you normally ride, that it actually takes you 12 minutes to get to schoo and that this exercise isn't going to end with anyone knowing how far your school really is. No. Wh ~~everyone is interested in is your showing that you understand how to solve the problem. Move~~ back step and imagine that it was also up to you to invent the method for solving it – that no one, in fac had ever even thought it possible to calculate the distance to your school, and that you couldn't ri there to measure it directly – and you have put yourself a little in the shoes of Eratosthenes and oth scholars of the Hellenic and Hellenistic world. It is an attitude which allows, indeed encourages, t formation of hypotheses, sometimes out of thin air, statements such as 'We don't know that this true, but let's assume for a moment that it is, and see where that gets us.' Or even such a statement 'We know that this is *not* true, but let's pretend for the moment that it is and ask "what then?" ' T criticize the results of an exercise like that by saying the results are 'wrong' (i.e., do not accord wi twentieth-century findings) is to miss the point.

Does this mindset in which the pursuit of knowledge was valued quite apart from any practic spin-off – where the method was often thought more important than the result, where hypotheses, ev those based on false assumptions, were encouraged – provide a clue to Eratosthenes's succes Perhaps. After all, the Hellenistic world had no practical need to know the circumference of the Eart However, that attitude predated Eratosthenes by several centuries. What's more, Eratosthenes's resul were remarkably *accurate* by twentieth-century standards. Did his success have something to do wi the widening of mental horizons and the mixture of knowledge from many cultures that followed t campaigns of Alexander? It did, but, again, Eratosthenes was not the only inventive man to enjoy th legacy. And the notion that the Earth isn't flat was nothing new either, nor was the idea of calculati its circumference. There had been estimates in Aristotle's time. But it was Eratosthenes who did t measurement and got it right – or so close to right that his calculation impresses us to this day – usi a line of thought that we can easily agree was correct.

Eratosthenes, 'son of Aglaos', was born not in Egypt or Greece but in the ancient city of Cyren west of Egypt on the northern coast of Africa. Citizens of Crete and Santorini had founded Cyre some 350 years earlier and it had become one of the most cultured cities of the Hellenistic worl though still subordinate to the Egypt of the Ptolemys. Cyrene counted some distinguished figur among its citizenry. Besides Eratosthenes there was Aristippos, who founded the Cyrenaic scho there. He was a pupil of Socrates. Aristippos's daughter Arete followed him as head of the school. H son Aristippos II succeeded her. He was nicknamed Metrodidactos, which translates as 'mothe taught'.

The date given for Eratosthenes's birth is the ' 126th Olympiad', referring to the Olympic gam that took place every four years. In modern dating, that puts it between 276 and 273 BC. He receiv most of his education in Athens at the feet of eminent scholars of the New Academy and the Lyceu Plato and Aristotle had originally founded these schools (in Plato's day the New Academy had bee simply the Academy) and, though much had changed about them by the time Eratosthenes arrived, o still couldn't do better by way of an education.

By the middle of the century Eratosthenes had written a few philosophical and literary works a some of these had come to the attention of Ptolemy III Euergetes. The 'brain-drain' from Athe being in the general direction of Alexandria, Eratosthenes in about 244 BC agreed to move there a become a fellow of the museum and tutor to the prince, Philopator. (It isn't to Eratosthenes's cred that his pupil, though a patron of arts and learning, gained a reputation for dissipation and crim equal to Nero's and Caligula's later in Rome.)

In the course of time Eratosthenes became a senior (alpha) fellow of the museum and upon t death of the chief librarian took over that post – an absolutely unparalleled vantage point from whi to keep up with everything that was going on in the intellectual world.

Eratosthenes’s colleagues gave him two nicknames: *pentathlos* and *beta*. The word *pentathl* came from athletics. It was a name for those who entered the ‘pentathlon’, which required five skill jumping, discus throwing, running, wrestling and either boxing or javelin throwing. Eratosthenes w no athlete. The nickname for him implied a jack-of-all-trades. *Beta* means ‘B’ or number two, second. Put those together and you get ‘jack-of-all-trades and master of none’. Whether these nam were fondly or snidely given isn’t clear. Probably snidely. It seems a bit odd that in an era followi so closely on the heels of Plato and Aristotle, who had their fingers in just about every intellectual p around, a man should be mocked for being a jack-of-all-trades. Perhaps in the three-quarters of century between Aristotle’s death and Eratosthenes’s arrival at Alexandria, scholarship had becom more specialized and specialists had begun to sneer at those who were not specialists. Eratosthen was evidently old-fashioned to be such a polymath, but he had been educated that way . . . and ho could a man focus very narrowly when he was head of the library, *the* repository of knowledge a ideas on every subject, holding a job which made him responsible for helping the Ptolemys add to th collection. Eratosthenes was bombarded daily by new thoughts and discoveries. Modern schola compare the breadth of his knowledge to that of Aristotle and Leonardo da Vinci. Whatever criticis Eratosthenes endured, his eclecticism served him well. ‘Beta’ is remembered while some who dubb him that have long since been forgotten.

Unfortunately, none of Eratosthenes’s many works have survived except in fragments. It’s n even certain that all the fragments attributed to him are genuine. Most information about him com through reports and references of others. However, there is enough to tell that Eratosthenes measurement of the Earth, and also his motive for attempting it, were rooted in his eclectic and fa ranging knowledge and interests. Eratosthenes was a man of the world, in the real sense of tho words. He refused to categorize people as Greeks opposed to Barbarians, adopting a mo cosmopolitan attitude which differed from the mindset of Greece in earlier centuries but was n uncommon in Hellenistic times. Perhaps it isn’t inaccurate to use a modern term and call this a glob point of view. Eratosthenes not only thought that way, but he followed through by collecti information about the people, products and geography of far-flung areas. He wrote about the history geographical measurement, recalling old ideas going back to Homer about the size, shape a geographical lay-out of the Earth. In fact, he did nothing less than pull together virtually all t geographical knowledge that had been accumulating up until his own time.

Over the centuries, this material had taken a variety of forms. It came from traders, explore travellers – as well as mathematicians and philosophers – and it ranged from fantastic tales to mo straightforward reporting, from speculation to measurements and estimates resting on what we probably recognized as shaky assumptions. Among the more reliable sources were eye-witne accounts of Alexander the Great’s expeditions and the measurements and records of distances cover on those marches. There were itineraries of coastal voyages and maps and charts connected with the There was a treatise on harbours by Timosthenes, the admiral of the Ptolemaic fleet, who also studi the winds. There was a book entitled *On the Ocean* by the merchant sea-captain Pytheas, who in abo 320 BC sailed north along the coast of Spain and France and reached Cornwall, then continued all t way up to the Orkneys and the Shetlands to latitudes near those of the midnight sun. Pytheas to bearings throughout his voyage and recorded them in his book, which also has descriptive passages:

> The barbarians showed us where the Sun keeps watch at night, for around these parts the night is exceedingly short, sometimes two and sometimes three hours, so that only a short interval

passes after the Sun sets before it rises once more.

Eratosthenes respected Pytheas’s information, though it must have seemed almost as fantastic a Homer’s, while many other scholars were contemptuous and disbelieving. Living as Eratosthenes d in Hellenistic Egypt, he may also have known of centuries-old and astoundingly accurate Egyptia geographical calculations.

Eratosthenes’s expertise on longitude and latitude surpassed any other of his day or earlier. H predecessors had divided the map into zones. He took that work several steps further by improving o a map devised about 25 years before his birth by a man named Dicaearchus of Messene. Dicaearchu had divided the known world by using two lines or bands that intersected one another – one runnin east—west, the other north—south. On Eratosthenes’s revised map the two lines crossed at Rhodes, little to the east of where Dicaearchus’s lines had met. The horizontal line passed near Gibraltar (the known as the Pillars of Hercules), ran the length of the Mediterranean and then followed the Tauru chain of mountains in southern Turkey (Toros Daglari on modern maps). That line is remarkably nea to following what we call the 37th parallel – an impressive achievement for men without the benefit the mathematical and astronomical knowledge that would go into later mapmaking. It was not y possible to figure out latitudes with very great precision, and it was virtually impossible to determin longitude (which would prove to be a problem in Eratosthenes’s measurement of the Earth). O Eratosthenes’s map the vertical line followed the Nile, which doesn’t line up so perfectly with Rhode on modern maps. He added six further lines drawn vertically at intervals between the western an eastern boundaries of the inhabited world, and six more horizontal lines drawn at intervals between i northern and southern boundaries, and he established and measured geographic zones, dividing th world horizontally between the tropical region, the temperate region and the polar circles.

Eratosthenes was also well-acquainted with state-of-the-art geometry, both from Euclid profound summing-up about 25 years before Eratosthenes’s birth and from his association wi Archimedes, one of the towering creative geniuses that Greek and Hellenistic civilization produce and also one of history’s greatest eccentrics. Most schoolchildren have heard the tale of Archimede solving a mathematical problem in his bath, leaping from the water, and running naked through th streets shouting ‘Eureka!’ This avid mathematician eventually lost his life when Roman troops sacke Syracuse. Archimedes, so the story goes, was drawing a mathematical figure in the sand when Roman soldier (who had missed hearing an order from his superiors to respect the person of th famous old man) asked him to pack up and move along. Archimedes unwisely told the soldier not interrupt his thought process.

The Hellenistic world revered Archimedes as an inventor (though he himself dismissed suc practical achievements as unworthy of notice) and a useful man to have around in a war. Legend has that he destroyed an entire Roman fleet by using burning mirrors. The Middle Ages thought of him a an engineer and a wizard and credited him with the invention of the Staff of Archimedes. This devic was a stick with a small flat disc that could be run up and down it. An observer held the stick up to th Sun and moved the disc along it until it appeared to cover the Sun, then noted on a scale the distanc from disc to eye, thus deriving the Sun’s apparent diameter.

Modern history and mathematics books recall Archimedes as a brilliant mathematician an geometer who contributed significantly to the understanding of circles and spheres. Archimedes wa in the habit of sharing his discoveries and his methods with Eratosthenes and even dedicated h greatest work, *Method*, to him. Eratosthenes must have welcomed, another scholar who was almost eclectic as he was himself.

Eratosthenes’s thoughts stretched to the horizon in all directions. Perhaps it follows that he wou have ~~longed to know not only what was beyond those horizons but how far ‘beyond’ was? Mappin~~ and systematizing things geographically was his bent. Would he not have been unusually curio about how large the total map was? How remarkable if it really should turn out to be, as Aristot speculated, ‘a sphere of no great size’! Eratosthenes’s thoughts often took a historical turn, and he w aware of previous attempts to measure the Earth or estimate that measurement. Would he not hav wanted to try his own hand at it, using Euclid’s and Archimedes’s newer understanding of geometry?

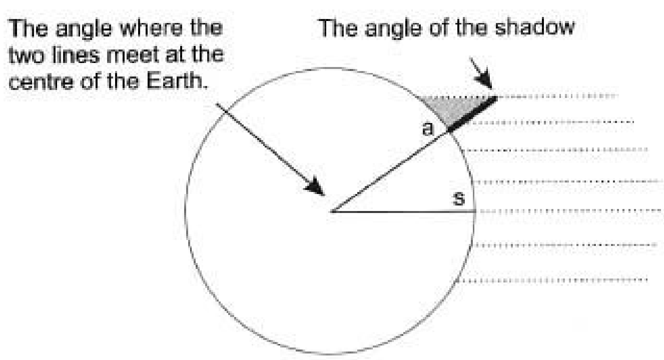
There is still one circumstance to be mentioned – a simple, trivial matter, yet Eratosthenes successful measurement of the circumference of the Earth would not have taken place without it. happenstance, perhaps, that such a small gem of information reached the ears of this man who realiz what it meant and what could be done with it. It is true that the fact that this snippet of news reache him *did* have something to do with the broadened mental horizons of the world, with improv communications from remote areas, with Eratosthenes’s own world centring on northern Africa, a with his habit of keeping his ears and eyes open and wanting to know everything and anything. He w indeed the right man in the right time and place. Perhaps there was no other so likely to run across th back-page news and recognize its worth:

In a well located at Syene (near modern Aswan), on the day of the summer solstice, a shaft sunlight penetrated all the way to the bottom of the well.

To Eratosthenes there was nothing trivial about this information. It meant that the Sun was shinin directly down at Syene, not at an angle, and he knew this showed that Syene was on the tropic. A stic set up at noon at Syene on the day of the summer solstice would not cast a shadow. A stick set up Alexandria (which he thought was the same longitude as Syene) *would*. Accordingly, Eratosthenes s up a stick at Alexandria on the day of the summer solstice and measured the angle of its shadow whe that shadow was at its shortest.

Figure 1.1 below shows the stick at Alexandria and its shadow, and what is meant by ‘the angle the shadow’. The figure illustrates how that must also be the angle ‘subtended’ by the arc Syene Alexandria at the centre of the Earth. To put that a bit more simply: if we draw a straight line from th point marked Alexandria (where the stick is casting a shadow) to the centre of the Earth, and a secon straight line from the point marked Syene (where the stick casts no shadow) to the centre of the Eart those lines will of course meet at the centre of the Earth. We want to know the angle between thos two lines where they meet. Geometry tells us, as it told Eratosthenes, that the angle at the centre of th Earth and the angle of the shadow at Alexandria will be the same angle.

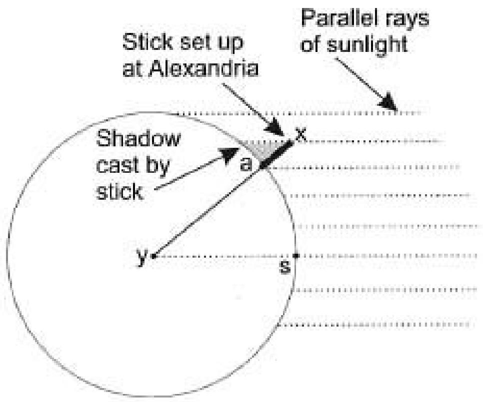
Figure 1.1



Because the Sun’s rays are running parallel as they strike the Earth, if a line is drawn from Alexandria (a) where the stick casts a shadow, to the centre of the Earth, and a second line from Syene (s) where there is no shadow, to the centre of the Earth, the angl where those two lines meet will be the same as the angle of the shadow at Alexandria.

Figure 1.2 illustrates Eratosthenes's measurement.

Figure 1.2



Because the sunlight shone all the way to the bottom of the well at Syene (s), Eratosthenes knew that the Sun was shining straight down on the Earth there. He set up a stick at Alexandria (a), where the Sun wasn't shining straight down, and he measured the ang (x) of the shadow cast by the stick. He knew that because the Sun's rays all run parallel as they strike the Earth, the angle (y) where line drawn straight down from Alexandria and a line drawn straight down from Syene would meet at the centre of the Earth would the same angle as the angle of the shadow cast by the stick (x). If Syene is due south of Alexandria, then the distance between Sye and Alexandria must be the same fraction of the Earth's total circumference as the angle at x or y is of 360°

Eratosthenes found that the shadow angle at Alexandria was 7⅕°, and so he knew that the ang between the 'Syene–Alexandria lines' (meeting at the centre of the Earth) was also 7⅕°. A circle ha 360°, and it is a simple process to find out how many of the Syene–Alexandria angles (7⅕°) it wi take to make 360°. Think of the cross-section of the Earth as a pie and the two lines coming fro Syene and Alexandria as cutting out a wedge of pie. How many wedges of that size can you cut fro the whole pie? Divide 360 by 7⅕, and it comes out to 50 wedges. If we say (as Eratosthenes did) th the distance between Syene and Alexandria at the surface of the Earth (at the pie-crust edge of the pi is '5,000 stades', then we can multiply 5,000 by 50 and conclude that the distance all the way arou the Earth – the circumference of the Earth – is 250,000 stades. Eratosthenes later fine-tuned this 252,000 stades.

What is this odd unit of measurement, the stade? That question brings up a problem in evaluati Eratosthenes's result. Whether or not that result matches modern measurements for the circumferen of the Earth depends on the length of 'stade' he was using, and it isn't known exactly what that leng was. If there are 157.5 metres in a stade, Eratosthenes's result comes to 39,690 kilometres or 24,60 miles for the circumference of the Earth. That is very near the modern calculation – 24,857 mil (40,009 kilometres) around the poles and 24,900 miles (40,079 kilometres) around the equator. Aft he had found the circumference, Eratosthenes calculated the diameter of the Earth as 7,850 mil (12,631 kilometres), close to today's mean value of 7,918 miles (12,740 kilometres).

Another way of figuring a stade was as ⅛ or ⅒ of a Roman mile, and that would ma Eratosthenes's result too large by modern standards. There was one additional small difficult Eratosthenes assumed that Syene lay on the same line of longitude as Alexandria. Actually, it doe not.

But this is nit-picking! No apology need be made for Eratosthenes. First of all, he arguably ca astonishingly near to matching the modern measurement. Second, he was probably, for all h

curiosity about the world, enough a man of his time to find the puzzle of how to solve this problem b
the ~~imaginative use of geometry at least as interesting as the actual measurement. The~~ *method*
ingenious and it is correct. If the numerical result is a little fuzzy because of a lack of agreement abo
the length of a stade and the impossibility of determining longitude precisely, that does not preve
our recognizing what a brilliant achievement this was or appreciating the intellectual leap involved
recognizing that it *could* be done and *how* it could be done.

Eratosthenes didn't focus his thoughts only on the Earth. He also raised them above the horizon consider astronomical questions of his day. When it came to measuring the distances to the Sun an the Moon, he must have realized that he had no tool at his fingertips to equal the news about the we in Syene. Nevertheless, he gave it a try, with far less success than he had in measuring the Earth circumference.

Another Hellenistic scholar, Aristarchus of Samos, also tried to measure the distances to the Moo and Sun. Little information exists about him as a person. He lived from about 310 to 230 BC and wou already have been a grown man when Eratosthenes was born. The island of Samos was under the ru of the Ptolemys during Aristarchus's lifetime and it is possible that he worked in Alexandri Archimedes was certainly aware of his contributions.

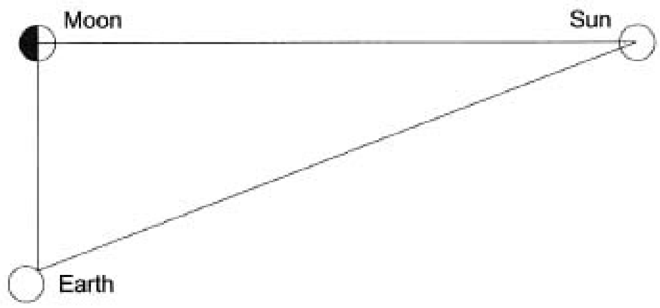
The only written work of Aristarchus that has survived is a little book called *On the Dimensio and Distances of the Sun and Moon*. In it he describes the way he went about trying to determine the dimensions and distances and the results he got.

The book begins with six 'hypotheses':

1. The Moon receives its light from the Sun.
2. The Moon's movement describes a sphere and the Earth is at the central point of that sphere.
3. At the time of 'half Moon', the great circle that divides the dark portion of the Moon from th bright portion is in the direction of our eye. (In other words, we are viewing the shadow edg on.)
4. At the time of 'half Moon', the angle (at the Earth as shown in Figure 1.3) is 87°.
5. The breadth of the Earth's shadow (at the distance where the Moon passes through it during a eclipse of the Moon) is the breadth of two Moons.
6. The portion of the sky that the Moon covers at any one time is equal to $1/15$ of a sign of th zodiac.

Aristarchus's fourth and sixth assumptions are both far from accurate. The actual angle at the Earth Aristarchus's triangle would be 89° 52', not 87°, and 89° 52' is very close to 90°. The angle at th Moon in Aristarchus's triangle *is* 90°. That makes lines B and C so close to parallel that, on a drawin the triangle would close up and be no triangle at all. The portion of one sign of the zodiac that th Moon covers is not $1/15$, and it isn't clear why Aristarchus, who must have known this from observatio chose that value.

Figure 1.3

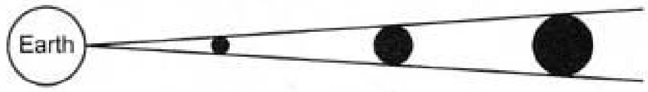


Aristarchus’s measurement of the relative distances to the Moon and the Sun: when the Moon is a half Moon, the angle at the Moo (in this triangle) must be 90°. So a measurement of the angle at the Earth determines the ratio of the Earth–Moon line to the Earth–Sun line; in other words, the ratio of the Moon’s distance to the Sun’s distance.

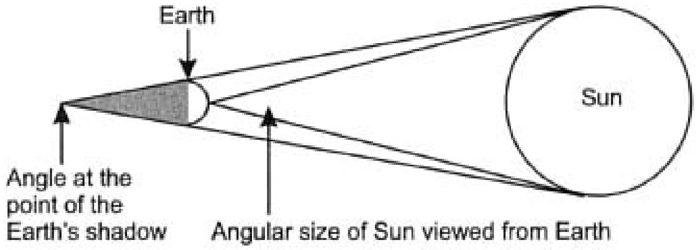
Aristarchus’s results are not what we now measure these relative distances to be. By h calculation, the distance to the Sun is about 19 times the distance to the Moon and the Sun is 19 tim as large as the Moon. The modern ratio between their distances is 400 to one. The measureme Aristarchus was trying to make was extremely difficult with the instruments available to him. It is simple undertaking to determine the precise centres of the Sun and the Moon or to know when tl Moon is exactly a half Moon. Aristarchus chose the smallest angle that would accord with h observations, perhaps to keep the ratio believable. Throughout antiquity and the Middle Age estimates of the relative distances to the Sun and Moon would continue to be too small.

Aristarchus didn’t stop with estimating the ratios, but found ways of converting them into actu numerical distances to the Sun and Moon and diameters for both bodies. He could see that tl *apparent* size of the Moon and the Sun (meaning the size they appear to be when viewed from Eart are about the same. During a solar eclipse, the Moon just about exactly covers the Sun. To put that more technical language: they both have approximately the same ‘angular size’. Angular size tel how much of the sky a body ‘covers’ and is measured in ‘degrees of arc’. Both the Sun and the Moo have angular sizes of about one half of a ‘degree of arc’. (For a fuller explanation of those terms, s Figure 4.4.) For that to be true, the two bodies don’t actually have to be the same size, for how larg they appear when viewed from Earth also depends on how distant they are. (See Figure 1.4a Aristarchus assumed that the Sun is much larger than the Earth, and that it was safe to assume als that the shadow cast by the Earth has about the same angular size as the Sun and the Moon (½ a degre of arc). (See Figure 1.4b.)

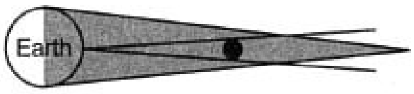
Figure 1.4 Aristarchus’s calculation of the size and distance of the Moon.



a. Surprisingly, all three of these bodies look the same size when viewed from Earth. We observe the ‘angular size’ of a body like t Moon or Sun, not its true size. It could be small and close or large and far away and still have the same ‘angular size’. Aristarchus saw that the Moon and the Sun have about the same angular size; that is, they *look* the same size when viewed from Earth, but he knew they are not the same true size.



b. (The angles shown in this drawing are much larger than those that really exist.)
Aristarchus assumed that the Sun is much larger than the Earth. If that is true, then the angle at the point of the Earth's shadow is about equal to the angular size of the Sun as viewed from Earth.



c. Observing an eclipse, Aristarchus concluded that the breadth of the Earth's shadow where the Moon crossed it was approximatel twice the diameter of the Moon. He knew the angle formed at the point of the Earth's shadow and also the angular size of the Moo There was only one distance to put the Moon where it would cover half the area of the shadow.

Note: These drawings are not to scale.

Aristarchus arrived at his fifth 'hypothesis' above – the breadth of the Earth's shadow (at th distance where the Moon passes through it during an eclipse of the Moon) is the breadth of two Moon – by observing a lunar eclipse of maximum duration, which means an eclipse in which the Moo passes through the exact centre of the Earth's shadow. He measured the time that elapsed between th instant that the Moon first touched the edge of the Earth's shadow and the instant that it was total hidden. He then found that that length of time was the same as the length of time during which th Moon was totally hidden. He reasoned that the breadth of the Earth's shadow where it was crossed b the Moon must therefore be approximately twice the diameter of the Moon itself (Figure 1.4c). If, he thought, the angle formed at the point of the Earth's shadow was the same as the angular size of th Moon, that gave him only one distance at which to put the Moon where it would cover half of the are of the shadow.

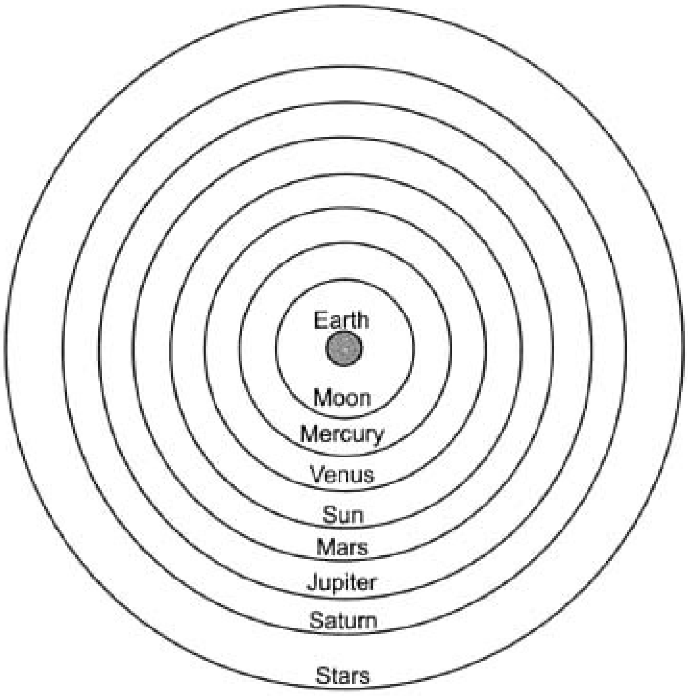
Aristarchus concluded that the Moon was ¼ the size of the Earth, and that the distance to the Moo was about 60 times the radius of the Earth. Both of those values are close to the modern values. Usin Eratosthenes's calculation of the Earth's radius, Aristarchus arrived at an actual distance to the Moo in stades. He had less success with the distance to the Sun. His earlier estimate – that the Sun distance is about 19 times the Moon's distance – was in error, and a second approach he tried, thoug it was ingenious and correct, required timing the phases of the Moon with a precision impossible his day.

It was another of Aristarchus's ideas that secured his place much more firmly in the annals astronomy. Hearing of it, one has a chilling sensation of stumbling into a prophetic vision. F Aristarchus suggested, 17 centuries before Copernicus, that the Earth is not the unmoving centre everything but instead moves round the Sun, and that the universe is many times larger than anyone his time thought – perhaps infinitely large.

For centuries it had been widely assumed that the Earth was the centre of everything. The accept picture of the cosmos was a series of concentric spheres – spheres embedded one within the other with the Earth resting motionless at the centre of the system. (See Figure 1.5.)

Plato and Euxodus of Cnidus, a younger contemporary of Plato, had introduced this model, ar Aristotle's model of the universe was a further development of it, though he differed from Euxodus to the number and nature of the spheres. However, it wouldn't be correct to think that everyon without exception, since the dawn of human thought had agreed that the Earth was the centre ar ~~didn't move. Some Pythagorean thinkers had decided in the fifth century BC, largely for symbol~~ic ar religious reasons, that the Earth was a planet and that the centre of the universe must be an invisib fire. Heraclides of Pontus, a member of Plato's Academy under Plato, proposed that the daily risir and setting of all the celestial bodies could be nicely explained if the Earth rotated on its axis onc every 24 hours.

Figure 1.5



But Aristarchus went further. Although information about his theory of a Sun-centred cosmo comes second-hand, no one disputes his authorship of the idea because there is plenty of seconda evidence. According to Archimedes:

> Aristarchus of Samos brought out a book of certain hypotheses, in which it follows from what is assumed that the universe is many times greater than that now so called. He hypothesizes that the fixed stars and the Sun remain unmoved; that the Earth is borne round the Sun on the circumference of a circle . . . and that the sphere of the fixed stars, situated about [that is, centred on] the same centre as the Sun, is so great that the circle in which he hypothesizes that the Earth revolves bears such a proportion to the distance of the fixed stars as the centre of the sphere does to its surface.

Aristarchus had done no less than move the centre of the cosmos to the Sun. In this astounding tur about, the Earth moves round the Sun and, rather than the sphere of the fixed stars making a revolutio of the heavens once every 24 hours, it is the Earth that turns, rotating on its axis – as Heraclides ha suggested. The stars are extremely far away. The implication is, infinitely far.

Did Aristarchus also speculate that the other planets move round the Sun? It would seem a logic next step, but there is no historical evidence that he did. In any case, it's unlikely that he understoo the enormous significance of his model, that it provides, at a sweep, the basis for explaining th planets' positions and movements far more simply than a model with the Earth as centre. It ~~impossible to tell from the surviving evidence whether Aristarchus really was personally disposed~~ t thinking that the Earth moved around the Sun or whether he made the suggestion merely for the sal of argument, as in 'Let's just suppose for the moment that this is how things work.' Why did th revolutionary suggestion came at this time and place in history? The simple answer may be that th was an intellectual environment that encouraged one to make suggestions and put forward hypothese even hypotheses based on assumptions that were known to be incorrect – in no way claiming the were true – as the starting point for an interesting line of enquiry.

With Aristarchus the question must also be turned on its head to ask not only why this ide emerged but why it died at birth. Seleucus of Seleucia, a Chaldaean or Babylonian astronom (Seleucia was on the Tigris river) in the second century BC, took Aristarchus's suggestion seriously not merely as a hypothesis. Seleucus believed Aristarchus was right. However, no one else for th remainder of antiquity did, and the remainder of antiquity was by no means a dark age when it came astronomy. It's only partly correct to blame this resistance on an ideological attachment to havin Earth and humanity the centre of everything.

If surviving information can be trusted, public opinion reacted almost not at all. Aristarchus's ide must have been too far removed from common knowledge and common sense to draw much popul attention. The historian Plutarch reports one comment from the Stoic Cleanthes (the Stoics we reputedly weak in natural science and even 'anti-scientific') that Aristarchus of Samos ought to b indicted on a charge of impiety for putting the 'Hearth of the Universe' in motion. There is no reco of anyone trying to take Cleanthes's advice. Some philosophers scolded Aristarchus for trespassing i an area of knowledge that was *their* sole domain; and there were also complaints accusing him undermining the art of divination.

As for astronomers, what mattered most to them was that there was no observational eviden whatsoever to support the vast distances to the stars that Aristarchus's scheme required, while ther *was* observational and physical evidence that made his Sun-centred arrangement seem highly unlikel

1. If the Earth moves round the Sun, then we on the Earth should see some variation in th positions of the stars, relative to one another, as we view them from different points along th Earth's orbit. No such variation had been observed (nor could it be with the technolog available at the time). Aristarchus saw that this objection wouldn't be valid if the stars we far enough away. Hence his suggestion that they were very far away indeed, perhaps even infinite distance. The fact that the position of the stars, relative to one another, does change Earth orbits – that there is 'stellar parallax motion' – wasn't confirmed by observation unt the mid-19th century.
2. If the Earth rotates on its axis, in fact, if it moves at all, this should have some noticeab effect on the way objects move through the air. Ancient astronomers realized that if the Eart rotates on its axis once every twenty-four hours, then the speed at which any point on i surface is moving is very great indeed. So, how could clouds, or things thrown through the ai overcome this motion? How could they ever move *east*? Even if not only the Earth but also th surrounding air rotates on the Earth's axis, solid bodies moving through the air should still i some way show the influence of the Earth's rotation.
3. It's plain to see that heavy objects travel towards the centre of the Earth. If this law applies heavy objects everywhere, then the centre of the Earth must be the centre of gravity for a things in the universe that are heavy. Furthermore, once a heavy object reaches the plac

towards which its natural movement sends it, it comes to rest. Applying this idea to the Eart the inevitable conclusion is that the Earth must be at rest in the centre of the universe and th it cannot be moved except by some force strong enough to overcome its natural tendency. Th argument was based on Aristotle's concept of 'natural' places and 'natural' movements. It i easier to see the validity of it if you realize that Aristotle thought of everything beyond th Moon being made up of something called aether, which was neither 'heavy nor light'.

4. The Sun-centred model did nothing to solve a problem astronomers had long been grapplin with: the inequality of the seasons measured by the solstices and the equinoxes.

It would be inaccurate, and unfair to Aristarchus's contemporaries, to say that his Sun-centred mod was suppressed because of their ignorance and closed-mindedness. The fact is, it was an inspire guess that we now have the means to know was right. But there actually was nothing coming fro observation then to recommend it over what was the more orthodox view of the universe – the Eart centred view that had been around for hundreds of years and that would be brought to its mo sophisticated form in the work of the astronomer Claudius Ptolemy (not necessarily related to th Ptolemaic dynasty) four centuries after Aristarchus. Ptolemy's model would brilliantly explain th movements of the planets *if* the Earth is the centre – and, indeed, it solved the problems of astronom *as they were perceived at the time* better than Aristarchus's model. Aristarchus's idea was a seed sow far too early, in a season in which it could not possibly germinate and take root. Ptolemy's Earth centred astronomy would dominate thinking about the cosmos until the 16th century AD.

That is not to say that no further progress was made in ancient times towards understanding th heavens.

Hipparchus of Nicaea, who lived in the second century BC, was one of the most skilled astronome the world has known, and he laid the foundation for much that was to follow. Hipparchus had at h disposal a priceless collection of Babylonian astronomical records – a legacy of Alexander conquests – which he put to splendid use in his own astronomy, meticulously comparing the positio and patterns of stars and planets over the centuries with those he observed. Like Aristarchus an Eratosthenes, Hipparchus tried to find a way to calculate the distances and dimensions of the Sun an Moon. Part of his inheritance from the Babylonians was eclipse records spanning many hundreds years. He also used a new line of reasoning, focused on the fact that there is no discernible change the Sun's position against the background of stars when we move from one point to another on th surface of the Earth. To put that in more scientific language, there is no 'solar parallax motion Hipparchus worked on the assumption that observers on the Earth only just miss seeing solar paralla – in other words, that solar parallax is just below the threshold of visibility – and took it from ther with little success in terms of matching modern calculations.

One of Hipparchus's most impressive achievements – which came from comparing his ow observations with observations made about 160 years earlier – was discovering the change in th relative positions of the equinoxes and the fixed stars. That is, if we look at the stars on the evening the spring equinox, and then again on the evening of a spring equinox some years later, the stars wi not be in the same position. In fact, they won't be in the same position again for 26,000 years! Th phenomenon is the 'precession of the equinoxes'. Though Hipparchus couldn't discover its cause, h gave an accurate estimate of the rate of this change.

Of all Hipparchus's writings only one youthful, minor work survives. Next to nothing is know about his life or where he spent it, except that his name indicates that he must have hailed original from Nicaea, in the northern part of what is now Turkey. Information about his accomplishmen comes only from the references of others, mainly Ptolemy, but that evidence is sufficient to show th ~~Hipparchus was an extremely fine astronomer and that he vastly improved observational techniq~~ues.

Where did Hipparchus stand in the competition between Aristarchus’s model of the universe ar the more orthodox one? Definitely pro-orthodox. Hipparchus was among those who did not acce Aristarchus’s Sun-centred cosmos, and he influenced others to reject it. Hipparchus felt obliged abide by the evidence of observation – observational astronomy was, after all, one of his fortes – an as we have seen, observation didn’t support Aristarchus and couldn’t confirm the enormous distanc required by the Sun-centred model. Hipparchus’s own work contributed significantly to Ptolemy later Earth-centred model of the cosmos. Some scholars even insist that Ptolemy’s astronomy was b and large a re-editing of Hipparchus’s, that Hipparchus was the genius and Ptolemy the textboo writer.

The Roman Pliny the Elder wrote of Hipparchus:

> 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 to indicate their several positions and magnitudes so that 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.

‘If anyone be found . . .’?