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The Remarkable Science of Ancient Astronomy

Course Guidebook

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Bradley E. Schaefer is Distinguished Professor and Alumni Professor in the Department of Physics and Astronomy at Louisiana State University. He earned his undergraduate degree in Physics in 1978 and his Ph.D. in Physics in 1983, both from the Massachusetts Institute of Technology. Professor Schaefer worked for 11 years at NASA's Goddard Space Flight Center and then was a professor at Yale University with a joint appointment in the Departments of Astronomy and Physics. At Louisiana State University, Professor Schaefer has won campus-wide teaching awards, including the Alumni Professorship and the Distinguished Faculty Award, which are given for excellence in teaching. Professor Schaefer has 218 publications in refereed journals.

Starting in the mid-1990s, Professor Schaefer became one of the members of the Supernova Cosmology Project, led by Saul Perlmutter of the Lawrence Berkeley National Laboratory. This group found that the expansion rate of the whole universe is accelerating. The implication of this startling result is that some unknown dark energy is powering this acceleration and that this mysterious quantity makes up around 68% of all the mass-energy of our universe. This was published in a paper in 1999, with Perlmutter as first author. As one of the discoverers of dark energy, Professor Schaefer received a share of the $500,000 Gruber Cosmology

Prize in 2007 as well as a share of the $3,000,000 Breakthrough Prize in Fundamental Physics in 2015. In 2011, Perlmutter won the Nobel Prize in Physics for the discovery work in the 1999 paper.

Professor Schaefer has written 31 refereed articles on the history of astronomy in journals. In addition, he has written 27 feature articles for the popular magazine *Sky & Telescope*, many of them featuring results presented in this course. Professor Schaefer is on the editorial boards for both *Archaeoastronomy* and the *Journal for the History of Astronomy* and has served on the editorial board for *Culture and Cosmos*. In 2004, he presented the keynote speech for the Oxford VII conference, the international quadrennial meeting for archaeoastronomy.

Professor Schaefer has worked on the astrohistory of many topics, including the canon of Sherlock Holmes, *The Hobbit*, the Great Escape of World War II, the so-called Chinese astronomical jade disks, the origin of the star and crescent symbol, the Voynich manuscript, the heliacal rise of Sirius, and the Crab supernova as possibly recorded in Europe. He also has done extensive work on the visibility of celestial objects, including the green flash, earthshine during solar eclipses, mountain shadows, the black drop during transits of Venus, and the astrophysics of suntanning.

In 1981, Professor Schaefer invented and started the annual MIT Mystery Hunt and then ran the first 4 hunts. After he left MIT with his Ph.D., the tradition was kept alive, and it has grown tremendously. The hunt is a simple search for an Indian Head penny hidden around campus. The clues are a vastly wide array of incredibly difficult puzzles and enigmas. The MIT Mystery Hunt was soon copied on many other university campuses and then by megacorporations, and hunts like it are now called by the generic name of puzzlehunts. ■

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INTRODUCTION

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SUPPLEMENTAL MATERIAL

The Remarkable Science of Ancient Astronomy

This introductory astronomy course covers the science of the skies, how ancient astronomers used the skies, and how the skies interact with all humans on many levels. The course will cover the entire world from many thousands of years B.C. up until the end of ancient astronomy around 1600 A.D., with a concentration from 3000 B.C. to 200 A.D.

The course starts with Stonehenge, that great monument with wonderful circles of standing stones an hour's drive west of London, with its famous alignment toward the midsummer sunrise over the Heelstone. Actually, the evidence makes a good case that it is really pointing at the midwinter sunset in the opposite direction. Stonehenge is just the most spectacular example of many stone circles and temples and burials throughout Eurasia from the Late Stone Age and the Bronze Age, many with intentional astronomical alignments. In the same tradition are the pyramids of ancient Egypt, with the Great Pyramid aligned north-south to the remarkable accuracy of $\frac{1}{20}°$, as an expression of their directional symbolism (with east for birth, west for death, and the never-setting stars in the north for immortality).

Starting around 600 B.C., the basic suite of Stone Age astronomy started changing rapidly with many remarkable discoveries. In breaking the supernatural away from the sky, the early Greeks started explaining eclipses, knowing the shape and size of our Earth, and crafting a worldview of the Earth's place in the universe. Around 130 B.C., the great Greek astronomer Hipparchus discovered precession (where the stars appear to move), quantified the skies with his now-lost star catalog, and developed a detailed solar and lunar model. Around the same time, an anonymous Babylonian scribe was studying the motions of the planet Jupiter, and he invented what can only be called part of calculus. Also around that time, a remarkably complex analog computer was made from bronze gears and was used to calculate calendars and planet positions and predict eclipses and the Olympic Games. Around 2000 years ago, the Maya, Indians, Babylonians, Greeks, and Chinese all measured various planet periods to accuracies of parts per million.

The regular task of ancient astronomers around the world was to use the skies to make tools for common and everyday needs. The ancient needs for timekeeping were many, and a wide variety of methods and mechanisms were devised, all pointing back to the Sun and stars for definition, measure, and calibration. These include the use of gnomons all around the world, the sundial throughout Eurasia, the timings of star rise for the 36 Egyptian decans, and the position of the Dipper stars around the pole throughout the Northern Hemisphere. Ancient astronomers were always the keepers of the calendars, with these determining the dates of festivals and holy days as well as predicting the times to plant and harvest crops. For direction finding, only the Sun and stars could be used, with the Arabs making the sophisticated technology of the astrolabe. For navigation past the simple strategy of following the coastline, the basis was direction finding and latitude sailing, with the Polynesian and Viking sailors enabling their magnificent voyaging only by fine-tuning with the Sun and stars. All old cultures also took frequent practical use of the skies as a source of celestial omens, including astrology, which guided the actions of kings and commoners. Perhaps the most famous example of this is the Star of Bethlehem, a celestial omen pointing to the birth of a very great king in Judea; surprisingly, the real historical origin of this sign in the sky was only recently discovered.

Ancient astronomy came to an end around the year 1600, with the great discoveries of Copernicus, Tycho, Galileo, and Kepler. Astronomy led the way and started the Scientific Revolution, with exponential growth in knowledge and skills continuing even to today.

The astronomers and sky phenomena have been the direct inspiration and origin of many philosophies that have guided cultures and the ages. This includes the Chinese mandate of heaven doctrine, rising from ancient planetary massings, and the mystery religion of Mithraism, probably rising from Hipparchus's discovery of precession. The most important philosophical change was when Greek astronomers (starting with Thales, Anaximander, and Anaxagoras) took the supernatural out of the heavens by instead explaining sky phenomena by naturalistic causes that could now be called physics. Once a culture was past the flat-Earth stage, all the wider questions (e.g., what is our world like?) have answers that only come from the astronomers, with these answers creating the worldviews common within each culture, having broad philosophical implications throughout societies. Toward the end of ancient astronomy, the Copernican principle is established, proving that humanity does not occupy any special position, and the Scientific Revolution is started by astronomers.

The sky forms the upper half of our human environment, so it is not surprising that it touches everyone, great and common, in many ways and throughout history.

LECTURE 1

Stonehenge and Archaeoastronomy

Ancient astronomers viewed the skies differently than we do. Ancient astronomy had different tools—and different goals—than does modern astronomy. Yet despite these differences, we also have a rich heritage coming to us from ancient astronomy. Ancient astronomers made remarkable discoveries and achieved remarkable feats that were built on many thousands of years of watching the sky. Perhaps the most famous example from ancient astronomy is Stonehenge. In this lecture, you will learn about the archaeoastronomy and history of Stonehenge.

STONEHENGE

- Stonehenge is a monument located on the Salisbury Plain, in south-central England, just under a 2-hour drive from London. The basic structure is a set of standing stones set in a circle that surrounds a horseshoe-shaped set of standing stones.

- The central set of stones consists of 5 pairs of very tall stones topped by a horizontal stone, called a lintel. Each of these so-called trilithons have the lintel stone pegged to the vertical stones with a mortise-and-tenon joint, which has a knob sticking out of the top of the standing stone that fits into a hole in the lintel so that the lintel cannot easily fall off. The tallest stone reaches 24 feet from the ground; the biggest stones weigh 40 tons.

- The horseshoe of trilithons is surrounded by a circle of stones. The basic circle originally consisted of 30 standing stones, each topped by 2 lintels to form a continuous ring running around the top. The stones in the circle are made of a sandstone rock type called sarsen.

- Each of the stones has been pounded into a roughly rectangular shape. This shaping of stones is rare among stones at other contemporaneous stone circles around the British Isles. Many of the original stones have fallen down or been taken away.

- The immediate vicinity of Stonehenge has a complex array of remains that go far past the basic monument. Centered on the monument is a circular ditch with a radius of 180 feet. The chalk dug out from the ditch was heaped into a bank running just inside the ditch. The ditch doesn't form a complete circle; there are sections to the south and to the northeast that form openings into the central area.

- The opening toward the northeast forms part of a long linear feature called the avenue, which is defined by 2 parallel ditches running out from the circular ditch around the monument. This avenue goes perfectly straight for 2000 feet before veering to the right and ultimately running down to the River Avon.

- At the start of the avenue, where it touches the circular ditch, is a now-fallen dressed, or cut, rock known as the Slaughter Stone. This name invokes an image of ritual sacrifice, and people imagined the victim laid out on the stone.

- Just a bit outside the ditch, just off-center in the avenue is the upright Heelstone, which is famous because it defines the astronomical alignment of Stonehenge; that is, on the morning of the June solstice, the longest day of the year, if you're at the center of Stonehenge, you'll see sunrise over the Heelstone.

- There are many more stones and pits within the central ditch area, including a circular array of 56 pits called the Aubrey Holes. Nearly on top of these Aubrey Holes are 4 undressed stones that define a rectangle called Station Stones, 2 of which are surrounded by small ditches.

- Close around the basic stone circle are 2 more rings of holes that are irregularly spaced, and the center of the whole circle has a stone called the Altar Stone, which is now fallen and lying mostly buried under a lintel fallen from a trilithon.

- Stonehenge and its surroundings were made by a culture of Neolithic farmers known as Beaker people. They flourished throughout the British Isles and western Europe from the Late Stone Age to the Early Bronze Age. Stonehenge was built in stages, from roughly 3100 B.C. to 1600 B.C.

- The larger area surrounding Stonehenge is filled up with contemporaneous monuments that are dominated by burial mounds of many types. And there are a variety of other circles, or henges, throughout the area.

- Stonehenge was built with only primitive tools. Archaeologists find many broken antler tips inside the pits and ditches. These were the tools used to dig in the ground.

- Perhaps the most impressive point about the construction is that the extremely heavy stones were transported tremendous distances to be brought to Stonehenge. The big sarsen sandstones were dragged 18 miles from Marlborough Downs to the north. The smaller bluestones were dragged, and perhaps floated by raft, from quarries in Wales about 150 miles away.

THE ARCHAEOASTRONOMY PARADIGM

- The word “archaeoastronomy” can generically refer to the study of astronomy as it was practiced in ancient times. But there is also a much more specific meaning having to do with how ancient peoples built monuments aligned to the stars.

- The basic paradigm of archaeoastronomy is that ancient peoples incorporated astronomy into their old temples and other structures by pointing to a particular direction on the horizon where something significant happens.

- Such directional symbolism is universal in all cultures. The reasons are widely varied, but they always exist, always go back to the astronomy, and often are charged with strong cultural traditions. For most ancient peoples, these alignments are a common way to interact with the sky. But the astronomical origins might have been partly lost on the common folk.

- The basic setup of archaeoastronomy is that some now-ancient building is pointing at some direction on the horizon. This pointing might use some obvious main axis of the building plan, or the architecture can somehow indicate a position for an observer to stand, plus some stone marking a direction to look.

- The position for the observer to stand could be given by the center of a circle, a throne, a statue, or the top of a grand staircase. The direction to look might be marked as down some central axis, along a wall, perpendicular to a wall, or by some distant stone.

- The astronomically significant direction on the horizon is usually one of the 4 cardinal directions or one of the 4 solstitial directions. The 4 cardinal directions are north, east, south, and west.

- The 4 solstitial directions are toward either sunrise or sunset on the dates of either the summer solstice or the winter solstice. These solstitial directions are the Sun's extreme north during summer and the Sun's extreme south during winter. The days of the solstices are close to June 21 and December 21 every year. For people in the Southern Hemisphere, summer and winter have to be reversed.

- In addition, there is a lot of talk about the Moon's equivalent extreme rise and set directions. Also, in rare cases, the significant direction can be toward the rise of some bright star.

- Halfway between the solstice dates, the Sun will equally illuminate both hemispheres, and these dates are called the equinoxes, which are close to every March 21 and September 21. There's nothing special that happens on the days of the equinox, but the solstices are when things turn around—both the sunrise changes and the season changes.

- With the seasonal cycle being so critical for all ancient peoples, it's plausible that these would be commemorated in stone and architecture. In all, archaeoastronomy is looking at the nearly universal commemoration of the 8 cardinal and solstitial directions, rarely including star-rise directions, in the monuments and myths of ancient cultures.

ARCHAEOASTRONOMY AT STONEHENGE

- If you stand at the center of Stonehenge on June 21, you can see through a gap between 2 upright stones, under their lintel, with the Heelstone viewed in the middle just poking up above the distant horizon, and that is where the solstice Sun rises.

- This basic astronomical alignment was recognized from antiquity, but it was only in 1965 that this alignment started a worldwide obsession with Stonehenge. This began with the publication of astronomer Gerald Hawkins's best-selling book, *Stonehenge Decoded*.

- On the back of the book, the blurb pushed one of the strong selling points—that all of the many astronomical calculations were made with a "computer." The public was intrigued by the recovery of long-lost ancient wisdom. This book launched storms of protests from archaeologists. It also launched the whole field of archaeoastronomy.

- Hawkins's computer work confirmed the alignment on the solstice sunrise. But he also proposed a series of other alignments and claimed that Stonehenge is an analog computer to predict eclipses. This led to the view that Stonehenge was a marvelous astronomical observatory that was millennia in advance of the rest of the world in science.

VIEWS OF STONEHENGE

- British antiquarians were the first to pay attention to and study Stonehenge, and they attributed the monument to Merlin or Druids, the intelligentsia of the Celtic peoples through the British Isles that are best known as being religious leaders with a passion for human sacrifice. This general view of Stonehenge has a strong hold on the public imagination. Now, the most widespread picture of the original Stonehenge is as a Druid religious temple with human sacrifice.

- Starting in 1965 with Gerald Hawkins, the astronomical alignments and the eclipse computer were widely taken to be the critical components of Stonehenge, to the exclusion of most else. With this, astronomers were telling us that Stonehenge was just one big astronomical observatory and computer. The fusion of the 2 themes was that some mystic Druid astronomer-priests ruled their society and built Stonehenge for their own astronomical observatory.

- In the last century, modern pagans invented a new religion centered at Stonehenge. These neo-Druids dress up in white robes, sometimes with fake beards, and parade around Stonehenge carrying large staffs. These groups model their rituals on what they imagine was done by ancient peoples, but there's no connection to or basis with the real Iron Age Druids of Britain.

- On the summer solstices from 1974 to 1984, Stonehenge became the venue for a free festival, featuring rock bands and free drug use. These hippies would get into gang fights with motorcycle gangs. The British police finally suppressed this in 1985, but the hippies fought back, in what became known as the Battle of the Beanfield, with arrests of 537 people.

- All of this rebranding of Stonehenge became absurd in 2003, when a British medical journal ran an article claiming that the monument design was intended to model female genitalia. The authors were a pair of Canadian gynecologists.

- Through all this, archaeologists were telling us that Stonehenge and all the tombs and burial mounds in the area were just part of a huge Neolithic burial grounds. It seems that we're fated to have every special interest group picturing Stonehenge according to their own interests. But the real picture for Stonehenge archaeoastronomy is much more complex, detailed, and confident.

Readings

Christer, *Stonehenge Legacy*.
Hadingham, *Early Man and the Cosmos*.
Hawkins, *Stonehenge Decoded*.
Magli, *Mysteries and Discoveries of Archaeastronomy*.
Ruggles, *Ancient Astronomy*.

Questions

1 What do you identify as the archetypical exemplars for ancient astronomy? In other words, what are the most famous discoveries, the most exciting astro-locations, the most important topics, and the greatest astronomers of antiquity?

2 In old times, for a relatively small number of scholars, ancient astronomy is various lines of theory and observations that we might call science. But these are not the concerns of the vast majority of astronomers or ordinary people throughout ancient times. What were the primary concerns of working ancient astronomers? What do you think were the primary concerns and sky interactions for commonplace people?

Activity

1 For Stonehenge, many special-interest groups model their interpretations based on their own desires, centered on their own narrow interests. To see how easy and alluring this mistake is, construct your own new interpretation of Stonehenge, perhaps based on your own favorite topic or on some modern ideal.

LECTURE 2

The Real Stonehenge

The popular picture in our minds for ancient Stonehenge is of Druids among the stones, dressed in flowing white robes, with long white beards. They are a combination of priests and astronomers. Stonehenge served partly as a temple for their sacred rituals and also as an astronomical observatory. The alignment of the stones toward the summer solstice and the extreme Moon positions were of high accuracy and required a genius to build. But this widespread image is wrong on almost every point. This lecture will correct these misconceptions and will examine evidence for the real situation and why this newer evidence is convincing.

DISPELLING THE NOTION OF DRUIDS

- The neo-Druids first appeared in the 20th century, gathering at Stonehenge since the 1960s, but these groups have no connection to the original Iron Age Druids.

- More importantly, even the original Druids appeared much later than Stonehenge. The original Druids flourished in the middle Iron Age, before their suppression by the Romans around 200 A.D. But Celtic peoples arrived in the British Isles only around 500 B.C.—around 2000 years after the iconic stones were put up and 1100 years after Stonehenge was abandoned. So, the Druids couldn't have had anything to do with the original design or expansion of Stonehenge.

ALIGNMENTS AND AN ECLIPSE COMPUTER

- Gerald Hawkins claims in his popular book *Stonehenge Decoded* that the monument was used both for moonrise alignments and as an eclipse computer.

- Hawkins proposed that the long side of the rectangle formed by the 4 Station Stones points at the extreme southernmost moonrise. By analogy to the term "solstice," this extreme point of moonrise is called a lunastice, or lunar standstill.

- The concept of an extreme moonrise position, or lunar standstill, is entirely a modern invention, first concocted in 1912 by British Vice-Admiral Boyle Somerville. Extensive research has concluded that no culture at any time before 1912 has any knowledge or interest in the idea of extreme moonrise positions.

- The absence of lunar standstill, or extreme moonrise, in books and other records of ancient astronomy is in very stark contrast to the omnipresent and universal recognition of the solar standstills. Both of these are similar concepts that are observed similarly. So, the utter absence of lunar extremes is telling us strongly that no ancient peoples knew about or used the concept.

- Hawkins's claim for his lunar alignments is simply that the stones point toward the interesting directions around the horizon, so therefore the original builders must have intentionally designed these features. But Hawkins's own statistics on his 24 claimed alignments show that they are based purely on chance.

- Hawkins's other big claim is that Stonehenge was an eclipse computer. He concocted a specific plan by which 6 markers could have been moved around the 56 Aubrey Holes following a fixed schedule, with certain configurations pointing to a danger period when an eclipse could happen.

- The entire idea of an ancient eclipse computer at Stonehenge is built around the number 56 for the Aubrey Holes. Hawkins came up with one particular scheme for moving markers, but there are 3 other completely different schemes on how to use the 56 Aubrey Holes as part of an eclipse computer.

- Other archaeoastronomers have devised eclipse computer schemes for many numbers other than 56. It appears that almost number can be turned into a purported eclipse computer, so there is nothing mathematically special about the number 56. There also doesn't appear to be anything archaeologically or culturally significant about the number 56.

- The Aubrey Holes were filled with the cremated remains of many people—they are graves. There's no evidence, either at Stonehenge or from other sites around the region, that these grave holes are also computer bits. And because they're graves, the holes were filled in to cover the bodies, so they weren't empty receptacles for moving stones around as part of a supposed eclipse computer.

- The eclipse computer idea is just a modern idea, whereas the practical reality is that the Beaker people at Stonehenge couldn't get the data or knowledge to have realized any such computer. So, we have to conclude that the eclipse computer idea is an anachronism, just a modern idea projected back in time as a fantasy.

LACK OF GENIUS AND ACCURACY

- The popular picture of Stonehenge highlights the accuracy of the alignments and supposes that it takes a genius to make the original design. But this alignment does not require any wisdom or genius.

- The existence of solstice sunrise extremes is obvious, with commemorations throughout the world, so this is common knowledge. Thinking to build something pointing in that direction doesn't require a genius, either.

- But what about setting up an accurate alignment? This is easy, too, and can be done by one person making observations of sunrises over just a few days. In fact, anybody can get an accuracy of a fraction of a degree with little effort.

- The Stonehenge alignment we see today is not especially accurate. In pictures, the solstice Sun appears above and to the left of the top of the Heelstone. The first gleam of the Sun appears a bit under 2° left of the Heelstone.

- The original alignment error was perhaps smaller than this, because the Heelstone originally came as a pair of stones, with only the Heelstone surviving. The missing stone was near the center of the avenue, about 10 feet north of the Heelstone. The idea is that the Sun rose near the middle, framed on the horizon by the 2 stones. This still has an error of about 1°. And the pair of stones is not well framed from the center of the circle, with one stone being obscured by one of the standing stones in the sarsen circle.

HEELSTONE

MIDWINTER SUNSET, NOT MIDSUMMER SUNRISE

- Popular accounts of Stonehenge astronomy often start with the midsummer sunrise as viewed over the Heelstone; that is, standing at the exact center of the circle, looking out straight down the avenue, on the summer solstice, we can see the sunrise over the Heelstone. The main axis of Stonehenge is indeed pointing toward the summer solstice sunrise.

- The overwhelming popular perception is that the basic Stonehenge alignment is toward the midsummer sunrise. But an axis line points in 2 directions. Looking in the reverse direction, the main axis points off to the southwest. Due to the symmetries in the Sun's rise and set, a line that points toward the midsummer sunrise also points to the midwinter sunset. So, we have an ambiguity as to whether the Stonehenge builders intended midsummer or midwinter.

- One reason to point to midwinter comes from the dating of the big feasts. A site next to Stonehenge was a big annual feasting site. The pig bones from this site tell us that these yearly feasts were close to midwinter. With the highlight of the year being around the winter solstice, it makes sense to think that the Stonehenge axis was intended for use at the time of the winter solstice.

- Another strong reason comes from many contemporaneous sites throughout the British Isles, where there is no ambiguity, and they are all pointing to the midwinter direction. These other sites were made around the same time by people from the same culture, so presumably their reasons for orientations would be the same.

- So, we have a coherent story that the intended alignment is toward the sunset on December 21. Undoubtedly, the alignment was used in association with some sort of ritual, even though we have not recovered the symbolism or theology with any confidence.

A HIGH-STATUS BURIAL GROUND AND PILGRIMAGE SITE

- Stonehenge is a high-status burial ground. The monument itself has many people buried in it. The whole area within view of the monument, for miles in all directions, has a very high density of burials.

- Within the central Stonehenge ditch alone, which has a diameter 360 feet, archaeologists have recovered 52 cremation burials, many cremation fragments, and many fragments of unburnt human bone. This sample comes from an estimated 240 individuals, fairly evenly divided between males and females. Their graves were mainly in the

Aubrey Holes and in the ditch. The bones can be dated with the radiocarbon technique, with death dates ranging roughly uniformly from 3000 B.C. to 2400 B.C.

- So, the rate of burials is an average of just 4 people per decade. With this rate, commoners were not being buried at Stonehenge. Rather, Stonehenge burial appears to have been reserved for people with high status, perhaps family members of a ruling dynasty.

- More than 1400 tombs are known in the Stonehenge area. Many of these are burial mounds called barrows. There are also many scattered graves and cremation collections. These barrows all date from after around 2400 B.C. So, it seems that early Stonehenge had burials inside the ditch, and then the big sarsen stone circles and trilithons were installed, after which burials were all in mounds, nearby and in sight of the trilithons.

- Archaeologists have never found any homes or villages close to Stonehenge. Nobody lived there.

- Barrows contain high-status burial goods, some of which traveled far and must have had high value. Isotopic analysis of bones and teeth show that some of the buried people were local to the Stonehenge area but that others came from distant places.

- Archaeological evidence paints a picture of people coming from all over the British Isles and from all over Europe, bringing herds of animals, and converging on Stonehenge for massive feasts at midwinter. And these feasts kept happening year after year.

- This sounds like Stonehenge was some sort of a pilgrimage site. Pilgrimage sites often have yearly meetings, and pilgrimages are made for many purposes. Based on evidence that the people buried around Stonehenge had an anomalously high frequency of trauma and defects, a plausible theory was proposed in 2006 that perhaps the monument attracted sick and injured people as part of a pilgrimage. Perhaps Stonehenge was a site for healing.

WHAT ALIGNMENTS TEACH US

- Archaeoastronomers love to highlight the deep insights that the horizon alignments give modern scholars about the builders and their society. But the midwinter alignment does not tell us anything special about Stone Age technology from 3100 B.C.

- The construction of the sightline is easy for one person to lay out in a few days. The astronomy of Stonehenge is trivial for a solstice alignment. And the other claimed astronomical features don't exist. So, we don't learn anything about ancient science from the alignment.

- And we don't learn anything about the theology or culture of the Beaker people. The mere existence of the alignment is not any significant part of any religion or society. The symbolism in the alignment is real, but it's just a small part of the inevitable rich symbolism at the site, most of which is now lost.

Readings

Cleal, Walker, and Montague, *Stonehenge in Its Landscape*.
Hawkins, *Stonehenge Decoded*.
Pearson and the Stonehenge Riverside Project, *Stonehenge*.
Ruggles, *Ancient Astronomy*.
Souden, *Stonehenge*.

Questions

1 All cultures have some form of celebrations or commemorations for solstices. Around the world, are there more midwinter or midsummer celebrations? In other words, do we humans tend to have holidays and rituals more around December 21 or June 21? Look at holidays worldwide, not just in Western culture. Do you see a difference from northern cultures to southern or equatorial cultures? How strong is this evidence for applying to Stonehenge as an argument on breaking the midwinter/midsummer ambiguity?

2 The mental image of Stonehenge as a Druid observatory and computer, with the astronomer-priests running the society, is powerful for controlling the popular imagination. But through all this, the archaeologists were laughing (or crying) because they know that all the evidence instead points to Stonehenge as just being an impressive and large mortuary complex for the elite. So, why has the popular image been created, been maintained, and refused to die?

Activity

1 Is there any astronomical symbolism incorporated into famous cemeteries? Pick a modern example, perhaps Westminster Cathedral, Arlington National Cemetery, Père-Lachaise Cemetery in Paris, or Forest Lawn Memorial Park in Los Angeles. Out of all the symbols of all types that were intentionally built into the cemetery, what fraction of them are astronomical? This might include a cathedral “pointing” to the sunrise on the day of the patron saint, famous buried astronomers, astronomical symbols on gravestones, or directional symbolism for the orientation of the graves. Satellite images and street views are now easily available on the Internet, so you can check out the directions and views. For your modern example, are the common people aware of the astronomical symbolism? For each astronomical symbolism, could a far-future archaeoastronomer pull it out from the archaeological record?

LECTURE 3

Alignments at Maes Howe and Newgrange

Stonehenge is the most famous example of ancient astronomy in any form. Part of this is the famous alignment with the solstice Sun. The alignment of 2 rocks pointing to some astronomical direction on the horizon could even be called the Stonehenge paradigm. This basic archaeoastronomy paradigm has been found to be a good explanation for many sites, 2 of which will be considered in this lecture: Newgrange and Maes Howe.

NEWGRANGE

- The British Isles have many hundreds of surviving stone circles. Most of these are awkward assemblies of uncut stones of many shapes. Part of the reason why Stonehenge is so impressive is because the big sarsen stones have been carefully dressed, or cut, to a uniform and regular shape.

- But the second or third most impressive monument in the British Isles, called Newgrange, also has well-shaped stones that show extensive panels of Neolithic art etched into the stone faces. Newgrange is a passage grave about 20 miles north of Dublin, Ireland, near the River Boyne.

- Newgrange was built around 3100 B.C., according to radiocarbon dating. This was just at the time when Stonehenge was being started. Artifacts at Newgrange show it to be in continual use up until around 2000 B.C. This means that the Newgrange builders and users were the contemporaries of the Stonehenge people, and they all shared a common culture of the Beaker people.

- Newgrange is a passage tomb, which is a large dirt mound that covers a stone passage and central tomb. Around the edge of the mounds are many stones acting as curbs at the base, with many of these showing wonderful etched designs, mainly spiral patterns. Inside the tomb, bones and cremated remains of many people have been found, along with a variety of grave goods.

- Many other passage graves and burial mounds are within a mile of Newgrange, all with human burials. Newgrange is part of a large Neolithic burial complex, just like Stonehenge.

- Newgrange has an obvious astronomical alignment, where the basic inner passage is pointing toward the winter solstice sunrise. For a few days at midwinter, the light from the rising Sun illuminates the entire passageway and strikes the far wall inside the tomb. For up to 17 minutes, the Sun penetrates to the inner tomb and only within 2 days of the solstice. The sunbeam lights up a wonderful triple-spiral carving on the back of the tomb, and there must be some now-lost symbolism in this light.

- With the rising of the passage, the only sunlight that makes it to the back of the tomb comes from the top of the entrance. And the top of the doorway has a unique feature called the roof box, which is like a transom. There is a clear path above the transom, blocked by no stones. After the tomb had been closed with a large stone, the path through the roof box remained clear. So, the solstice sunrise would perpetually shine into the tomb, always shining on the bodies of the buried people.

INSIDE NEWGRANGE TOMB

MAES HOWE

- About 530 miles away, just north of Scotland, in the Orkney Islands, is another prominent passage grave with an obvious solstice alignment: Maes Howe, which appears as a prominent dome-shaped mound, now set in rolling fields near the edge of a freshwater loch.

- About a mile from Maes Howe is the large stone circle called the Ring of Brodgar, plus the set of thin slabs making up the Standing Stones of Stenness. The immediate area has many burial mounds, henges, chambered tombs, and standing stones.

- Maes Howe and the other main monuments in the area were built sometime around 3000 B.C., as determined from radiocarbon dating of remains in the grounds. This makes them contemporaneous with the first stages of Stonehenge and with peoples of the same culture.

- The astronomy at Maes Howe is the alignment toward the position on the horizon of the midwinter sunset. Like at Newgrange, the solstice Sun shines all the way down the passage, illuminating the back wall of the central tomb. Even when the tomb had its entrance blocked with a big stone, the stone was not tall enough to cover the top of the doorway, thus perhaps forming another roof box where light could reach the inner sanctum even when the tomb was closed.

- This solstitial alignment is roughly accurate but lacks precision; that is, sunlight hits the back wall for a length of time from one month before the solstices to one month after. The most impressive light phenomenon occurs 22 days before and after the solstices. This is because the tomb's passage is pointed a bit north of the actual solstice sunset direction. So, on other days, the sunlight comes in before sunset, while the Sun is still a little above the horizon.

- It's plausible that the orientation is symbolic, with it only being of lesser importance that the Sun strikes the back wall on the day of the solstice. Alternatively, the builders could have designed the tomb so that the sunlight illuminated their ancestors' bones for a good time around the solstice, with the exact solstice date not being of high importance. Still, we are left with a prominent alignment to the solstice.


RING OF BROGDAR

WINTER SOLSTICE ALIGNMENTS

- The 3 solstitial alignments of Stonehenge, Newgrange, and Maes Howe could well be part of an intentional pattern by the builders. The people who made and used the monuments were contemporaneous and all from the same culture, the Beaker people.

- From the bones at Stonehenge, we know that the technical people came from all over the British Isles and Europe and that the users came from at least as far as Scotland and Wales. So, these 3 solstitial alignments are reasonably connected.

- Having 3 of the major monuments in the British Isles all with solstitial orientation is not likely by chance alone. If not by chance, then there must be some causal reason, and that can only be by the intention of the builders. So, we have a reasonable (but not convincing) argument that the solstitial alignments were built intentionally.

- We can learn another useful point by considering the 3 major monuments together: The axis at Stonehenge is ambiguous, pointing in 2 directions: both toward the midsummer and midwinter solstices.

- But the axes at Newgrange and Maes Howe are not ambiguous: They're both pointing only at the midwinter solstice. This suggests that the axis at Stonehenge was also intended to point to the midwinter solstice.

RECUMBENT STONE CIRCLES

- The British Isles have many stone circles, all built by the same culture of the Beaker people and all reminiscent of the circle at Stonehenge. One subset of these stone circles, called the Scottish recumbent stone circles, provide proof of the archaeoastronomy paradigm.

- These all have standing stones set in a circle, except that one of the stones (known as a recumbent) is lying flat, or on its side. This recumbent stone is closely flanked by the 2 tallest standing stones. As you move around the circle away from these tallest flanking stones, the height steadily becomes shorter and shorter.

- This is a very particular arrangement shared by all. With this design, the obvious axis is for an observer standing at the center of the circle, looking out over the recumbent stone, seeing the distant horizon bordered by the 2 flanking stones.

- The number of known recumbent stone circles ranges from 50 to 80, depending on how we count ruined or partially destroyed circles. These are all in a small region of Scotland, near Aberdeen, all located inside a region that is 40 by 60 miles in size.

- There are few radiocarbon dates, but it looks like the circles were all made around 3000 B.C. This means that we have a uniform population of circles: all the same in a particular style, all made around the same time, and close to each other.

- The research of astronomer and archaeologist Clive Ruggles proves that the circle designers intentionally oriented the main axis, that this intended direction could only have been set up astronomically, and that far-horizon visibility was critical. This forms a strong validation of the basic archaeoastronomy paradigm—that ancient monumental structures used astronomical alignments around the horizon.

- But just because the alignment was astronomical does not mean that we know the reason for the alignment.

TOMBS ACROSS EURASIA

- Throughout Eurasia, we can find small sets of standing rocks enclosing inner chambers, with the apparent use of these as tombs. The simplest and most common shape is simply to have 3 standing stones with one large flat capstone on top.

- Many are not so simple, often with some sort of a passage. Many of these were originally covered in dirt, as burial mounds and passage graves, with the dirt having since eroded back to the rock. Some of the tombs are more elaborate, with circular towers with a small doorway.

- Generally, these tombs have a single well-defined entrance that points off in one direction. This entryway defines a single position on the horizon, even though that direction itself has a substantial imprecision.

- The dates of these tombs are poorly known and vary widely, with typical dates from 5000 B.C. to 2000 B.C. Many of these are graves for a single person, such as a locally powerful person. Sometimes these tombs are communal graves, with multiple bodies being placed inside over many years. Generic names for these sites are tombs, graves, sepulchers, or dolmen.

- Throughout the 1990s, British historian Michael Hoskin visited around 2700 tombs throughout the Mediterranean region and found that each region and island had their own distinctive alignment patterns.

- Overall, we see the consistent burial customs of the people, including the orientation of the tomb, and these vary from region to region. Grave orientations throughout Eurasia, North Africa, and the Middle East all have similar patterns within each region.

- All of these alignments can only be done astronomically. The celestial symbolisms brought to the ground are a ubiquitous way in which ancient astronomy was experienced by the common people.

SOLSTICE CELEBRATIONS

- Many more solstice alignments have been recognized around the world. Many ancient monuments are oriented on the sunrise positions and often at the extreme positions of the solstices. Archaeologists and archaeoastronomers can pull these alignments out of the ancient monuments and ruins. But all this misses out on the many additional ways of celebrating the solstices that do not leave any mark on old stones.

- We can get a good idea of the importance of the solstices for ancient cultures by looking at historical and modern cultures. And it turns out that solstice celebrations or commemorations are in every society worldwide for which we have reasonably complete information—that is, solstices are universally important. With this, we should expect that all ancient cultures also placed importance in the solstices.

CARDINAL ALIGNMENTS

- In addition to the solstice alignments, the cardinal alignments of north, south, east, and west are also universal. For cases where we know the reasons for east-west lines, none of them are pointing intentionally toward the equinox sunrise or sunset. Rather, the cardinal orientations appear to all be related to some sort of directional symbolism.

- A frequent source for astronomical alignment is the symbolic connection of east and west with sunrise and sunset. Sunrise has a strong metaphorical connection with hope and birth. Sunset has a strong metaphorical connection with death and decline.

Readings

Burl, *A Guide to the Stone Circles of Britain, Ireland, and Brittany.*
Hawkins, *Stonehenge Decoded.*
Hoskin, *Tombs, Temples, and Their Orientations.*
Krupp, *Echoes of the Ancient Skies.*
Magli, *Mysteries and Discoveries of Archaeastronomy.*
Ruggles, *Ancient Astronomy.*
———, *Astronomy in Prehistoric Britain and Ireland.*

Questions

1 What fraction of claims and stories relating to ancient astronomy that you read about in newspapers or on the Internet is wrong? What is the fraction of incorrect information in general for all topics?

2 Look at the map of Washington DC, with the roads predominantly on a north-south and east-west grid, plus some dominant diagonal avenues tilted at close to 30° from east-west. The grand monumental architecture around the White House and the Mall area are all cardinally oriented. Is this an equinoctal alignment or a celebration of American directional symbolism? Furthermore, like Stonehenge, the view from the circle of stones at the center of power (the center of the Capitol rotunda) has a view down the main ritual avenue (Pennsylvania Avenue) pointing accurately to the (winter) solstice sunrise, as laid out by an astronomer (Andrew Ellicott). Should a far-future archaeoastronomer excavating the American Capitol conclude that the country was ruled by astronomer-priests?

Activities

1 What are the traditions for orienting graves in the Western world? Check out the current reality by going to a local cemetery and asking the cemetery manager or gravedigger what the customs are. You can also check this out with satellite images or street-view images of local graves. Check out an old graveyard. Have the orientations changed? From your modern experience, what fraction of the people at funerals knows the astronomical symbolism behind these orientations?

2 Many of the grand monuments around the world have intentional orientations, some of which are astronomical and some of which are topographical. Look at satellite or aerial images of the Mukden Palace in Manchuria and see the orientation of its buildings, walls, and grounds. You can recognize the Chinese precedent being followed that provided the astronomical symbolism for the astronomical orientation. Then, look at the orientation of the Blue Mosque in Istanbul and see how it is oriented with respect to the qibla (the direction to Mecca). Look at the Taj Mahal and explain its orientation. Check out the Japanese Imperial Palace in Tokyo; Angkor Wat, built by the Khmers in Cambodia; the Prophet's Mosque in Medina; both the old and new Saint Peter's Basilica in the Vatican; the street grid in ancient Babylon; Monk's Mound in Cahokia, Illinois; the Temple of the Golden Pavilion in Kyoto; and the great temple of Borobudur in Indonesia.

LECTURE 4

Astronomy of Egypt's Great Pyramid

The Great Pyramid—near modern-day Cairo, Egypt—is at the top of the list of the Seven Wonders of the World, due to its huge size, its awesome scope, and the technical feat of building it. In this lecture, you will learn why it is a wonderful case study for astronomy in the ancient world. With the Great Pyramid, there is the central use of astronomy in the old culture and philosophy, the somewhat-unsolved mystery of how to align the Great Pyramid with such spectacular accuracy, and the likely solved mystery of whether the ventilation shafts were pointed at stars.

CARDINAL ALIGNMENT

- The Great Pyramid's square base has its edges accurately aligned north-south and east-west—that is, the alignment is cardinal. Furthermore, this alignment is accurate to $\frac{1}{20}°$, a deviation of 8 inches (or 20 centimeters) over the entire 230-meter baseline on the side. This is astounding accuracy to achieve not only in surveying the lines, but also in building along this line in stones. Such a true north-south alignment can be made only with astronomy.

- Many other Egyptian pyramids also have this same cardinal alignment, although with a typical accuracy more like 1°. This repetition of the same accurate orientation lets us know that the orientations are not random alignments that are overinterpreted by modern people, but rather are intentional alignments.

- From hieroglyph texts, the symbolism was that the circumpolar stars never set, so symbolically, they never die. Circumpolar stars are those close to the North Pole and are always visible as the Earth rotates under the sky, each star appearing to go in endless circles above the horizon, never setting, and therefore immortal.

- These northern stars were called the Imperishable Ones, and they're associated with the afterlife, in which it is the stated goal of the pharaoh's soul to travel to the Imperishable Ones—to the north. So, the Egyptian religion made the need to incorporate the strong cardinal symbolism into the pyramid's architecture.

- A central mystery of the Great Pyramid is how the ancient Egyptian builders could have aligned the edges north-south and east-west. Even with the most sophisticated modern technology, a lot of effort and special work is required to match the Great Pyramid's accuracy.

- Over the last century, various workers have proposed many different methods by which the original architects could have drawn up an accurate north-south line. For example, in principle, the Egyptians could have observed the direction of sunrise and sunset on midsummer day and bisected those 2 directions to find north. Or they might have done this with some bright star.

- Another possibility is to look for the direction of the shortest shadow around noontime. A much more accurate version of this is to look at the shadows of a vertical pole, or an obelisk, on the morning and afternoon sides of noon, when the shadows are exactly the same length, and then north will be the direction exactly halfway between those 2 shadows.

- All of these methods can with care get true north with an accuracy of $1°$ or a bit better, but all of these methods have a hard time getting to an accuracy of $\frac{1}{20}°$.

- Archaeological remains and hieroglyphics texts can give us some clues as to the alignment method. Texts and inscriptions from before and after the 4th dynasty of the Old Kingdom describe a ceremony called the stretching of the cord, with the pharaoh personally helping to determine the layout for the corners of temples.

- Some of the texts tell of the pharaoh gazing at stars to the north, while others tell of the use of shadows. Two types of artifacts have been identified as being involved with the alignment ceremony: *merkhet* and *bey*, which are both sticks with markings and indentations. We have no idea how they were used, although various proposals have been made.

- With all this, there is no agreement as to the alignment method, and many ideas are still outstanding. The ceremony does tell us more, in that the ancient Egyptians had astronomical observations central to their beliefs and these beliefs concern the pharaoh himself.

PYRAMID AND TEMPLE ORIENTATION

- Archaeological surveys can help us understand the sociology and accuracy of the cardinal alignments. Juan Antonio Belmonte, from the Canary Islands, has led a joint Egyptian-Spanish mission to measure the orientations of large numbers of pyramids and temples throughout Egypt.

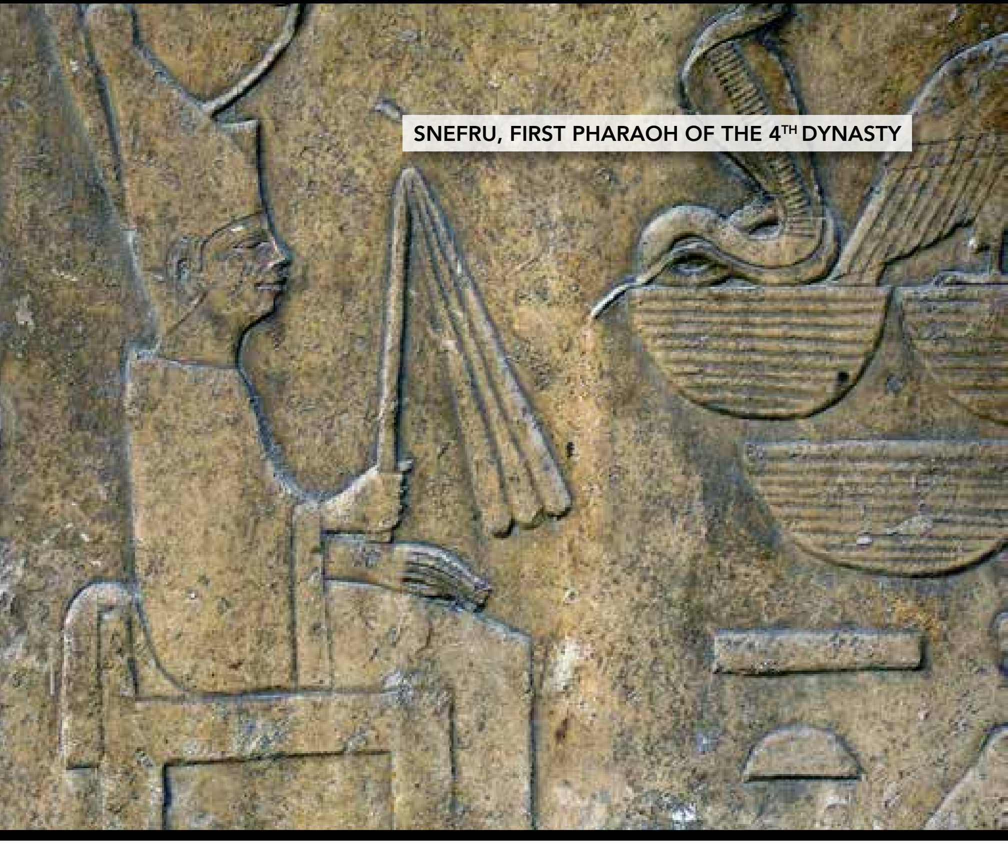
- Their plan was to look for concentrations of orientations among buildings of similar provenance. For example, they looked to see whether the main entrance would always point to the west, or to the Nile. If we find many widely separated structures with the same orientation, then we can be sure that the orientation was intentional.

- They find that the original architects' choices for the axes of their buildings had multiple motivations. Many temples and pyramids were oriented with respect to the nearby banks of the Nile. Many were cardinally aligned. Some were aligned on stars, Sirius in particular.

- The accurately cardinally oriented pyramids and temples appear only in Lower Egypt—that is, northern Egypt along the Nile. They start suddenly with Snefru, the first pharaoh of the 4^{th} dynasty, and continue through the 12^{th} dynasty. This spans time from around 2600 B.C. to 1800 B.C., roughly 800 years.

- The many pyramids and their temples that are nearly cardinally oriented have a typical scatter around perfect orientation of about 1°. For Lower Egypt from the 4^{th} to 12^{th} dynasties, most of the structures that could have a measured orientation have come from just the 4^{th} and 5^{th} dynasties, because many of the later pyramids are too ruined to get any sort of an accurate orientation.

- For the 9 pyramids from the 4^{th} and 5^{th} dynasties, the average orientation of their square bases is just $\frac{1}{6}$° off true north. The scatter of the individual pyramid orientations is about $\frac{1}{2}$°. It's easy to get an accuracy of 1°, or even $\frac{1}{2}$°, but it's difficult to get an accuracy of $\frac{1}{20}$°.



SNEFRU, FIRST PHARAOH OF THE 4TH DYNASTY

- A plausible means by which the Great Pyramid has such impressive accuracy is that the it was only oriented by the Egyptians to an accuracy of ½°, and it is random chance that they happened to get it to $\frac{1}{20}$° off true north. With many pyramids all cardinally oriented to about 1°, some single pyramid must be the closest to exactly true north-south, and that pyramid happens to be the Great Pyramid.

- Such an idea is reasonable and even expected, while it doesn't require any anachronisms or anything exciting.

SPENCE'S PROPOSAL

- In 2000, Kate Spence at the University of Cambridge published in the prestigious British journal *Nature* a claim for how the pyramid was aligned. She proposed that the alignment was made by pointing to the direction that 2 particular stars were exactly vertical; that is, as stars revolve around the North Pole in their usual daily circle, 2 stars that are exactly opposite each other across the pole will appear exactly vertical twice every 24 hours. When this happens, the direction of that vertical line would be exactly north.

- The star positions shift around slowly due to the precession wobbling, but Spence realized that 2 stars in particular would work perfectly around 2467 B.C.: Kochab and Mizar. Her idea is that the Egyptian surveyors would hold up a vertical cord forming a plumb line and wait until the instant when Kochab and Mizar appear exactly vertical, and then the plumb line would show exact north.

- Spence's article in *Nature* was immediately echoed in the press worldwide, but immediately, experts in many fields started howls of protests. There is no positive evidence for Spence's claim, other than the existence of the stars that so happen to align in that year.

- But the existence of that alignment says nothing about whether the Egyptians knew about it, much less cared anything about it if they did know. There's no precedent or later example for her method in Egypt—or any other culture in the world. The lack of any connections with anything else we know from history or archaeology points to the conclusion that this hypothetical method was never used by anyone.

PYRAMIDOLOGY

- The Great Pyramid has attracted vast amounts of attention from fringe thinkers. The term "pyramidology" describes the theory about various significances associated with the Great Pyramid. Early examples are claims that the dimensions of the Great Pyramid encode the number of days in a year, the mathematical constant pi, the golden ratio, and the date of the start of World War I.

- Another favorite claim of pyramidologists is called pyramid power, an idea that flourished in the early 1970s, with extensive press coverage. Its claim is that the basic pyramid shape channels unknown powers. Pyramid-shaped containers were said to preserve food, sharpen razor blades, and trigger sexual urges.

- A control experiment is one in which 2 tests are made with only one difference between the 2 cases, so then any difference in the outcome can be directly attributed to the one changed situation. This is the core of the scientific method, where we let nature tell us about reality.

- Many people have tried such experiments to prove the existence of pyramid power, but they have all been failures for the concept. Nevertheless, fringe and occult people are still putting out pyramid power websites, books, and products.

PYRAMID PASSAGES POINTING UP

- There is a set of alignments that might have been intended by the ancient Egyptians. They have to do with the 4 so-called ventilation shafts leading from the king's chamber and from the queen's chamber deep inside the pyramid.

- Two ventilation shafts from the king's chamber go off at angles from the horizontal of 45° directly south and near 31° directly north. The astronomical claim is that these 2 shafts are intentionally pointing to the polestar Thuban (toward the north) and to the belt of Orion (toward the south).

- Similarly, the 2 shafts from the queen's chamber rise at angles of near 38° to the north and to the south. Further, less publicized, claims also have these shafts pointing at prominent stars, Kochab and Sirius.

- No one is claiming that these shafts were used for actually sighting the stars by some observer within the pyramid. The 2 shafts from the queen's chamber both have special doors blocking the way, and the shafts don't even get to the outer surface of the pyramid. This means that the shafts might have been symbolically aligned.

- It is plausible that the shafts were symbolically pointing to stars. The primary reason is that we know from the hieroglyphic Pyramid Texts that the pharaoh's goal was to go to the "imperishable stars" near the North Pole, so it makes sense to have a passageway pointed at the stars for the pharaoh's spirit to escape through. The importance of the stars to guide the dead to the afterlife is emphasized by the frequent appearance of starscapes on the roofs of tombs and on the inside of coffin lids.

- While the angles of the airshafts could well be artifacts from construction or randomness, these ideas seem to be trumped by the hieroglyphic texts telling us what the ancient pharaohs saw as the important symbols for their passage through the underworld to their afterlife. It appears that the airshafts in the Great Pyramid are intentionally pointed at specific stars.

Readings

Belmonte, "In Search of Cosmic Order."

———, "On the Orientation of Old Kingdom Egyptian Pyramids."

Lehner, *The Complete Pyramids*.

Nell and Ruggles, "The Orientations of the Giza Pyramids and Associated Structures."

Spence, "Ancient Egyptian Chronology and the Astronomical Orientation of Pyramids."

Questions

1 How could you set up your own north-south line and do it with accuracy? This is the problem faced by the pharaoh's astronomers, and they solved it to 0.05° for the Great Pyramid. Decide whether you allow yourself modern technology (a compass, GPS, or sextant) or any modern knowledge (such as when at night Polaris is exactly vertical with the true pole). A problem is to know how accurate your line is in pointing north. Your challenge is to get to the 0.05° level of accuracy.

2 This lecture highlighted many wrong claims about the astronomy of the Egyptian pyramids, and there are many more infamous examples to be given. These are easily and conclusively proven false, yet they dominate as the majority of the pages on the Internet. Why do the fringe workers put forth pyramidology claims? Why have such claims not died long ago, but instead continue to be strong?

Activity

1 There are large pyramids in the Sudan, Mexico, and China. Each set has its own consistent orientations. Use your favorite satellite-photo application to examine the structures and see their orientations. Then, work out why each ancient civilization chose to build its pyramids with the given orientations.

LECTURE 5

Chaco Canyon and Anasazi Astronomy

In this lecture, you will learn about the astronomy of the Anasazi Indians living in Chaco Canyon of New Mexico about a millennium ago. We know a lot about their astronomy, based on their well-preserved archaeological remains and the ethnography from their descendants. Chaco Canyon is the perfect site to illustrate all the features of archaeoastronomy. Astronomy was important for the Anasazi, from practical tools to providing a large part of their worldview.

CHACO CANYON

- Chaco Canyon is a wide and deep canyon carved out of the desert in northwestern New Mexico, near the Four Corners point. The altitude is just over a mile high, and the area averages 8 inches of rainfall per year. The ground is mostly rock and dirt, with small grass clumps and sagebrush, and little in the way of trees to block the distant horizons.

- From around 830 A.D. to 1150 A.D., the canyon area was a center for a vibrant culture, which we now label as Ancestral Puebloan, or Anasazi. Beginning in 1130, a severe draught lasting 50 years led to the abandonment of the canyon. The people moved to nearby river valleys with more reliable water.

- This split the population to become the various Pueblo tribes, including the Hopi and the Zuni. These direct descendants have been described by the Spanish from 1540, by ethnographers in the late 1800s, and into modern times, so a lot is known about their culture. These peoples are extremely conservative, especially with regard to their religion, which leads to an expectation that many current practices of the Pueblo groups are similar to those of their Anasazi ancestors.

- Chaco Canyon contains a complex array of ruins, dominated by 12 great houses, the biggest and most famous of which is Pueblo Bonito, which was a huge single building with outer walls in the shape of the letter D. There were an estimated 800 rooms, and the back portions got up to 5 stories high.

- Pueblo Bonito has more than 25 kivas inside its structure, plus 2 huge kivas close by. A kiva is a mostly underground circular room used for various purposes, mainly involving sacred rituals.

CHETRO KETL, GREAT KIVA RUINS

- Chaco Canyon appears to have been a religious center used for pilgrimages. From the number of rooms in Pueblo Bonito, about 2000 people could have lived there. But the area has few graves, few hearths for fires, and not much in the way of garbage heaps, or middens. So, it appears that the permanent population was much smaller, perhaps just a hundred people.

- It appears that some sort of a small elite occupied the site full time, being fed by the surrounding people, but periodically a large influx of pilgrims came to Chaco, filling the rooms and using the kivas for rituals. The Anasazi descendants have a variety of annual ceremonies, all timed by the movements of the Sun, so it's reasonable to think that the pilgrimage to Chaco was also timed by the Sun.

CARDINAL ALIGNMENTS

- In the plan for Pueblo Bonito, the D shape has a prominent straight wall pointing within ½° of east-west. This could be by happenstance, or it could be by intention as a cardinal alignment. But the nearby Puebla Alta also has a D shape with the straight wall pointing east-west. With this, the orientations were likely intentional. Pueblo Bonito was a ritual center, so it's plausible that it would have used this symbolism from their cosmology.

- The Anasazi and their descendants certainly had prominent directional symbolism. This can be seen with the universal and critical alignment of the axes of the kivas to the north-south line. The kivas serve as an expression and omnipresent reminder of the sacred directions. As with all such ceremonial orientation throughout the world, the kivas were aligned only with moderate accuracy—and such alignments must be made with respect to the sky.

- The most remarkable manifestation of the cardinal directions is the so-called Great North Road, which is a wide road constructed with long stretches to within ½° of true north. This is a road with no apparent function. The fact that the road runs straight over obstacles, rather than going around them, forces us to think that there is some very strong reason for all the work.

- With this, most researchers conclude that the Great North Road is mainly some ceremonial path, perhaps used by pilgrims, and expressing some cosmological vision of the world.

THE HORIZON CALENDAR

- Most calendars around the world have the year as their basic unit of long time, and these are almost always based on the movement of the Sun. When the Sun is high in the sky, it's difficult to measure its position. The easiest way to measure the Sun's movement is to watch its position on the horizon at the instant of sunrise. When the first gleam of light comes up, it's obvious where on the horizon the light appears.

- Another requirement for observations leading to a calendar is that the horizon should not be nearby, with no trees along the line of sight. Another requirement is that the terrain must have stark features on the horizon to note the position of the Sun. Distant mountains or islands or hills are perfect for noting where along the horizon is the first gleam.

- The Anasazi and the modern Pueblo Indians have an optimal situation to use a horizon calendar. They have clear skies in the morning, distant mountainous horizons, and few trees. So, it's no surprise that they developed a horizon calendar.

- Indeed, all the tribes have special Sun-watching clans charged with watching the sunrise. Each pueblo and village has their own Sun priest for this purpose. For a sunrise calendar to work, there must be a designated station to watch from.

- One hallmark of these Pueblo solar calendars was the use of the Sun's position on the horizon to predict when an upcoming ceremony will be. This is based on the experience of the Sun watchers, who know exactly where the Sun will rise some set number of days before the solstice. The idea is that the Sun watchers can anticipate the date of the upcoming celebration so that there is time to prepare for the feast and rituals.

- Both the Hopi and the Zuni have explicit solstice ceremonies as the most important of the year, so it's reasonable to think that their Anasazi ancestors did, too.

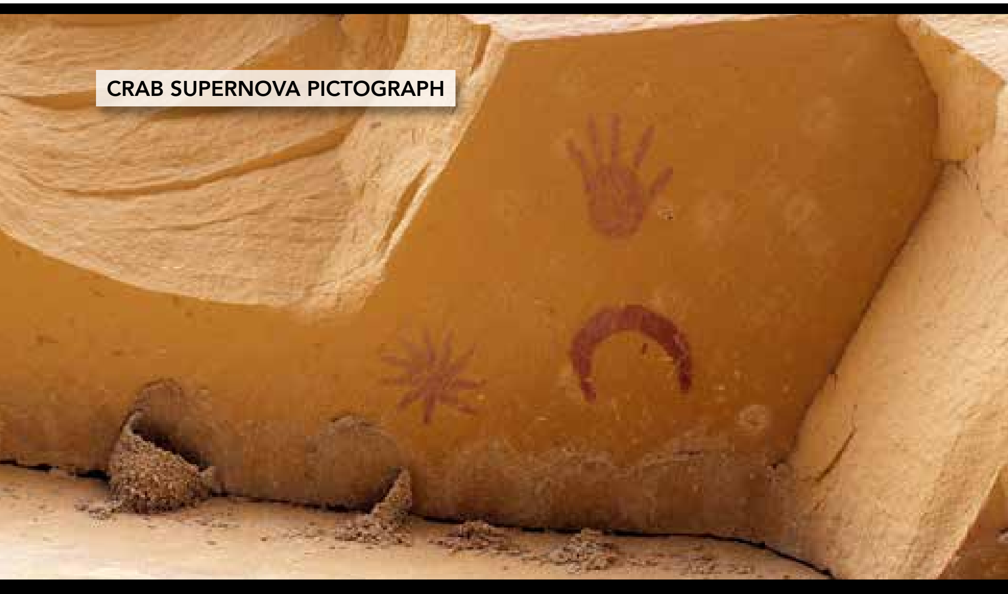
- The modern Pueblo Indians also have a lunar component to their calendar that runs at the same time as their solar calendar. Their lunar months always start with the first appearance of the thin lunar crescent low in the west just after sunset. Each month is given a name based on seasonal connections.

- The Pueblo Indians have special officials for watching the Moon and announcing the months. Every month has a special ceremony, and every ceremony has its month. The lunar months were also used to guide planting and harvesting.

- These practices were universal among the Pueblo Indians in the 1800s. The apparent strong cultural continuity back to the Anasazi implies that the people of Chaco Canyon had similar astronomy, with the religious and agricultural calendars guided in similar ways by local people looking up at the sky.

THE CRAB SUPERNOVA PICTOGRAPH

- The most famous astronomy at Chaco is the so-called Crab supernova pictograph, which appears on the underside of a small overhang about 20 feet up a cliff. This picture is near the ruins of a Great House called Peñasco Blanco on the western end of the canyon. There's no way to date this pictograph, but the nearby Great House was occupied from 900 to 1125 A.D.



CRAB SUPERNOVA PICTOGRAPH

- The pictograph shows a thin crescent shape next to a 10-pointed star shape. These shapes really can only be a star and crescent Moon, as based on later iconography from the Pueblo Indians.

- In 1975, a group of astronomers offered a surprising claim: that this star and crescent could be a literal depiction of the Crab supernova, together with a crescent Moon nearby in the sky on the morning of July 5, 1054.

- There was, in fact, a supernova explosion in 1054, as recorded by ancient Chinese astronomers, and the Anasazi almost certainly would have recognized a very bright new star in the morning sky and maybe depicted it in Chaco Canyon.

- However, research has shown that the pictograph actually depicts a Sun-watching station. This is astronomical, but not any supernova. The pictograph illustrates how these ancient astronomers used the sky on a daily basis to construct a horizon-based calendar.

THE SUN DAGGER ON FAJADA BUTTE

- Fajada Butte is an isolated tower of rock inside Chaco Canyon. It's covered with many old carvings in the rocks, each displaying the usual Anasazi icons. Figures carved into the rock are called petroglyphs, while figures painted onto rocks are called pictographs.

- One set of petroglyphs served as some sort of a Sun shrine, commemorating the summer solstice. It was discovered in 1977 by Anna Sofaer, an artist who was cataloging Anasazi rock art. She found a spiral pattern near the top of the butte, and she happened to visit it around noon a week before the summer solstice.

- This spiral was partially sheltered by a fall of 3 rock slabs. While she was watching, she saw a slim and long wedge of light pass over the top of the spiral. The shadow was created when the nearly vertical sunlight just barely slipped through a crack between 2 of the rock slabs.

- Sofaer believed that this dagger-shaped light beam was an intentional marking of the solstice. She and others returned on the day of the solstice and confirmed that this Sun dagger did indeed point through the center of the spiral.

- What she found was an apparent marking of the summer solstice. The Sun dagger piercing the heart of the spiral could not be used to determine the date of the solstice with any useful accuracy. And based on the characteristics from later Puebloan examples, this was certainly not a Sun-watching station used for the horizon calendar.

- Rather, it was a Sun shrine. The Pueblo Indians have a series of often simple rock-enclosed places where they leave small offerings for the gods. Prominent among these are shrines to the Sun. Because later traditions of the Pueblo peoples match the situation atop Fajada Butte, we can be sure that the Sun dagger is a Sun shrine.

- Geologists have demonstrated that the positioning of the 3 rock slabs was entirely natural. With this, the Anasazi could have only randomly spotted the dagger of light, and then chose where to draw the spiral petroglyph. The exact positions of the rock slabs were measured and recorded.

- Sofaer's discovery is picturesque and evocative, so it immediately captured the attention of many people worldwide. The Sun dagger has become an icon of Chaco Canyon and of all archaeoastronomy.

- For the Sun dagger, we can get a proof of intention by the Anasazi by getting additional evidence by finding more examples. With the wide publicity given to the Sun dagger, archaeologists started looking for and finding many more Sun daggers. Because the large numbers of examples found cannot be by chance, there must have been intention on the part of the artists. This is the proof that the Fajada Butte spiral was knowingly carved into the rock as a solstice marker.

Readings

Ellis, "A Thousand Years of the Sun-Moon-Star Calendar."
Fagan, *Chaco Canyon*.
Lekson, *The Chaco Meridian*.
Sofaer, Zinser, and Sinclair, "A Unique Solar Marking Construct."
The Solstice Project, "The Sundagger Explorer: Interactive Model of the Ancient Calendar Site in Chaco Canyon, New Mexico."

Questions

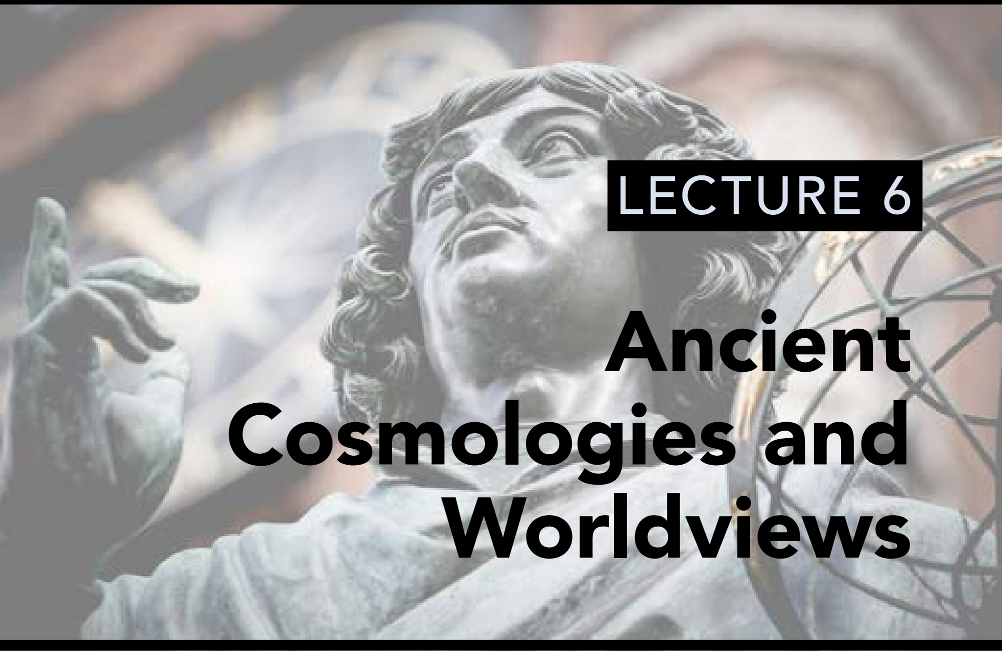
1 The Crab supernova pictograph has spawned a modern cottage industry of looking at any unexplained collection of ancient pictograms as somehow representing a star and then attributing this to some known supernova. You can try this out yourself to see how easy it is. Tour your neighborhood, examining graffiti, logos, and billboards for symbols that you think could depict a bright star. Browse through photo collections of pictographs from ancient times worldwide and see what fraction you could try to push as being a depiction of a supernova. With this, what do you think is the likelihood that any of the claimed supernova pictographs is really of a supernova?

2 The Chaco astronomers had accurate cardinal directions, elaborate directional symbolism, various commemorations of the solstices, a functional lunisolar calendar based partly on horizon positions, and constellations backed by lore—but nothing more. Is this the complete tool kit of ancient astronomers worldwide toward the end of their Stone Age? How much innovation, genius, or skill is needed for any of the activities in this tool kit?

Activities

1 Have you seen the Milky Way in its splendor? Have you ever taken a long look at the dark night sky? If your answer is no, then correct the situation by going to some dark-sky place on a moonless night and spend an hour or more simply seeing what is up there. Find some place where you can lay outside with a fairly clear horizon and far away from all lights. Choose a clear moonless night, and stay for more than an hour, or even all night. Then, just lay back and watch the stars go by. Trace out the Milky Way. See if the meteors track back to one radiant as part of a meteor shower. Follow the motions of the stars. Watch the stars fade to invisibility (due to the haziness in the air) as they set toward the horizon. Note the position of Polaris at the start and see whether it has moved much by the end. Pick out some of the brighter constellations. Make up your own constellations, and the stories to go with them. Check whether the stars near the horizon are twinkling more than stars near the zenith. With a star chart, pick out the planets in the sky and see how you might characterize them. Do the planets twinkle? Also, pick out star clusters, gas clouds, and whole galaxies. The point for this course is that you should have the experience of night sky like all the ancient astronomers and peoples.

2 Make your own horizon calendar. You will need an observing location with a far horizon to the east for sunrise (or to the west for sunset). And you will need patience, as it will take a full year to calibrate the full calendar. Simply go to your observing platform every day at the time of sunrise (or sunset) and note the exact position of the first (or last) gleam of the Sun against the detail on the distant horizon. A modern way to do this is to take a daytime picture of the horizon, mark off a gridline made with a ruler onto the photo, number each grid line, and then refer to horizon positions by the corresponding number (and fraction) on your grid. A listing of the positions for each day (with interpolation in your grid for cloudy or missed days) then becomes your calendar.



LECTURE 6

Ancient Cosmologies and Worldviews

All people and all cultures face the 3 big questions: Where did our world come from? What is our universe like? What is the fate of the universe? Everyone everywhere has pondered these big questions. The answers to these questions have a large component based on what is seen in the sky. This is the cosmology of people. For ancient peoples, their astronomy created much of their worldview, which pervaded and influenced a wide array of social actions and influenced the further development of their astronomy. This lecture will consider astronomy-based worldviews, including how they developed with knowledge that we would call astronomy and how they changed over time.

GREEK WORLDVIEW THROUGHOUT THE AGES

- We can know the worldviews of the ancient Greeks because they tell us about them in many documents from the earliest times. The changing worldviews of people living in Greece are directly influential for all of Western civilization.

- For the Greeks around the time of Homer and Hesiod, the world was born out of chaos, which is a vast void of formless mass. It was never stated where that chaos came from. Out of this void emerged Gaia (the Earth), Eros (love), and Tartarus (the underworld). From them, various gods were born and started fighting, mating, and dying. Mankind was created by Prometheus out of mud, which Athena breathed life into. In brief, that is the ancient Greek answer to where their world came from.

- The early Greeks pictured their universe as the small area around the Aegean Sea, surrounded by regions filled with barbarians, all on what we would call a flat Earth. Below the Earth was the underworld, and above the Earth was the heavens, inhabited by the gods. The whimsical gods were responsible for everything in Nature. This is the early Greek answer to what their universe was like.

- The early Greeks were pretty vague as for answers to the third question: What is the fate of our universe? They thought that the destinies of people were decreed by 3 sisters called the Fates, who controlled even the destinies of the gods. The pre-Christian view in ancient Greece seems to have been that gods might come and go, but a world, of some sort, would continue indefinitely.

- This is the worldview of the earliest Greeks, up until 600 B.C. The advances in astronomy and other sciences over the upcoming centuries made for large changes. In particular, astronomy led the way, so the Greeks eventually broke free from the worldview that everything was driven by the supernatural. Only then could they try to explain the real universe using naturalistic causes and effects.

- By the height of classical Greece, new knowledge had changed many parts of the early Greek worldview. Part of this was the large-scale expansion of geographical and cultural knowledge as Greeks traveled far and wide. They saw that the world was a huge place, with Greece but a small part.

- At the same time, Greek scholars realized that the Earth itself was even much larger. They realized that the Earth was essentially spherical in shape and that the known world was only a small part.

- Within a few centuries, by the time of Hipparchus around 120 B.C. and Ptolemy around 140 A.D., the Greek worldview was expanded even more. They placed our Earth as just being a small part of a large system of the Sun, Moon, planets, and stars. They were even able to calculate planetary distances that were of the right order of magnitude.

- With this, the Greek answer to what their universe was like changed from a small regional area covered by the home of gods to a vast system of planets and stars with the Earth in the middle.

- At the time of the great Roman emperor Constantine, his order for a general conversion to Christianity throughout the empire brought about a large change in the worldview. For the question of where the world came from, the answer was switched to the creation story as told in Genesis. And for the question of the fate of the universe, the answer became that the world would someday end in apocalypse and Judgment Day.

- The next big changes in worldview for someone living in Greece did not arrive in force until the 1600s. Around this time, sailors, navigators, and explorers had largely mapped out the geography of the Earth. The Scientific Revolution was just starting, and this soon greatly changed the worldview from astronomy.

- The Earth was eventually seen to be billions of years old, having been made out of a gas cloud that collapsed to form the Sun and planets. The universe is huge beyond understanding, expanding from the big bang, and it will keep expanding forever, getting colder and darker and emptier.

CHINESE WORLDVIEW

- The Chinese had a completely independent worldview. The Chinese cultural dominance around Asia made for their worldview becoming widespread throughout many nations.

- The Chinese had no one dominant origin myth. Instead, they had a variety of contradictory creation stories, such as that the world was created out of chaos with no divinity, that the first being Pangu was born of a cosmic egg and later parts of his dead body turned into all the parts of the Earth and skies, or that yin and yang came together to make everything in proportion.

- The earliest Chinese lived on a flat Earth. Sometime around 400 B.C., philosophers started speculating about the shape of the Earth. By sometime around 2000 years ago, they settled on a spherical Earth and were even pointing to the universe as being infinite in size.

- Central to the Chinese philosophy was the relation between man and heaven. The will of heaven was writ in the sky. The worship of heaven was tightly connected with astronomy. The emperor was subject to the will of heaven, and this became the mandate of heaven doctrine that was the core of imperial policy for 4 millennia.

- This mandate of heaven doctrine gave a long view of the future, where dynasty after dynasty would keep winning the favor of heaven. This cycle would go forward indefinitely.

- For the very long future, there were the astronomical cycles imported with Buddhism from India. This view has the whole universe going through a never-ending cycle of creation and destruction, with each cycle lasting billions of years.

WORLDVIEW OF AUSTRALIAN ABORIGINES

- The Australian Aborigines have the oldest surviving culture on Earth. The first immigrants to Australia came around 50,000 years ago, and the peoples remained essentially isolated for virtually all of their subsequent history.

- Very ancient rock art and stone tools are closely similar to more recent examples, so the complex cultures found by the European explorers were largely the same as they had been for many tens of thousands of years. The Aborigines give us living access to a very old worldview.

- What we see is a worldview with a flat Earth, a close-in sky-dome, and the skies controlled by ancestor-heroes and magical animals. Even though the myths and details of the Aborigines are very diverse, the basic worldview and many of the myths are universal throughout Australia.

- For the question of where the world came from, there is a consistent answer across Australia: The world started out as a featureless desolate land. Many supernatural beings slept beneath the surface of the Earth, having a wide range of shapes, both animal and human. As they emerged, they moved around the landscape, leaving their imprints on the land.

- All the prominent features in the landscape were made by one of the ancestors, all told in stories passed on, all creating sacred sites. All the plants and animals, all the rocks and land, and all the lights in the sky were made by adventures of these spirits. Details vary greatly from group to group.

- For the question of what their universe was like, the Aborigine picture is consistent across all groups. They view the Earth as a flat disk surrounded by an ocean, all covered with some sort of a sky-dome, above which live the ancestors, spirits, and the dead people. The universality of this throughout Australia suggests that this common idea came over with the first settlers of the continent and thus represents a very old view.

- For the question of the fate of the universe, there don't seem to be any real answers told to ethnographers. Perhaps little consideration was given to a future any different from the present.

SIZE OF THE EARTH

- For answering the question of what our universe is like, each culture is first faced with the sub-question as to the size of the Earth. For all cultures in their youngest days, it appears that they all follow the flat Earth with a sky-dome idea.

- As travelers and traders and warriors move farther from their homelands, their worldviews expand. Around 400 B.C., the Greeks, Chinese, and Indians all started realizing that the Earth was spherical. By around 2000 years ago, the round shape of the Earth was common knowledge throughout Europe, Asia, the Middle East, and North Africa.

- Astronomers started to measure the actual size of the Earth. The first measure with good reporting was made by Eratosthenes around 200 B.C. His circumference was 250,000 stadia, for a radius of near 40,000 stadia. With our best estimate of the stadia length, this equals 4600 miles—only 16% larger than the modern value.

- Efforts at precise measurement only underlined what was common knowledge: that the Earth was spherical and that it was an incredibly large body.

PHILOSOPHY CHANGES FROM ASTRONOMY

- Astronomy has taken many cultures from their original worldview of just the local valleys to knowing the size of the Earth, the solar system, and the distance of the stars. This perspective has substantially changed the philosophies of many peoples.

- The perceived size of the world connects directly to broader views in humans and cultures. It's more difficult to be a bigot when you live in a large world. And the sheer immensity of the universe forces a strong measure of humility in humans.

- Perhaps the biggest philosophical effect of astronomy comes as it provides an alternative to myths, legends, gods, and heroes. A supernatural worldview creates blinders that stop the development of the culture. The alternative is the mechanical view that we would call physics. Historically, astronomy has provided a path by which the old superstitions are replaced. This may open the way to overthrow other traditional beliefs and customs, as well.

Readings

Irving, *History of the Life and Voyages of Christopher Columbus*.
Johnson, *Night Skies of Aboriginal Australia*.
Krupp, *Echoes of the Ancient Skies*.
Morison, *Admiral of the Ocean Sea*.
Ruggles, *Ancient Astronomy*.

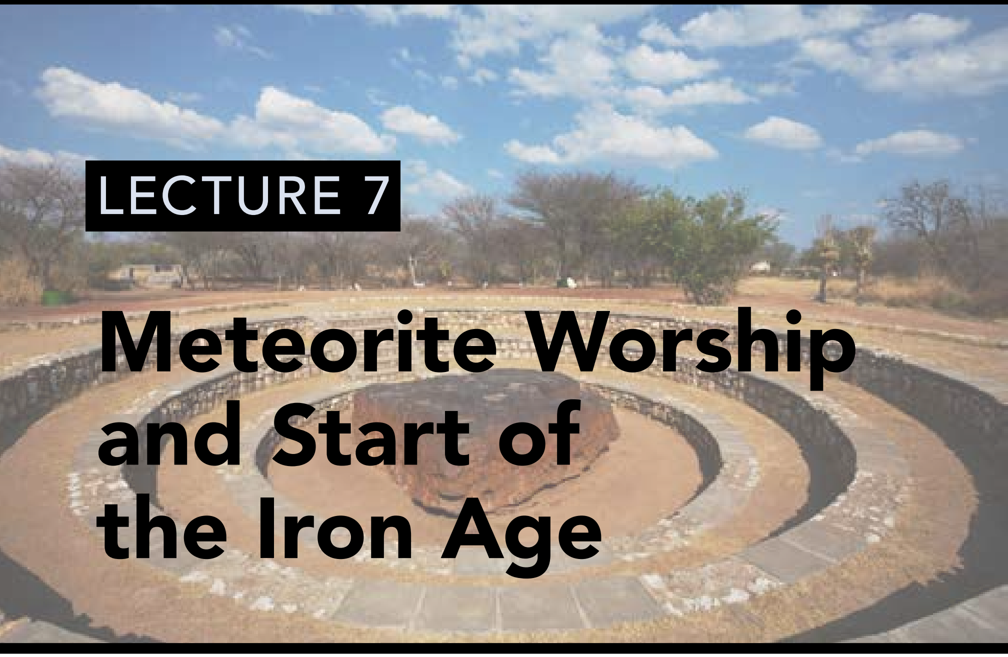
Questions

1 What are your answers to the 3 big questions (Where did the world come from? What is our universe like? What is the fate of our universe?)? What parts of your worldview are based on what is up in the sky? What parts of your worldview affect your opinions and actions?

2 Ask a friend the 3 big questions. How similar are your friend's answers to your own? How much of this similarity is due to a shared worldview within your culture? Are the differences simply due to people paying attention to topics of personal importance? How are your friend's opinions and actions affected by his or her worldview?

Activity

1 It is actually fairly easy to run the Eratosthenes experiment with minimal equipment. The goal of this activity is for you to get a real understanding of how the Greeks, Arabs, and Chinese measured the size of the Earth long ago. You'll have to travel at least 500 miles or have a distant friend who will help you. First, you'll have to get a straight distance between your 2 sites. This could be done simply by driving directly between the 2 sites and correcting the odometer mileage for not driving straight. With lesser accuracy, you could use the airplane flight time and assume a typical jet cruise speed of 570 miles per hour. Label this distance D. Second, you'll need to measure the angle (as viewed from the center of the Earth) between the 2 sites, Θ. This can be measured easily if your 2 sites are roughly north-south of each other. On some days near each other, put a vertical stick in the ground (a gnomon), measure its length (L_{gnomon}), and measure the length of the noon shadow (L_{noon}). With some simple trigonometry, the noon Sun will be at an angle of $Z = \tan^{-1}(L_{\text{noon}}/L_{\text{gnomon}})$ from the zenith. The difference in the zenith distance between the 2 sites, $Z_1 – Z_2$, is then equal to Θ. Alternatively, you could measure the altitude of Polaris from your 2 sites, and this equals your latitude, λ. For this north-south case, we have $\Theta = \lambda_1 – \lambda_2$. If your 2 sites are basically east-west, then you can get Θ by some simple timed observations. For both sites, simply time sunrise and sunset. From this, the time of local noon is halfway between, T. Make sure that both times are on the same time zone or adjusted to the same time zone. The time difference between the 2 local noon times ($\Delta T = T_1 - T_2$ in hours) gives the difference in longitude, with 1 hour corresponding to 15°. To get Θ for the east-west sites, for sites with a latitude, λ, we can use the equation $\Theta = (15° \times \Delta T) \times \cos \lambda$, where ΔT is in hours and Θ is in degrees. If your 2 sites are not north-south or east-west, then you can measure both noon shadow lengths and local noon times and then use Pythagoras's theorem to get the total Θ. Third, with D and Θ, we can make the basic Eratosthenes calculation. The radius of the Earth is $D(\Theta/57.3°)$. The 57.3° is just to convert from your Θ measure in degrees into the units of radians.



LECTURE 7

Meteorite Worship and Start of the Iron Age

The skies interact with humans in many ways. But meteors and meteorites are unique among astronomical phenomena in having a blatant physical connection. You can see the heavens coming down to Earth, and sometimes you can pick up the heavenly body. As you will learn in this lecture, these rocks have been taken to be gods, creating and dominating religions worldwide from the long past up until recent times, and were also used as raw material for their iron content, even being the inspiration for the basic idea of the Iron Age.

METEOR STREAKS

- A meteor is the streak of light you see flaming in the sky. Most ordinary meteors are just small grains of sand, broken off an asteroid or expelled from a comet. These small rocks speed through our solar system and randomly hit the Earth. They travel faster than 10 miles per second, and their friction with the air makes them glow. If the meteor is large enough, then the rock can reach the ground. The rock on the ground is called a meteorite.

- For ancient peoples, meteor streaks took on a variety of meanings. A very widespread story is that each meteor is some person who just died and is going to the afterlife. This same basic idea appears throughout Eurasia, Australia, Africa, and the New World.

- Rarely, the incoming rock will be sufficiently large that it survives passage through the atmosphere and falls to the ground. And people can and do see and report this. Seeing the streak in the sky and the simultaneous fall of a rock at your feet is very good for making a connection. So, we see reports from many societies connecting the weird rocks with meteors. People everywhere for many millennia have reached the conclusion that rocks fall from the sky as meteors.

- These observations were repeated as popular sky lore. But the sky lore of old was filled with dragons, fire wheels, and many impossible sightings. So, ordinary skepticism was needed to assess such claims. Western scientists accepted that rocks could fall from the sky only soon after 1800, when 3 very well-observed meteor falls took place in both France and Connecticut.

RED RIVER METEORITE

- The Red River meteorite is a large iron meteorite that fell in north-central Texas a long time ago, perhaps many thousands of years ago. The original rock weighed close to a ton. Due to the explosive energy of its fall, there could have been no close-up witnesses who survived. And we don't know about any distant witnesses among the Plains Indians.

- After things had cooled, the core rock remained on the ground. Its size is around 4 feet long and roughly 2 feet in diameter. Its surface has a metallic sheen, with a small amount of rust. Such a rock was completely unlike any other rock in the region.

- Local Indian tribes took to honoring the meteorite as a god of healing. They would rub up against the stone and would place trinkets and pipes under the stone. They also broke off small pieces. This god of healing was used and claimed by at least 3 tribes in the area.

- The meteorite was first reported to the settlers by explorers in 1772, as based on stories from the Indians. The first settlers to see the meteorite were a band of traders in 1808. They had mounted an expedition from Natchitoches, on the Red River, in central Louisiana, to trade for mustang horses with the Indians far inside Texas. During the expedition, the local Wichita Indians showed their healing god to the traders. Through ignorance, the traders got the idea that the rock was pure platinum.

- When the expedition returned to Natchitoches, 2 splinter parties were formed, both aiming to steal the healing god. The first party couldn't move the meteorite far, so they hid it. The slower party with a wagon found it and started moving it to the Red River. During this journey, they were attacked by Indians, likely trying to save their god. Finally, they reached the Red River, built a raft, and floated their prize down to Natchitoches, then to New Orleans, and finally shipped it to New York City.

- In New York, the assayers showed that the rock was not made of platinum, but rather of iron, and was comparatively worthless. Professor Benjamin Silliman of Yale University was the next to analyze it. He had witnessed a big meteor fall over Connecticut in 1807, with his research proving that there were indeed stones falling from the sky.

- Silliman found that the composition was 90% iron and the rest nickel, proving the meteoritic origin of the rock. For almost a century, the Red River meteorite was the largest meteorite in any collection.

BLACK STONE OF THE KAABA

- The Black Stone of the Kaaba is the holiest relic of Islam. Tradition says that the stone came from heaven, to show Adam and Eve where to build an altar. Later, the archangel Gabriel showed it to Abraham, who built the first temple, now called the Kaaba, and placed the Black Stone as a cornerstone. Its original color was said to be white, but it has turned black by absorbing the sins of men.

- The Kaaba is a cubic-shaped building in Mecca, originally used as a shrine devoted to the many Arabic gods. The Black Stone was just one of 360 idols.

- In 605 A.D., the Kaaba was being renovated after a fire, and 4 rival clans could not agree on who would set the cornerstone. They decided to ask the next person who came through the gate to make the decision.

- The next person through was the prophet Muhammad, still 5 years before he received his first revelations. Showing his wisdom, Muhammad had a cloth brought, placed the Black Stone in the center, and had each of the clan leaders hold a corner to carry the stone to the Kaaba. This kept the honor for all the clans. Then, Muhammad himself put the stone in place.

- The Black Stone was later attacked by a minion of a mad Egyptian caliph. Later, it was kidnapped by the Qarmatian sect. When it was returned, it was recognized because it was a rock that would float on water. The Black Stone is now fragmented into 8 or more pieces, but the individual fragments have not eroded from the frequent handling they receive.

- We have the question as to the physical nature of the Black Stone. Islamic tradition strongly has it falling from heaven, so a meteoritic identity was the long-time default answer. But it can't be a meteorite, because no type of meteorite will simultaneously float, have flecks of white, break into fragments, and survive the tremendous erosion of the frequent handling. For the same reasons, the Black Stone cannot be any other usual type of rock.

- In 1980, Elsebeth Thomsen, a geologist at the University of Copenhagen, proposed a new idea that starts with the famous Wabar meteor crater, which is in the middle of sand dunes in the Empty Quarter of Saudi Arabia.

- Sometime long ago, a large iron meteorite broke up on entry into our atmosphere, and several large fragments created craters in the sand. The impact energy melted large amounts of sand and infused it with superheated meteoritic material.

- The flash-melted sand quickly cooled and froze in place, forming a type of rock called impactite. It had a glassy and fragile structure, with many small airholes throughout. The melt contained varying amounts of dark meteoritic material, making for parts that are both light and dark in color, closely spaced together.

- Thomsen's idea is that the Black Stone of the Kaaba is actually the impactite from the Wabar meteor crater, not the meteorite itself. The impactite idea fits perfectly with what is known about the character of the Black Stone. But the Black Stone can't be examined. And we don't know whether the Wabar crater is younger or older than Muhammad.

- In all, the holy relic of Islam seems probably to be of meteoric origin, likely as the fused desert sand from ground zero of the Wabar crater.

KICK-STARTING THE IRON AGE

- Many historians have traditionally divided the progress of cultures into ages based on the dominant material for the technology of the time. All cultures started out in the Stone Age, where tools and weapons had stone as the cutting edge. Then, people learned that they could mine and smelt copper and tin to form weapons and tools of copper and bronze. The Bronze Age was followed by the Iron Age, with iron providing superior weapons and tools.

- We now know that iron weapons and tools are much better than bronze ones. But people in the Bronze Age didn't know this, and Bronze Age metallurgists could not get iron metal by chance, because iron ore melts at too high a temperature to get with fires from ordinary usage.

- Metallic iron was discovered on the ground all over the world in the form of nearly pure iron metal in meteorites, with many of them up to 90% pure iron metal.

- Archaeologists find many finely hammered iron tools and weapons throughout the world from dates that are certainly in the Bronze Age, when iron smelting had not yet been discovered.

- Bronze Age metalsmiths were working with meteoritic iron for more than a millennium. Over the years, they must have tried many ways of working the metal. Knowing the existence of the wonderful metal, they would have focused on iron ores. Experimentation extended over roughly the 2 millennia of the Bronze Age, before iron production from ore was developed.

- The first real smelting of iron took place in Anatolia, Turkey, around 1200 B.C. From there, it rapidly spread across Eurasia and into Africa. This was the start of the Iron Age.

- Without inspiration from meteorites, the transition would have come at a much later time, with broad and deep changes throughout history.

CAPE YORK METEORITE

- The Cape York meteorite allowed the Eskimos to jump from the Stone Age directly to the Iron Age. The Eskimo, or Inuit, peoples now occupy the icy cold northern part of North America. They arrived from Siberia roughly 5000 years ago. They lived in a harsh environment with just Stone Age technology.

- Then, sometime around the mid-8th century A.D., the so-called Dorset people found a large field strewn with meteorites on a small peninsula, part of Cape York, on the far north side of the western coast of Greenland. The small area had 4 huge iron meteorite hulks, each weighing from 3 to 34 tons. Plus, many small fragments littered the area. These small fragments could be picked up and cold-hammered into many useful tools, including knives, arrowheads, and harpoon tips.

- The amount of nearly pure iron was enormous, about 100 tons. The iron became a highly prized trade good. Tools made with the Cape York meteorite have been found as far as 1400 miles away.

- This one meteorite is what allowed the Inuit to jump out of the Stone Age into the Iron Age. The Inuit did not have the needed technology, any iron ore, or even trees for powering any smelting, so they had no chance of getting iron on their own.

Readings

Flores, ed., *Journal of an Indian Trader.*
Lewis, *Rain of Iron and Ice.*
Schaefer, "Meteors That Changed the World."
Thomsen, "New Light on the Origin of the Holy Black Stone of the Ka'ba."

Questions

1 With meteoritic iron available worldwide, why didn't societies throughout the Americas and Australia hop from the Stone Age to the Iron Age?

2 In King Tutankhamun's tomb, meteoritic iron was more valuable than gold. In modern times, some classes of meteorites are worth much more than their weight in gold. Why?

Activities

1 It is fascinating to hold a real meteorite in your hands. Go out and get one. Some museums have specimens that you can hold, but you can relatively cheaply purchase your own alien rock. Look at it, feel it, and heft it. Does this rock seem different from local rocks you'd find lying around? From the point of view of some ancient farmer or priest, does it look to be special or powerful or godly? If not, then is the historical power of meteorites derived only from having seen them fall from the heavens? From the point of view of some ancient metalworker, would you think to try working this rock? Looking at the meteorite, if you realized its worth as a great metal, would this inspire you to recognize local iron ore as being something to work at?

2 Go outside on a clear, dark night, with no trees overhead, and look up for meteors and meteor showers. No equipment is needed. It helps to get to as dark a sky as possible, so get far outside any city and get away from local streetlights. The rates are higher in the early morning hours. Plan to spend an hour or more so as to catch more than a few. Meteors will appear as flashes of light lasting just a fraction of a second; most will be faint, near your limits of vision. The best yearly meteor showers are the Perseids (around August 11–12), the Geminids (around December 13–14), and the Quadrantids (January 3), with peak rates of 120 meteors per hour. As you watch these small rocks streaking in our atmosphere, cast your mind back to ancient times and imagine what you would think is going on in the sky.

LECTURE 8

Eclipses, Comets, and Omens

In ancient times, anything that happened in the sky could potentially be interpreted as an omen. Although any celestial prophecy could be either positive or negative, some classes of phenomena were in practice universally regarded as negative, including eclipses and comets. The universality of these fears suggests that there is something very deep in human nature or constant in human experience that identifies such events as being bad or evil in some way. As you will learn in this lecture, the oldest astronomy of eclipses and comets always expressed and encapsulated these fears.

THALES'S ECLIPSE

- The great Greek historian Herodotus described how a solar eclipse stopped a long-running war. The setting was in the middle of Asia Minor, now Turkey, and the year was 585 B.C. Asia Minor was divided between 2 large kingdoms, the Lydians to the west and the Medes to the east.

- In Herodotus's story, Thales predicted the year in which a total solar eclipse would stop the 5-year war between the Lydians and the Medes. The exact nature of Thales's prediction has long been controversial for scholars. There is no realistic way that Thales could have made such a prediction, even one that only cites the year of the eclipse.

- In any case, a total solar eclipse during a battle between early Greeks caused a long-running war to stop. It's easy to see why, with an old worldview, any event in the sky can only be a message from the gods. The message from a solar eclipse can only be negative, and it was sent during a battle, so the gods were clearly telling both sides to stop the war. The whole episode of Thales's eclipse shows us the power of solar eclipses as divine commands.

NICIAS'S ECLIPSE

- A lunar eclipse in the ancient world could be just as decisive. In the decades around 420 B.C., the Greek world was dominated by 2 rival powers, headed by democratic Athens and militaristic Sparta. Athens led the Delian League, which effectively became the Athenian empire. Sparta led the Peloponnesian League, with a strong army on land and a weak naval force.

- From 431 to 421 B.C., the first part of the Peloponnesian War raged between these rival powers, with Sparta invading the region around Athens each summer and the Athenian navy raiding the coast of the Peloponnese. In 421, a peace treaty was signed, as negotiated by the Athenian general Nicias.

- The Peace of Nicias lasted until 415 B.C., when Athens sent a very large expeditionary force to Sicily. The goal was to capture the town of Syracuse, which was a colony of Corinth, both of which were key allies of Sparta. Nicias was one of the 3 generals of the force.

- The Athenians landed near Syracuse, and won some victories, but were not able to break into the walls of Syracuse. By August of 413 B.C., it was obvious to the Athenians that they could not win. Nicias was their sole surviving general. He decided on a sneak evacuation of his army and navy by night, to be completed before daybreak. He chose the night of August 28, perhaps because the full Moon's light would help in the troop movements onto the ships.

- In the middle of the evening, as the loading of the ships began, a total lunar eclipse started. The Athenian troops freaked out. Nicias consulted with the priests. Lunar eclipses were always frightful omens, so the sign from the gods was read to be a warning against the evacuation. The loading stopped. The priests suggested that they wait one lunar month before any evacuation was tried again, and the superstitious Nicias agreed.

- This delay in the evacuation killed the morale of the Athenians. Furthermore, because of the delay, the Syracusian navy was able to cripple the Athenian fleet. The Athenians were now trapped on Sicily, with no hope for supplies or help. When the Athenians desperately tried an overland march to a friendly city to the north, their army was cut in pieces and defeated.

- Only a handful of survivors made it out. Athens was horrified by the disaster. The majority of their land and sea forces were lost. Their allies started to revolt against Athens. Amazingly, Athens managed to hold out for a while. But by 404 B.C., Athens had surrendered to Sparta. The fall of democratic Athens was tipped by Nicias's superstitious fear of a lunar eclipse.

EXPLAINING ECLIPSES

- The Athenian astronomer Anaxagoras had put forth a correct physical explanation of eclipses before the start of the Peloponnesian War. In 450 B.C., Anaxagoras was tried and convicted of impiety by an Athenian court, ostensibly because his explanations for the Sun and eclipses did not invoke the gods.

- The Roman historian Plutarch tells us that Anaxagoras's knowledge was at first known only by a few people, due to the Athenian religious zealotry. But Anaxagoras's discovery eventually spread widely. Within 2 or 3 generations, the fear had gone.

- Plutarch tells us about a strikingly similar case involving the embarkation of Greek warriors going against Syracuse. In 357 B.C., a wealthy Greek diplomat named Dion was mounting an expedition to attack Dionysius, the tyrant of Syracuse. In Greece, Dion collected 800 veteran mercenaries. On the night before the embarkation, the Moon eclipsed during a luxurious banquet. This time, however, armed with the knowledge offered by Anaxagoras, Dion easily calmed the warriors. They embarked on the voyage to Syracuse, where they managed to overthrow the tyrant.

- We see a huge change in the attitudes of the Greeks in the decades between the 2 expeditions to Syracuse. The difference was the knowledge that eclipses are just shadows.

LOSING THE FEAR

- Eclipses start out as being universally feared—as dread omens. The symbolism is easy to see. The extinguishing of the Sun looks like the death of the Sun god. Any breaking of the harmony of nature is horrible when your life depends on the reliability of the cycles in the sky.

- Another reason for the fear is that eclipses were unpredictable. Startling events are scary. The unexpected makes for a breaking of the cycles of nature. It was only in Hellenic times that the Greeks started to be able to predict eclipses with useable reliability. The ability to predict eclipses spread throughout Eurasia and was reinvented repeatedly.

CAESAR'S COMET

- Unlike eclipses, the ancient world never reached a clear understanding of comets. Spectacular comets appear once every decade or 2 on average. Perhaps the most famous comet of the ancient world followed the death of Julius Caesar.

JULIUS CAESAR

- On the Ides of March in 44 B.C., roughly 60 senators were on hand for the assassination of Caesar. They saw it as the death of a tyrant. Caesar's will had several fateful bequests, including to adopt his grand-nephew Gaius Octavius, also known as Octavian, as his son and heir.

- Caesar's heir vowed to hold games in honor of Caesar's victory. These games had been promised by Caesar himself. The games ran just 4 months after Caesar's assassination. On the first day of the games, a spectacular comet appeared in the sky. This comet was so bright that it was visible during the daytime. With such blazing, it could only have been a sign for a very important person. We're told that it was visible only for 7 days, during the games dedicated to Caesar's victory.

- This comet was also likely seen and reported by the Chinese, and we have their records of the dates and position of this appearance. Modern astronomers have used the sparse Roman and Chinese data and have been able to derive an approximate orbit for the comet.

- Caesar's comet is the classic case of a comet associated with the death of a king or emperor. Octavian immediately declared that the comet was the soul of Caesar being carried to heaven. Suddenly, Caesar was divine, an opinion that the Senate voted to support a year later. Suddenly, Octavian was the son of a god, and his authority in the chaotic Roman politics became inevitable.

- Octavian used this comet in an effective propaganda campaign. This provided a simple rallying symbol for use by the Caesarian forces. Over the next few years, with brilliant political maneuvering, Octavian gained complete control over Rome. The Roman Republic was changed to the Roman Empire. Octavian was granted the name Augustus. We now know him as the greatest Roman emperor: Caesar Augustus.

NERO'S COMET

- This comet not only provided the justification for deifying Julius Caesar, but it also set the pattern for all later Roman emperors. Each in turn was made a god, simply following the example of Caesar's comet.

- Caesar's comet showed that comets meant the death of the emperor. This was strengthened when a later comet in 54 A.D. was tied to the death of Emperor Claudius, who was poisoned by his wife Agrippina. She placed her son Nero on the imperial throne at the age of 16, and Rome was initially run on Nero's behalf by the philosopher Seneca.

- Six years into Nero's reign, in 60 A.D., another bright comet lit up the sky. To avoid fate, Nero exiled and then murdered the most likely successor.

- About a year later, Seneca wrote a book on comets. He discusses everyone's prior speculations, and this speculation runs over an incredibly wide range of causes for comets, including fiery whirlwinds, sparks from planet and star conjunctions, and some form of lightning. It was clear even to Seneca that no one had any real idea of what was going on.

- Seneca takes particular care to distinguish the emperor-killer comet of Claudius from the comet seen in the first part of Nero's reign. He said that the 2 comets were different in character because one went from the north to the west, while the other went from the north to the east. Seneca was trying to calm the murderous fear of Nero.

- Four years after the first of Nero's comets, in 64 A.D., another bright comet appeared. Nero lost control and murdered dozens of people from the Roman aristocracy. Even Seneca committed suicide, as ordered by his former student—all because a comet provided a bad omen.

MONTEZUMA'S COMET

- The appearance of a comet also contributed to the fall of the Aztec empire. A comet and a prophecy spooked Montezuma II, who became the Aztec emperor in 1502, into giving away the empire, but this is only part of a much more complex story. Rather, the story of Montezuma's comet shows that comets were also very deeply feared in the New World.

FEAR OF COMETS

- In general, comets foretold the deaths of kings and emperors, or the end of the world. Fear of comets was universal. Seneca tells us that the root of the problem is that these events were not understood and they were unexpected. They were breaks in the harmony of nature.

- This deep fear of comets and eclipses can be overcome for 1 of 2 reasons. First, if the event becomes predictable, then the fear goes away. The event simply becomes part of the sky cycles. Second, the fear goes away if the underlying nature of the event becomes understood. In particular, eclipses are not frightening when you realize that all you're seeing is either the shadow of the Earth or the shadow of the Moon.

Readings

Espenak, *Mr. Eclipse*.
Ramsey and Licht, *The Comet of 44 B.C. and Caesar's Funeral Games*.
Schaefer, "Comets That Changed the World."
———, "Lunar Eclipses That Changed the World."
———, "Solar Eclipses That Changed the World."

Questions

1 Comets are now understood physically (humans have had spacecraft hitting, landing on, and returning samples from comets), and their movements are accurately predictable (once discovered). Yet humans still have a great fear of comets. Why?

2 Novas and supernovas in the sky are "new stars" that were neither understood nor predictable. So, were novas viewed as evil or good?

Activities

1 Go outside and see a lunar eclipse. Seeing this is easy, and needs no equipment. Total eclipses are the best, with the Moon turning bloodred and dimming sometimes to invisibility; we can easily see the symbolism expressed by most ancient peoples that the eclipse is the death of a god. But partial eclipses are still interesting and evocative. Search on the Internet for dates of upcoming eclipses that will be visible to you.

2 Use a simple observation of a lunar eclipse to accurately measure the size and distance of the Moon. The simple observation is to compare the radius of curvature of the Earth's shadow edge to the radius of curvature of the Moon itself. This has to be done near the middle of the partial phase. You can make a reasonable judgment by eye, but a careful sketch by hand allows for better accuracy. The use of binoculars can give a better view, or you can take a photo at maximum zoom of the Moon and measure from a printout of your own picture. Or, if no lunar eclipse is handy, then you can use any such photo that you find on websites such as Astronomy Picture of the Day (http://apod.nasa.gov/apod/astropix.html).

The idea of this is to draw a circle that fits the edge of the Earth's shadow with some angular radius Θ_{shadow}, and also one that fits the edge of the Moon itself with an angular radius Θ_{Moon}, and simply to get the ratio of the radii. For a very distant Sun (i.e., being much farther than the Earth-Moon distance), the size of the Earth's shadow is close to the same size as the Earth itself. So, your measured ratio ($R = \Theta_{\text{Moon}}/\Theta_{\text{shadow}}$) is just the ratio of the size of the Earth to the Moon ($R_{\text{Moon}}/R_{\text{Earth}}$).

Historically, astronomers throughout Eurasia actually had a reasonably accurate measure of the R_{Earth}—for example, from the Eratosthenes experiment—and you can personally make the same measure as in the Activity for lecture 6. The radius of the Moon is then $R_{\text{Earth}} \times R$ or $R_{\text{Earth}} \times (\Theta_{\text{Moon}}/\Theta_{\text{shadow}})$. And you can use this size to also get the distance to the Moon. For this, you need some real measure of the angular radius of the Moon (Θ_{Moon}), not just the ratio of radii. You can mount a small coin or a ball onto some wall top or post (perhaps with clay or tape or by impaling the ball on a spike); then, move your head such that the coin appears the exact same size as the full Moon next to it. Then, measure the distance between the coin and your eye ($D_{\text{coin-eye}}$) and the radius of the coin (R_{coin}). Then, you can calculate that as $\Theta_{\text{coin}} = R_{\text{coin}}/D_{\text{coin-eye}}$, in units of radians.

The radius of the Moon has a similar relationship with $\Theta_{\text{Moon}} = R_{\text{Moon}}/D_{\text{Moon}}$, in units of radians. With $\Theta_{\text{Moon}} = \Theta_{\text{coin}}$, you can solve for the distance to the Moon as $D_{\text{Moon}} = R_{\text{Moon}}*(D_{\text{coin-eye}}/R_{\text{coin}})$. Put in terms of quantities that you have measured, the Moon's distance is $R_{\text{Earth}} \times R \times (D_{\text{coin-eye}}/R_{\text{coin}})$. With such reasoning, the ancient Greeks had a good idea of the scale of our Earth-Moon system.

LECTURE 9

The Star of Bethlehem

The most famous case of a divine symbol in the heavens is probably the Star of Bethlehem, which is used nowadays as a symbol of the birth of Jesus Christ more than 2000 years ago. The original symbol, as given in the Christian Bible, was a sign in the heavens leading a group of wise men to Jerusalem and then Bethlehem, where Jesus was born. Many possibilities have been proposed over the last 4 centuries for what the Star of Bethlehem actually was, including a comet, a rare event involving bright planets, or even an exploding star. In this lecture, you will learn about one possible explanation.

BACKGROUND

- As a historical question, the only evidence on the Star of Bethlehem comes from a handful of verses in the second chapter of the Gospel of Matthew in the New Testament of the Christian Bible. This gospel was written in Greek, sometime around 80 or 90 A.D.

- The basic nativity narrative is explicitly set in the time when Herod was King in Judea, and Jesus was born in Bethlehem, just 5 miles south of Jerusalem. Some wise men, or Magi, to the east of Jerusalem "saw his star in the east" and then traveled to Jerusalem.

- There, King Herod was troubled by the star, while the priests and scribes had not seen the star. The priests told the wise men about the prophecy that a ruler of Israel would be born in Bethlehem, so they walked to the small town and found the baby Jesus with Mary. The wise men gave him gifts and departed by a different route.

- The nature of the star is wrapped up with the date of Jesus's birth. Traditionally, Jesus was born on December 25th in 1 B.C. But of all the proposed dates, the traditional date is the one that we know is certainly wrong. As for the day of the year, the birth must have been in the springtime, because we're told that the shepherds had lambs in the fields, and lambing happens in the spring.

- As for the year of the birth, the traditional year came from an attempted calculation made centuries later with bad assumptions. We know that the traditional year must be wrong because Jesus was born when Herod was alive, and Herod certainly died in March of 4 B.C.

- So, the traditional date and year were invented later. We aren't given much other useful information. The only useful information that we have is that Jesus was born while Herod was alive, and in the springtime. Herod died in 4 B.C., and he had near his death ordered the murders of all children up to the age of 2 years. So, Jesus was born within 2 years before some time close to Herod's death. Thus, Jesus was born in the springtime of 6 B.C., or maybe 7 B.C. or 5 B.C.

OLD IDEAS

- Up until the 1600s, people just considered the Star of Bethlehem to be a miracle, a divine creation placed into the sky, with the event being beyond physics.

- In 1606, the great astronomer Johannes Kepler hypothesized that the star was a natural phenomenon, created as a by-product of a triple conjunction of Jupiter and Saturn as they moved around the sky.

- His idea originated because in 1604, Kepler discovered a very bright supernova close to a triple conjunction of the planets Jupiter and Saturn. This supernova is now called Kepler's Supernova, and it still attracts astrophysics researchers today.

- Kepler realized that there was a similar triple conjunction of Jupiter and Saturn around the time of Jesus, so he mistakenly suggested that these planets made a much earlier supernova, which was the Star of Bethlehem.

- Kepler's naturalistic idea started a long series of claims for other non-miraculous astronomical events that could have been the star. These usually were impressive events in the sky and include Halley's Comet in 12 B.C., a Venus-Jupiter occultation in 2 B.C., and a nova seen by the Chinese in 5 B.C.

- However, the star certainly was not a comet, because the very deep and universal fear of comets would not allow them to be used as a symbol for the birth of a very great king. The date for the Venus-Jupiter occultation was 2 B.C., which was after Herod was dead. And the object reported by the Chinese in 5 B.C. was described by them as a broom star, so it was certainly a comet and not a nova.

- A more recent and prominent astronomical solution came from British astronomer Mark Kidger, who published a book in 1999 claiming that the star was a 1925 nova that he postulated had also exploded previously. This particular nova has been given the modern name DO Aquilae.

- Kidger's idea was that even though only one eruption of this nova has been seen, this nova could actually be a recurrent nova. Moreover, he postulates that it also erupted in 5 B.C. and was reported by the Chinese.

- Kidger's claim achieved prominence on the Internet and in bookstores, but it's wrong. One easy reason is simply that in 5 B.C., the Chinese reported a comet (that is, a broom star), so there is no evidence of a nova at any time around the birth of Jesus. But a deeper refutation comes from astrophysics.

- In 1925, DO Aquilae only got as bright as would be just barely visible with binoculars, and recurrent novas always reach the same peak brightness for all of their eruptions. Thus, any prior eruption would have been invisible to the Magi.

- Extensive research on recurrent novas has proven with high confidence that DO Aquilae is not a recurrent nova and had no eruption for a million years prior to 1925.

MOLNAR'S ARGUMENT

- In 1999, Michael Molnar, an astrohistorian from Rutgers University, published a book that offered a convincing and reliable answer to the question of the origin of the Star of Bethlehem. His solution has taken the scholarly world by storm and is now the default answer due to its forceful logic and compelling evidence.


VENIMO
ADORA

- Molnar has proven that the star was indeed a historical event, but not one that most people would expect. Molnar's solution is applicable only to the historicity of the star and does not tell us about the historicity of any other part of the Nativity story. As such, Molnar's solution is perfectly acceptable to people of all religions and faiths.

- Michael Molnar's argument can be divided into 3 major points.
  1. The only people whose perception of the star matters for using the star is the Magi, who were astrologers, not astronomers, so they would be unlikely to take notice of astronomical appearances. Astronomical events, however spectacular, are completely irrelevant to ancient astrologers. Therefore, this first point is that all astronomical answers must be incorrect, because such astronomical events would have no notice or meaning to an ancient astrologer.

  2. To discover exactly what the Star of Bethlehem must be, Molnar realized that we have to look at the question from the point of view of an ancient astrologer. His second point is that the Star of Bethlehem can only have been an astrological natal horoscope. The presence of the astrological technical term "star in the east" twice in the Nativity story offers good evidence, and Molnar's astrological solution offers a realistic way for how the star operated exactly as described in the story.

  3. Molnar looked over long stretches of time, and he found that the date 17 April 6 B.C. had a horoscope that strongly pointed to the birth of a very great king in Judea. The power of this celestial prophecy would have been strong enough to send the Magi traveling to Judea. His third point is that the Star of Bethlehem is a natal horoscope for the particular date of 17 April 6 B.C.—a date derived from the positions of the planets that happens to be in springtime of a year shortly before the death of Herod. The match is perfect.

- Such a powerful horoscope, with so many features aligned in a particular way, is extremely rare. There are very long odds that such a rare horoscope would happen to fall in the springtime of a year around 6 B.C.

- This coincidence in time of independent events is so improbable that it becomes strong evidence that there must be some sort of a causal connection between the horoscope and the star as reported in the Gospel of Matthew.

- Molnar has established that the star in Matthew has a real historical origin derived from real events up in the sky. However, Molnar's result does not establish the historicity of any other part of the Nativity story. There is still a wide array of possibilities that fit in well with Molnar's result. For example, the following are 2 extreme scenarios, both where the star originated as a horoscope.

  1. The first scenario would be that of biblical literalism. In this case, the Magi cast the horoscope to realize that a very great king would be born in Judea, traveled to the capital of Judea, were directed to Bethlehem, found Mary and Jesus, offered their gifts, and returned home by a different path. This scenario is perfectly consistent with Molnar's solution.

  2. In a second, very different, scenario, the Magi might not have existed at all, and no one around the time of Jesus's birth even realized the power of the 6 B.C. horoscope. Sometime before the Gospel of Matthew was written, a Greek-speaking convert to Christianity discovered the 6 B.C. horoscope. Once the 6 B.C. horoscope was recognized, it would've been easy to invent a pious fable about earlier Magi using the same horoscope. In this alternative scenario, the origin of the star as reported by Matthew is still the horoscope for 17 April 6 B.C.

- These 2 extreme scenarios allow Molnar's solution to coexist with traditional Christian beliefs and to coexist with non-Christian religious views. There's a whole range of possibilities spread between these 2 extreme scenarios. This spectrum of possibilities includes varying degrees of historicity for all the other aspects of the Nativity story. And throughout all this, Molnar's solution neither rejects, nor depends on, the divinity of Jesus.

Readings

Barthel and van Kooten, eds., *The Star of Bethlehem and the Magi*.
Hughes, *The Star of Bethlehem*.
Molnar, *The Star of Bethlehem*.
Schaefer, "The Star of Bethlehem is *Not* the Nova DO Aquilae."

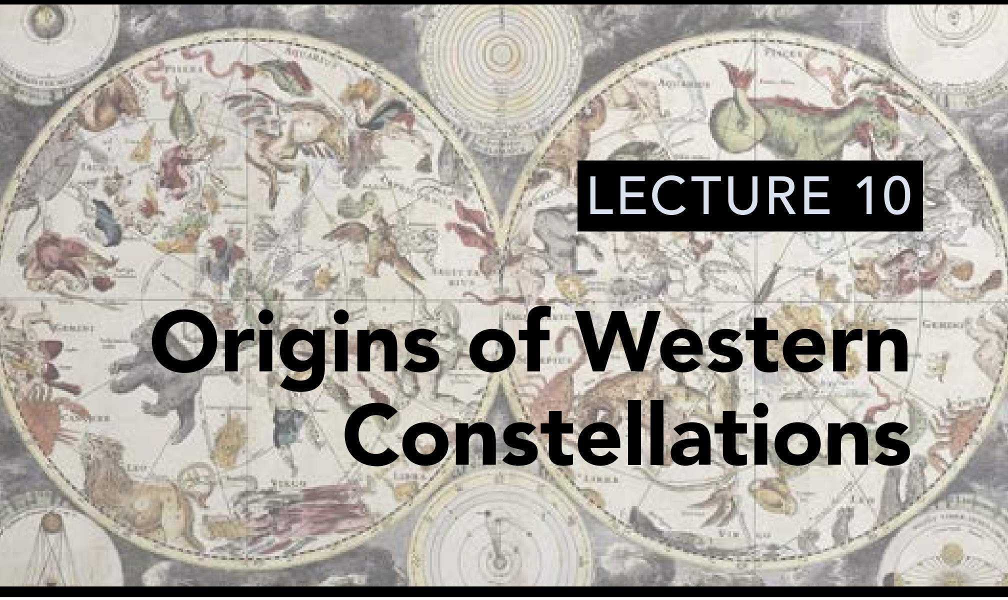
Questions

1 Within Christian theology, why does the nature of the Star of Bethlehem matter? In a higher or a broader view, how does it change anything whether the Star of Bethlehem was a comet, a natal horoscope, a luminous angel messenger, or an invented story?

2 Michael Molnar is just saying that the Star of Bethlehem has a historical origin from a connection to a particular natal horoscope, with the connection first made perhaps around the time of Herod or of the gospel writer. Does Molnar's solution run counter to any theology for any branch of Christianity, any other religion, or any variation on agnosticism or atheism?

Activity

1 Perform your own small informal survey of what people think is the nature of the Star of Bethlehem. Do your informants think that the star is a pious story (with no historical events connected), an astronomical event (something real up in the sky), a miracle (with no explanation from physics), or an astrological event (a configuration of planets that only an astrologer would appreciate)? Be careful to not ask leading questions. For each informant, ask where he or she got his or her answer from (perhaps from parents or some religious advisor or from their own analysis). In miniature, this will give you a sample of how popular astronomical ideas are transmitted among ordinary people.



LECTURE 10

Origins of Western Constellations

The invention of constellations is universal. This creation of constellations speaks to the fundamental human traits of pattern recognition and storytelling. Constellations have a wide variety of practical uses, including as a storybook for passing along myths and legends and morality tales, for finding directions and navigation, for telling time and making the calendar, and for forming a backdrop and coordinate system for measuring planet positions for purposes of astrology. In this lecture, you will learn about the path that has led to the formation of modern Western constellations.

MESOPOTAMIAN CONSTELLATIONS

- The path to the modern Western constellations goes directly back to the Greeks. But most of the Greek constellations go directly back to the peoples in Mesopotamia. This constellation information goes from times around 3200 B.C. up to 500 B.C., and it's pretty sketchy.

- The location is up and down the Tigris and Euphrates river valley, in what is now modern Iraq. The dominant political kingdom or dynasty depends on the part of the country and the time and includes the Babylonians, the Assyrians, the Persians, the Kassites, and more.

- Before 1400 B.C., we only have glimpses of recognized stars and constellations. For example, some constellation names are from the Sumerian language, which died out around 2000 B.C. So, presumably these few constellations are at least that old. Around 1700 B.C., the Prayer to the Gods of the Night appeared on cuneiform tablets, mentioning 10 prominent constellations by name only, including the Wagon and the Yoke.

- It's only around 1400 to 1100 B.C. that we find evidence for a large number of constellations. This includes symbols on large stone boundary markers that show icons for the Sun, Moon, planets, and many constellations, all placed as witnesses of the king's land grant.

- Starting around 1200 B.C., a series of tablets, called astrolabes, appear, with schematic lists of the names of 36 constellations, 3 for each month. Many of these constellations were possibly new inventions.

- The character of these Mesopotamian constellations can be divided up into 3 types: gods and heroes (including the Great Twins and the Standing Gods of Ekur), animals (including the Scorpion and the Lion), and farming items (including the Plow and the Wagon).

- The first detailed description of the Mesopotamian sky comes from a cuneiform tablet called MUL.APIN. Many faithful copies of this tablet are known, dated from 687 B.C. to 281 B.C. This text lists all the constellations and tells us the relative positions of each in many ways.

- Extensive research by Bradley E. Schaefer has shown that the observations reported in MUL.APIN come from 1370 B.C., to an accuracy of 100 years, and a latitude of 35.1° north, to an accuracy of about 80 miles. This puts the anonymous observer squarely in the Assyrian empire, near its capital of Assur.

- This is just around a time of a cultural flowering there. At the same time, we're suddenly getting the first archaeological evidence for the formation of many of the constellations.

- The Mesopotamian constellations evolved somewhat over the next few centuries. The most important change was the creation of the modern zodiac. Before about 550 B.C., there were just 11 random constellations that happened to lie near the ecliptic, the path of the Sun. These constellations all had greatly varying sizes and had not been treated as anything special.

- By about 500 B.C., these had been upgraded to 12 constellations by breaking off the claws of the Scorpion into a separate constellation. This was called the Claws early on but later became the independent constellation Libra, the Scales.

- Also, the 12 constellations were formally divided up into 30° arcs along the ecliptic. This zodiac then served as a coordinate system for measuring planet positions and as a marker for the Sun's position—and hence for the calendar.

- In all, the Mesopotamian star pictures have a poorly known history, stretching over millennia. The system was nearly fully formed by around the 14th century B.C., and observations from this time were passed down for another thousand years.

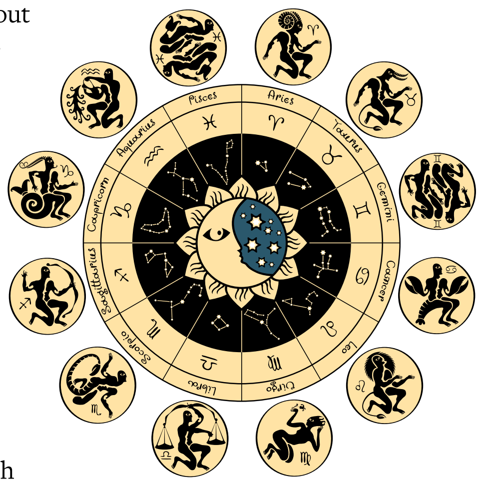
HELLENIZED SYSTEM

- We have few direct sources for the earliest Greek constellations. The earliest source is from Homer around 750 B.C., in his epic *The Iliad*. He places his whole worldview onto the shield of Achilles, including a description of the skies. Homer tells us about the Pleiades, the Hyades, Orion, Boötes, the Bear (which he called the Wagon), and the Dog of Orion.

- Perhaps a generation after Homer, the Greek writer Hesiod mentions only the same constellations as Homer. This tempts many scholars to think that the early Greeks had only these few constellations—or only a small number, for the most prominent stars. This might be correct, but it might also be simply fooling ourselves due to the lack of surviving documentary evidence for the less prominent constellations.

- From the time of Homer and Hesiod up to roughly 370 B.C., there's little direct evidence about the Greek constellations. From this scant evidence, we know that the Greeks somehow received a major influx of constellations from Mesopotamia.

- One primary way that we know this is because Greek star calendars started using the 12 zodiac signs with uniform arclength of 30°. These star calendars are called



MODERN RENDERING OF ANCIENT ZODIAC

parapegmas and usually list sky phenomena for many days of each month, along with weather predictions. The parapegmas were also constructed in stone with movable pegs, for display in public forums.

- The earliest ones for which we have good reports date to around 430 B.C., and they were common by that time. This Greek use of the uniform zodiac certainly was directly taken from the nearly identical uniform zodiac of the Mesopotamians. This uniform zodiac was finalized around 500 B.C. in Babylon. So, this major transfer of constellations to Greece must have occurred sometime between 500 and 430 B.C.

- The next significant source of information on the Greek constellations is a book called *The Phaenomena*, by the astronomer Eudoxus, around 366 B.C. This book is now lost, but we know its contents closely because the Greek poet Aratus largely duplicated it in his best-selling poem, also called *The Phaenomena*, written in 275 B.C.

- Eudoxus's book gives a long and detailed description of all the constellations. This is the first source that tells us about the full Greek pantheon of constellations. Later works on the Greek constellations all use the system of Eudoxus, with only small variations. So, his book served to define and codify the star pictures.

- Eudoxus's book, as copied by Aratus, contains many lore items that depend on the latitude and year of the observation. Given the known positions of the constellations and the known motions of the stars due to the Earth's precession for each lore item, how close the reported case comes to the actual case in the sky can be evaluated.

- Eudoxus gives us a total of 171 itemized observations that depend on the date and latitude. Schaefer's analysis of all these lore items shows a consistent year and latitude throughout: The latitude of the observer was 36° north, with an uncertainty of 50 miles north/south, and the year of the observations was 1130 B.C., with an uncertainty of 80 years.

- This shows that Eudoxus did not construct the lore repeated in his book. Just as Aratus and Hipparchus copied this same lore in later centuries, Eudoxus must have been repeating lore from some 800-year-old source.

- Given the derived latitude and date, the original source could only have been close to the same Assyrian observer who provided the lore for MUL.APIN; that is, a large fraction of Eudoxus's book actually originated from Mesopotamia from 8 centuries earlier.

- The constellations in Eudoxus are a mixture of old Mesopotamian origin and apparently new Greek invention. Twenty of Eudoxus's star pictures are straight copies from Mesopotamia. Ten of Eudoxus's constellations had the identical stars as in Mesopotamia, but they'd been renamed. So, the majority of the classic Greek constellations were taken directly from the Fertile Crescent.

- Still, there are many constellations that are not from Mesopotamia, and we can't find any evidence for some other plausible source. The names and lore for these constellations are characteristically Greek. These minority of Greek constellations seem to be of Greek invention, and the dates of these Greek inventions are difficult to know.

- Our picture of the creation of the ancient Greek constellations is one of patchwork borrowing and invention.

ADD-ONS BY MANY

- The classical set of Greek constellations was set by Ptolemy's *Almagest* around 150 A.D. This contained a star catalog, and everything was broken down into 48 constellations. Some of the stars weren't collected into specific constellations, but most of the visible sky was covered. Over the next 1700 years, we have a patchwork of adding constellations.

- Berenice's Hair, named for Queen Berenice II of Egypt, is a clustering of stars near the tail of Leo that appears as a few dozen faint points, which give the impression of being somewhat hazy, like hair, and about the right shape. This constellation was mentioned by many Greek writers. But Ptolemy's *Almagest* has this same fuzzy star cluster forming the tuft on the end of the Lion's tail.

- Only in the 1500s was this constellation promoted to be one of the regular and main constellations, when it was included by the great Danish astronomer Tycho Brahe in his star catalog of 1602. The official name is now in Latin, called Coma Berenices.

- Tycho's catalog included only one other constellation not in Ptolemy's 48 original Greek constellations. This was named Antinous, after a Greek youth who was the favorite and lover of Roman Emperor Hadrian. Ptolemy notes the stars of Antinous but does not promote them to be one of his 48 constellations. Antinous was used haphazardly by Renaissance astronomers but then was largely forgotten.

- The Western constellations were next added to around the start of the Scientific Revolution. These were added for 3 reasons: to have constellations in the previously invisible southern skies for use by navigators, to fill in gaps in the northern constellations, and for astronomers to invent constellations to ingratiate themselves with wealthy or powerful patrons.

- These new constellations were invented by the Dutch astronomer and mapmaker Petrus Plancius in the 1590s, by the Polish astronomer Johannes Hevelius in the 1690s, and by the French astronomer Nicolas Louis de Lacaille in 1763. In 1922, the newly formed International Astronomical Union standardized the constellations and their boundaries into 88 official constellations.

Readings

Condos, *Star Myths of the Greeks and Romans*.
Schaefer, "The Latitude and Epoch for the Formation of the Southern Greek Constellations."
———, "The Latitude and Epoch for the Origin of the Astronomical Lore of Eudoxus."
———, "The Origin of the Greek Constellations."
White, *Babylonian Star-Lore*.
Wilk, *Medusa*.

Questions

1 Look at some constellations, with and without the classical figures overlaid. What fraction of constellations have any real resemblance to their named image? Does this matter?

2 In Bradley E. Schaefer's work on the origin of the ancient constellations, he has used precession and visibility to derive the latitude and epoch for various sets of old lore. For the 172 lore items recorded by Eudoxus (c. 366 B.C.), he derives an average date of 1130 ± 80 B.C. and a latitude of 36.0° ± 0.9°. This gives the year and place for the observer of the lore and thus only sets a limit on the date of the constellation invention. From the limits on the 6 southernmost constellations (barely peeking up over the far southern horizon), he gets an epoch of 700 ± 300 B.C. and a latitude of 33° ± 2°. This would be for the creation of these 6 constellations. For 113 useful lore items in the MUL.APIN cuneiform tablets, he derives a year of 1370 ± 100 B.C. and a latitude of 35.1° ± 1.2°. The quoted error bars are with the standard 1-sigma convention, where the real value will be within the stated range 68% of the time and twice the stated range 95% of the time. With these quantitative measures, how can you get all these to fit together? For example, do you think that

the same observer(s) who created the MUL.APIN lore also created the lore repeated in Eudoxus? And when was the bulk of the constellation invention? Could the lore and constellations have been made in Greece (latitude range 37° to 42° north) or Egypt (latitudes south of 31°)?

Activities

1 The character of the Mesopotamian constellations is fairly evenly divided between gods and heroes, animals, and farming items. Can you make similar or different characterizations for the 48 classical Greek constellations (as given in Ptolemy's great *Almagest*)? At the end of this guidebook is a list of the Greek constellation names, translated to English where possible and with Ptolemy's ordering. With this activity, you can partly get into the heads of the ancient constellation makers, seeing what were their major interests and concerns. From the nature of the object/person being immortalized, can you pick out which ones came from Mesopotamia (landlocked farmers with irrigation central for their economy) and which were invented by the Greeks (from a mountainous region, close to the sea, obsessed with their myths)?

2 Go outside on some clear night and spot some constellations. You can do this from a city or suburbia, but then you'll only see the brighter stars in the figure. Binoculars can help a lot for seeing the fainter stars that fill out the figure. You'll need to get some star charts going to sixth magnitude—for example, from books, the Internet, or a planetarium program.

LECTURE 11

Chinese and Other Non-Western Constellations

All cultures everywhere, for which we can recover adequate information, have their own sets of constellations—with attached lore. The path to the Western constellations is particularly well known, and broadly important to the history of astronomy, but this is just a small sample of the constellations used by ancient astronomers. To get a sense of the richness of ancient constellations, we must look at constellations worldwide. In this lecture, you will be introduced to non-Western constellations.

LUNAR LODGES

- The set of Chinese constellations known as the lunar lodges, or lunar mansions, is about 5000 years old and is among the most important constellations for the Chinese, and for many cultures throughout Asia.

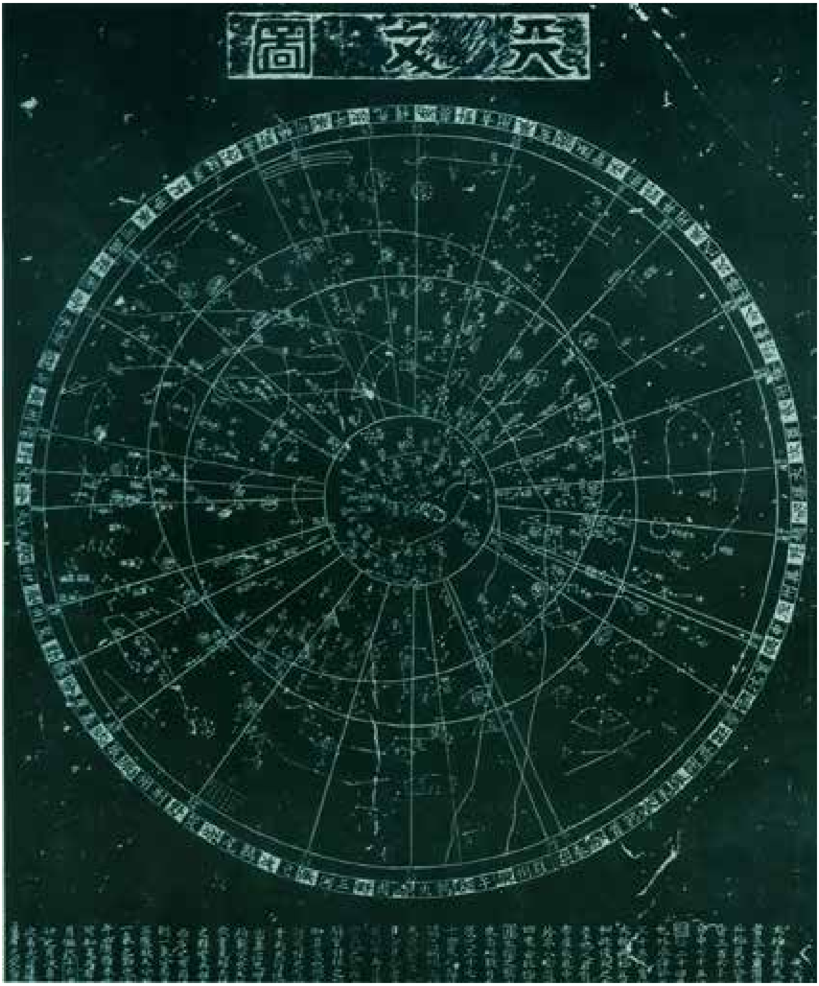
- The lunar lodge system consists of a set of 28 constellations spread out around the sky, scattered widely around the celestial equator and the ecliptic. Each of these constellations has a single star selected, called the determinative star or the junction star. The entire sky is then divided up into 28 regions.

- Each determinative star defines half of a great circle, passing from the North Pole, going exactly through the determinative star, and ending up at the invisible South Pole. The area of sky that is between 2 adjacent half-circles is the area for the lunar lodge associated with the constellation.

- The lunar lodges have been used as tools for a variety of purposes through the millennia. Likely the first was simply to serve as calendar markers—that is, for keeping track of the positions of the Sun and Moon. Later, around the 1st century A.D., the Chinese realized the nature of the path of the Sun along the ecliptic.

- Then, the determinative stars came to serve as a grid for measuring longitudes in the sky. This was applied to the Sun and Moon for calendric purposes, to the planets for astrological purposes, and to the stars and comets for what we could call scientific purposes.

- Soon enough, the individual lodges themselves started taking on astrological meanings; that is, each lodge had traits and geographic connections, interpretable in connection with the positions of the planets.



SUZHOU STAR CHART

- The 28 lodges have been grouped into 4 sections of 7 lodges each. These are given the symbols of the Azure Dragon, the Black Tortoise, the White Tiger, and the Vermillion Bird. Each of these is viewed as a single large constellation, stretching out along the ecliptic, the path of the Sun and planets. Each of these totem animals has an associated direction, a season, a color, and an element.

- Archaeologists have unearthed a lacquer box from 433 B.C. with all 28 lodges named in order. From a few centuries earlier, the document called the Monthly Ordinances of the Chou lists 23 of the lodges. Some individual lodges are mentioned even earlier, including on Shang oracle bones dating to around 1100 B.C.

- An astronomical method can be used to date the origin of the Chinese lunar lodges. This is based on the determinative stars being selected, at least approximately, as being near the celestial equator. This can be quantified by the average angular distance of the determinative stars from the equator.

- The average distance can be calculated as a function of time over an interval of many millennia, and the date of the lodge formation will be close to the year when the distance is smallest. Using this method, Bradley E. Schaefer derived that the Chinese lunar lodges were created sometime around 3200 B.C., with a margin of error of ±500 years, from 3700 B.C. to 2700 B.C. The lodges are roughly 5 millennia old.

- Perhaps the most intriguing feature of the Chinese lunar lodge system is that there are similar lodge systems in both India and Arabia. All 3 of these systems feature 28 unevenly spaced constellations, spread out roughly along the equator, defining a coordinate grid for the sky and being used for the local calendars and astrology.

- Furthermore, Japan, Mongolia, Korea, and Vietnam have lodge systems that are clearly derivative from China, with changes that are mainly just in the names. Cambodia, Thailand, and Persia have lodge systems clearly derivative from India. Also, there is a Coptic lodge system in Egypt taken from the Persians. So, the basic lunar lodge system is very widely used throughout Asia. These systems have around half duplicated stars, with the other half being distinctly different.

- The Indian system has a lodge formed from the Pleiades. The next lodge has the same stars of the Hyades as does the Chinese lodge, but the determinative star is different, being the bright red star Aldebaran. And many of the lodges have completely different constellations.

- The Indian system also has its determinative stars selected as being near the celestial equator, the year at which the average distance from the equator is the smallest can be calculated. With this, Schaefer derived a date of 1700 B.C. for the formation of the Indian lodge system.

- In India, a 27-constellation version is sometimes used. Both the Indian and Chinese lodge systems have been extensively used for the last 2 millennia for purposes of astrology. Both systems are even now widely used.

- The Arab lunar lodge system also has many of the same constellations as the Chinese and the Indians. But we have only sparse sources and know little about their origin or use. A precessional dating of the origin for the *manzils* (the name for the lunar lodges in Arabia) is 200 B.C., with an uncertainty of 600 years. With the coming of Islam in the 7th century A.D., the use of the Arab *manzils* was forgotten.

- The lodge systems are definitely genetically related. Between China and India, 20 of the constellations are essentially identical, while 9 of them have identical determinative stars. The Arabian system has similar statistics. Such matches in the structure, uses, constellations, and determinative stars cannot be by chance alone. There must be some causal connection.

- We don't have any evidence that blatantly shows us which is the first lodge system. Both the Chinese and Indian systems can apparently be traced back to around 1500 B.C. from ancient texts and archaeological sources. Both could have started perhaps long before these earliest surviving records.

- There is an asymmetry between the Chinese and the Indian systems based on the brightnesses of their determinative stars. For the Chinese system, the stars that are different are exclusively the faint stars. This is highly improbable by chance alone. But this exclusion is not in the Indian system. So, there must be some mechanism that makes this asymmetry.

- The obvious mechanism is that the original culture chose the stars for positional reasons, and they had to choose faint stars to match. When the receiving culture changed the determinative stars, they would have lost the positional reasons and would make their changes to get rid of the faint stars, selecting brighter stars instead. This is a reasonable argument that the first lodge system was invented in China.

CHINESE CONSTELLATIONS

- There are 283 Chinese constellations tiling the northern sky. This can be compared to the traditional 48 Greek constellations covering the same area. Implications for this are that the Chinese generally had small constellations involving a relatively few stars each, and many of the Chinese star pictures are made up of fainter stars, often so faint as to be nearly invisible. Furthermore, it's difficult to come up with a list of 283 significant items, so many of the Chinese objects and people in the sky are rather mundane and trivial.

- The creation of these constellations was probably early in the Han dynasty, around 200 B.C. Part of the reason for knowing this is that some of the constellations would be anachronisms for the earlier Zhou dynasty that ended in 256 B.C. Part of the reason is that a strong imperial system is being commemorated in the sky, and this only started with the Chin dynasty from 221 to 206 B.C. We also have no real evidence for any earlier invention before the Han dynasty.

- The nature of the Han constellations was not for positional astronomy purposes—for example, for calendars or astrology—and there are no stories or myths attached to most of them.

- Rather, the purpose of these constellations is to exemplify and glorify the system of imperial government. The star pictures were put into the sky to illustrate and justify the power of the Chinese emperor for everyone to see.

- This was an age when the first stable emperors ruled over all of China, when the concept of the imperial system needed reinforcing. These constellations were attributed to 3 high court officials who lived during the early Han dynasty or shortly before.

- The imperial skies were arranged primarily by the distance from the North Pole. The reason is that the star closest to the North Pole was likened to the emperor himself: The pole is the one place of stability, never moving, and the polestar never sets, connecting the emperor to the immortality of the gods. All the other stars are always in motion, circling endlessly around the emperor, and many of them setting.

CONSTELLATIONS FROM THE MILKY WAY

- Some of the classic Greek writers included the Milky Way as just another one of the constellations, and all cultures tell stories about the Milky Way as if it were just another constellation.

- Certainly, the Milky Way looks different from the other constellations, but it has the same functions for storytelling in the sky. Frequently, around the world, the Milky Way is taken to represent a river or a road. This is reasonable, given its long and thin shape.

- The Milky Way that we see across the sky is not uniform. It bulges bright and wide around Sagittarius and Scorpius, showing us the way to the center of our galaxy. There are bright and dim areas. In some places, the Milky Way has dark patches or long, dark rifts. We now know that these are caused by ordinary interstellar dust clouds, lying flat in the plane of our galaxy, blocking out the background starlight, creating silhouettes of the clouds.

- In the northern skies, the only blatant example is the Great Rift in Cygnus, where there is a dark streak running down the middle, paralleling the body of the Swan. While this rift is obvious if you look at it, there doesn't seem to be any historical mention of it in any culture.

- The southern Milky Way is effectively not visible from anywhere in Eurasia or North America. This is a bit of a shame, for northerners, because the southern Milky Way is bright and beautiful. It's also full of dark holes and dark rifts. The most famous of these is the so-called Coal Sack right next to the Southern Cross.

- The Australian Aborigines have formed a remarkably imaginative constellation out of the dark areas of the Milky Way. They see a long rift that leads up to the big dark circle of the Coal Sack. This is taken to be the neck and head of an emu. At the base of the long neck is a complex set of broad dust clouds that can easily be taken to be the body and legs of the emu.

- The Inca in Peru also identified the long rift ending near the Coal Sack as being another long-necked animal, the llama. The 2 bright stars Alpha and Beta Centauri formed the eyes of the llama.

Readings

Lankford, *Reachable Stars*.
Monroe and Williamson, *They Dance in the Sky*.
Staal, *The New Patterns in the Sky*.

Questions

1 The movie *Shrek* has an evocative dialog that hits all the key points of constellation invention. After watching the movie, itemize the higher issues relating to constellation formation that are highlighted or illustrated. The relevant scenes are when Shrek and Donkey are out by the fading campfire, looking at the skies above. These are about 4 minutes long near the middle of the movie. You can also try finding it as a film clip on the Internet by searching something like "Shrek constellation scene."

2 The construction of constellations is universal for all cultures. Why?

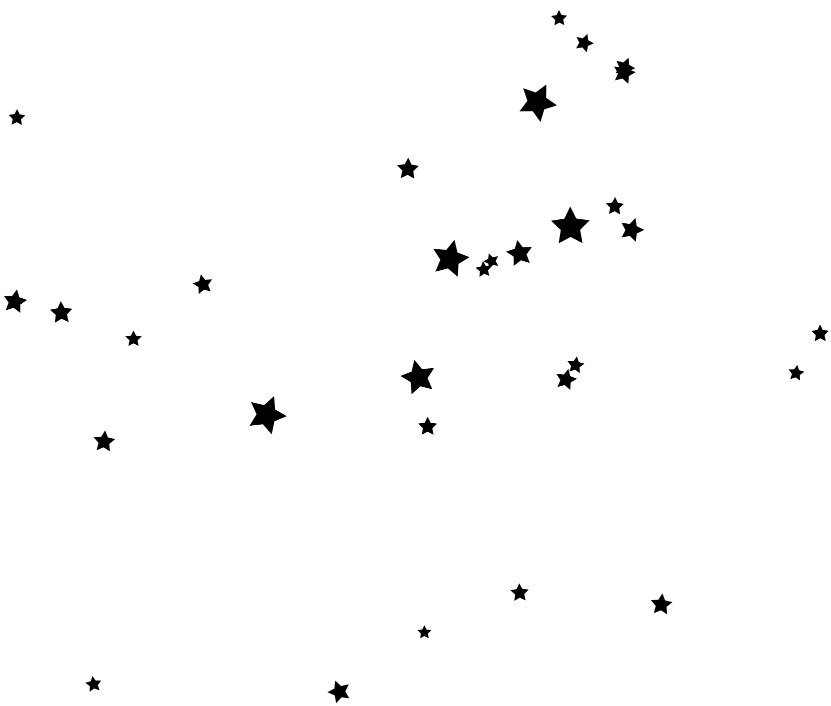
Activities

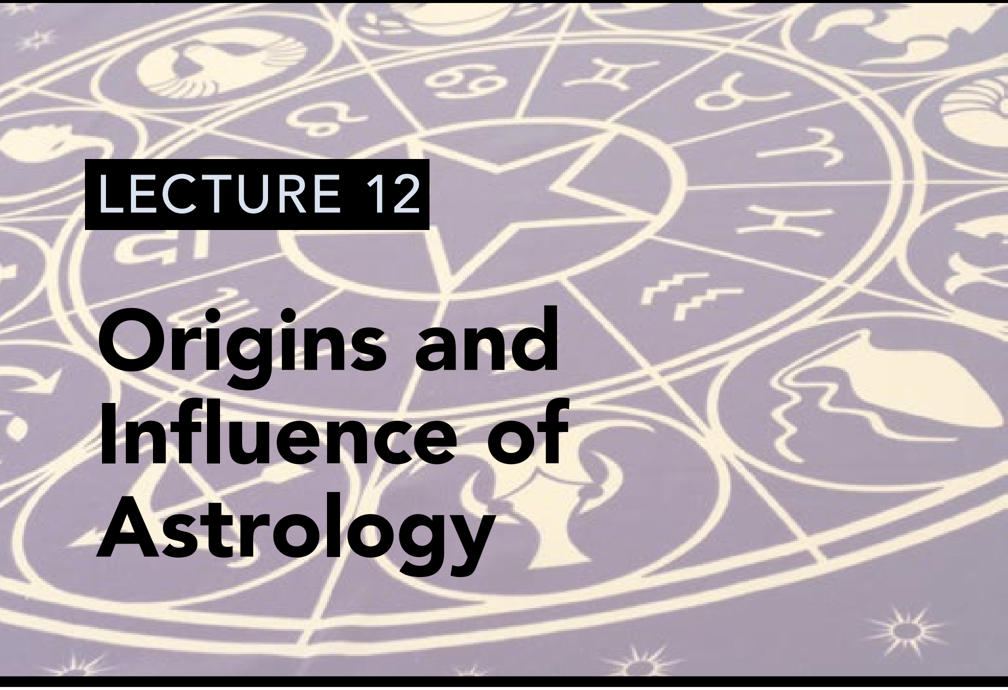
1 Invent your own set of constellations. Go outside on a clear, dark night; adapt your eyes to the dark; notice the many stars; and then make up patterns of your own for many constellations. The pictures and stories that you project up onto the stars can be whatever you want. Your constellations might be many or few, large or small, and perhaps telling some overall story or just a collection of many items. You can use any celestial object in addition to stars. What items will you immortalize, and what stories will you tell in your sky?

2 Invent your own constellation from a set of stars. The star map below is that of a real section of sky (in Cassiopeia), with the brightness of the various stars indicated by the size of the star symbol. Your task is to create your own constellation using some or all of the stars, give it a name, draw a sketch of how the figure is mapped onto the sky, and give a 1-sentence legend for your new constellation. Then, show the same stars to friends and have them independently construct their own constellation pattern and lore. Compare the constellations and lore.

Your constellation's name: ______________________________

Your legend: ______________________________





LECTURE 12

Origins and Influence of Astrology

Astrology is not a science, but it starts off by looking for causal connections between physical events, which could be looked at as the first step toward science. The original motivation for keeping records of the skies and the later motivation for measuring the stars and planets came from astrology. The primary topics of the science of astronomy happened to be similar to those of astrology, and leading practitioners of ancient astronomy generally acted as astrologers. This overlap continued into the 1600s. To understand ancient astronomy, we have to understand ancient astrology, which is the subject of this lecture.

ORIGIN WITH MESOPOTAMIAN OMENS

- Western astrology goes back to Mesopotamia, more than 4000 years ago. Fortunately, we have extensive sets of documents through that whole time, so we can chart its growth and function.

- Astrology started out as a simple collection of omens. The Mesopotamian version of omens was usually as simple as saying, "if *x* happens, then *y* will happen."

- Omens first started appearing as a well-established system sometime around 2300 B.C. The earlier records are pretty sketchy, so the use of omens likely started even earlier.

- By the time of the Old Babylonian kingdom, around 1800 B.C., we start to see compilations of omens. The earliest listed omens did not yet use the standard format of "if *x* happens, then *y* will happen." Archaeologists have found clay tablets with cuneiform texts listing omens, from a wide region around the Tigris-Euphrates.

- The same omens were repeated in many surrounding countries. The predicted results for these omens always concern the king, battles of the kingdom, agriculture, and the gods. The emphasis on the higher affairs of state suggests that the Old Babylonian astrology was not a folk tradition, but rather a product of a royal court or higher priesthood.

- There are more than 7000 of these omens that have survived on clay tablets. The full body of omens is probably much larger than would have been memorized in a purely oral tradition. This suggests that any systematic use of the proto-astrology had to await the development of writing and also that the system would be associated with the small fraction of the society that was literate.

- We also see that the Mesopotamian omens concern a wide variety of sky events. They were paying attention to novas, meteors, the apparent brightness of planets, the direction of the wind, and the color of the stars. The simple positions of planets are not yet a dominant concern. We're seeing a completely different basis than that used by later astrology.

- It's only toward the end of the era, around 500 B.C., that Mesopotamians start concentrating on the positions of the planets along the ecliptic, using their newly invented constellations of the zodiac.

- The Mesopotamians saw these omens as signs from the gods. But they didn't view the predicted result as being inevitable. It was a warning, rather than unavoidable fate, and the tablets tell us about rituals designed to stop the disasters.

- In the 5^{th} century B.C., the character of Mesopotamian astrology started changing. Soon after 500 B.C., the zodiac was created as 12 regions of equal size along the ecliptic. Planet positions were reported with regard to this zodiac.

- By 410 B.C., we have the first natal horoscopes, where planet positions are reported on the zodiac for the time of birth of a child. By around 200 B.C., the use of natal horoscopes was common in Babylon.

ASTROLOGY IN THE CLASSICAL WORLD

- The Greeks first started hearing about the Babylonian astrology around the time of Plato, around 370 B.C. Then, in 331 B.C., Alexander the Great conquered the Persian empire, which suddenly brought many Greeks in close contact with Babylonians.

- From 290 B.C. on, we start hearing of many Greek discussions and use of Babylonian astrology, which was a mixture of continuing Babylonian innovations and new Greek input.

- By around 100 B.C., we have what can be called Hellenistic astrology. This new brand of astrology was based on planetary positions within the zodiac. The highlight was the natal horoscope, cast for the time of a child's birth. A variety of invisible features were added in addition to the planets.

- After Hellenistic astrology was established, it quickly spread to other countries. Egypt under the Ptolemaic dynasty adopted the zodiac and horoscopes.

- Hellenistic astrology was enthusiastically taken up by both the Roman upper and lower classes. The person attributed with taking astrology to Rome was the Greek astronomer Posidonius, around 70 B.C.

- Horoscopes and predictions for the emperors became high politics. From the death of Julius Caesar in 44 B.C. to the time of the Emperor Marcus Aurelius in 180 A.D., imperial decrees expelled astrologers from Rome and Italy a dozen times. But they kept coming back. The Romans eventually spread astrology all around the entire classical world.

ORIGIN WITH CHINESE OMENS

- Chinese astrology is the other big traditional system. All aspects of the 2 major traditions are completely independent. Like for the Western system, we have enough documentary evidence going back far enough that we can see a detailed development and history. In broad strokes, the history of Chinese astrology progressed in parallel and on a similar timescale as Western astrology.

- The earliest record of Chinese astrology is preserved in the book *Shujing*, traditionally said to be compiled by Confucius around 500 B.C. Still, it preserves very old traditions. During the reign of King Chung-k'ang, with a nominal date of 2134 B.C., we hear that 2 astronomers did not predict a total solar eclipse and were beheaded as punishment. This suggests that Chinese astronomy is very old; eclipses were feared; there was already a bureaucracy high in the royal court; and the job of the earliest astronomers included astrology.

- Another way to get a look at the oldest Chinese astrology is through the lunar lodges, which are the system of 28 constellations spread out around the sky. They certainly date to before around 1100 B.C., and correlations in the positions of their determinative stars can be used to date the origin of the system to around 3200 B.C.

- The Chinese used the lodges to describe the position of the Sun, Moon, and planets in the sky. This could be for purposes of calendar making and/or astrology. Once a lunar lodge system is in place, then it's easy to start various forms of celestial divination.

- Other ancient records are found in the oracle bones, which are bones of oxen and turtles that are inscribed with a question for the gods. Large numbers have been unearthed from the Shang dynasty, dating to around 1100 B.C.

- The diviners were seeking guidance from signs in the sky, including solar eclipses, lunar eclipses, sunspots, novas, solar haloes, and comets. These show that the Shang kings made frequent sacrifices to stars.

- What we're seeing in China is the same situation as in contemporary Mesopotamia, where the astrological interest was in all types of sky phenomena, with little attention paid to the positions of planets.

- Chinese astrology and Chinese astronomy both have a strong character of being attached to the royal court. With the close link between state astrology and imperial power, astronomers were partly under orders of secrecy, while independent astronomers were outlawed.

- Their interests were largely for divination, which is to say that they were astrologers. They were key for the endless making of new calendars, but their motivation was to uphold the virtue of their imperial bosses as expressed by the mandate of heaven.

- They did keep large databases of observed astronomical phenomena, which were interpreted as omens for the ruler. And they invented constellations, but only as astrological symbols for the imperial power.

- In the Warring States half of the Chou dynasty, around perhaps 400 B.C., a new concept entered Chinese astrology: to connect particular constellations in the heavens with particular states in China. This was the *fen-yeh* system, or the so-called field division system. Each of the 12 states was matched up with either 2 or 3 of the 28 lunar lodges. Then, planet events in one constellation would have their effect only for that one state.

- The Warring States period was the time when planetary astrology came to dominate. The planet positions in the lodges were considered to influence individual states, by the court astrologers advising the kings. When all the states were collected into a single empire by the Chin and Han dynasties, the court astrologers would advise the emperor to make actual decisions about human welfare all around the parts of the empire.

ASTROLOGY IN THE CHINESE WORLD

- During the Han dynasty, around 2000 years ago, came the invention of what is now called the Chinese zodiac. This is the cycle of 12 animals—such as the rat, the ox, and the tiger—one each assigned to Chinese years.

CHINESE ZODIAC ANIMALS

- Each animal has a complex set of compatibilities and antagonisms versus the other animals, and this is used as a guide for advice on love and marriage. Further, the zodiac animals are assigned months, days, and hours.

- The procedure used by the astrologers was to locate the planets in the lunar lodges and check the date and time against the various calendar cycles. Then, the astrologer would determine the many connections, including with an element, a color, a totem animal from the large encompassing constellation, and a state or province within China and one of the 4 palaces. The astrologer would give the customer some interpretation based on these associations.

- Almost anything can be connected with almost anything. This gives the astrologer an incredibly large array of choices as to which connections to highlight. Presumably, the prudent astrologer would select the connections that most benefit their relation with the client.

INDIAN ASTROLOGY

- The Indian astrology system started out as a series of omens, sometime around the 1st millennium B.C. Their native form of astrology is described in the old texts of the Vedas. These included a wide variety of omens and rituals, all relating to a wide variety of celestial events.

- Sometime in the century around 100 A.D., Hellenized astrology was introduced. By 300 A.D., the Indian system had taken most of the key features from Western astrology.

- Its essence was to cast horoscopes based on the positions of the planets in the Babylonian zodiac. But Indian astrology has a variety of differences from Western or Chinese astrology.
  - The Indians keep up with precession. As the Earth's pole tilts around, the Western zodiac is tied to the positions of the equinoxes and solstices, while the Indian zodiac is tied to the stars.

  - The Hindus defined 2 invisible planets, Rahu and Ketu, which correspond to the points where the Moon's path crosses the ecliptic.

  - Indian astrology makes a central use of their lunar lodges.

  - All of the specific interpretations are different. They're targeted to abide by Hindu philosophies.

- In India, the nature of the connection between astrology and the stars is largely one of calculation. Due to the Hindu fascination with astrology, their astronomical sciences became largely computational and theoretical. They were focused mainly on doing a good job at eclipse predictions and deriving planet positions from Ptolemy's *Almagest*.

- Astrology is still going strong in India.

MAYAN ASTROLOGY

- A complex astrology system arose independently among the Maya in Mexico. They were centered in the lowland jungles of the Yucatán. The classic Mayan culture flourished from roughly 250 to 900 A.D. One of the few surviving Mayan texts is devoted to astronomy and the positions of the planets.

- Unfortunately, little is known of the details or the history of Mayan astrology. None of their constellations are known with any useful certainty. And scholars are even now arguing as to whether the Maya had some sort of a system of constellations that has similarities to the zodiac. We have no omen lists.

- Still, we can get a reasonable idea about the nature of Mayan astrology from various sources. For example, the city astrologers would get together in advance to prearrange great battles and whole wars based on the phase of Venus.

- Mayan astronomy was remarkable for its accurate measures of the planetary cycles, and they had reasonable methods to predict eclipses. Still, Mayan astronomy made few other advances. All of Mayan astronomy that we see is just observations of planet positions as a numerological exercise for astrology. Unfortunately, most Mayan records have been lost, so it's difficult to assess what else they did, or did not, know.

Readings

Campion, *A History of Western Astrology*.
Molnar, "Astrological Omens Commemorated on Roman Coins."
———, *The Star of Bethlehem*.
Ptolemy, *Tetrabiblos*.

Questions

1. How has astrology managed to survive for millennia despite its utter failure as a predictive science?

2. Why didn't the ancient Egyptians develop their own astrology?

Activities

1. Invent a new way to connect to the sky for divination. Modern Western astrology is pretty stereotyped, where a horoscope is cast featuring the planet positions (with respect to the zodiacal signs) being interpreted with nominally standardized rules. But there are myriad ways of using sky phenomena, and ancient astrologers from around the world have used many schemes. Just to use sky targets that are visible to the unaided eye, maybe you could base your invented system on the paths of meteors, eclipsing stars, sunspot counts and positions, the configuration of aurora, or the phase of the Moon. If you allow yourself to go

to sky events visible with telescopes, you could base your new astrology system on asteroids, the positions of exoplanets around nearby stars, or the configurations of the 4 bright Galilean moons around Jupiter.

2 What is the rate of real belief in astrology in modern and ancient times? Common expectations are that the ancient peoples of many cultures had a much higher belief rate in astrology than we have today. Nowadays, the usual polls in first-world countries return something like from 15% to 50% of the people believe in astrology, depending on the question asked and depending on the population. But are these figures accurate? Perhaps these numbers only reflect the people who had some vague interest in the past, with no real belief. Real belief would only be tested by the person actually making some nontrivial decision based on astrology.

To test the prevalence of real belief in astrology, you can run 3 trials: (1) Ask many of your friends 2 questions: "Do you believe in astrology?" and "When was the last time that that you based some decision upon astrology?". What do your statistics show you for this modern first-world population? (2) For current or recent events in the news, find and recognize any case that you can where someone has made a real decision based on astrology. For the events that you find, were the decisions for significant or trivial choices? With what you find, can you really say that 15% to 50% of the people believe in astrology? (3) The previous 2 trials were to get you started for thinking about the same questions as applied to ancient times. Historical settings have many astrologers, and presumably the influence of astrology (in its myriad of forms) was much more powerful in olden times, but can you pull out other real cases where people actually based real decisions on astrological advice?

LECTURE 13

Tracking Planet Positions and Conjunctions

The positions of planets have been the focus of most of astronomy as a science, even up to around 1900. For astrology, the central focus is on the exact placement of planets within the 12 uniformly sized zodiac signs. However, as you will learn in this lecture, there are other ways in which planetary positions can be used for celestial prophecy.

THE MANDATE OF HEAVEN

- In ancient China, around 2000 B.C., the mythical sage-kings were ruling relatively small confederations of tribes of Neolithic farming communities. The first of the Chinese dynasties, called the Hsia dynasty, was founded by the great engineer named Yu. The start of the dynasty was sometime around the middle of the 20^{th} century B.C.

- At that time, all 5 planets came to an incredibly tight conjunction. On 26 February 1953 B.C., they all were within an amazingly narrow distance of 4.3°. This is by far the tightest planetary massing from at least 3000 B.C. to 5000 A.D.

- The Chinese took the temporal coincidence between the conjunction and the start of the Hsia dynasty to be causally connected. For more than 2 millennia, this conjunction was idealized by Chinese calendar makers as being the start of time.

- The sage-king Yu was succeeded upon his death by his son. The dynasty continued with 18 kings. Over time, the kings became less just and less virtuous. The last king in the Hsia dynasty, Chieh, was a cruel tyrant whose reign was filled with decadence.

- The time was ripe for rebellion. The leader was from the vassal kingdom of Shang. Then, on 26 December 1576 B.C., 4 planets plus the Moon formed a tight mass within a circle of 6°. The people of the time concluded that this meant the start of a new dynasty. The leader of Shang went on to conquer, and he founded the Shang dynasty. Many stories are told about the virtue and justice of the first Shang king.

- This was the beginning of the pattern known as the mandate of heaven. According to this idea, a tight planetary conjunction would announce the start of a new dynasty, led by a virtuous ruler. Later rulers would become more decadent and cruel.

- At some point, heaven would withdraw the right of the dynasty to rule, a new tight planetary conjunction would appear announcing the change, a virtuous rebel leader would appear, the old dynasty would be overthrown, and the new dynasty would start. This was presented as a never-ending cycle.

MEASUREMENT OF POSITIONS

- China wasn't the only ancient civilization to track the planets. The measurement of positions of the Sun, Moon, and planets is called astrometry, and it was all important in ancient astronomy.

- For low-accuracy positions, we can just look up at the planets against the background stars. Such crude positions are perfectly adequate for many purposes—for example, spotting tight planetary conjunctions. For low- and moderate-accuracy Sun positions, we can use the sunrise or sunset position on the horizon, or the position of a shadow on a sundial.

- For middle-accuracy positions, some sort of sighting apparatus is needed. Stonehenge and other megalithic monuments used large rocks to set up sightlines toward the horizon.

- For higher-accuracy positions, you need something to measure angles. This could be 2 sighting sticks with some sort of a protractor measuring the angle between. These came in many varieties and can be generically called quadrants. The modern version of this is the sextant, used by navigators until recently.

SEXTANT

- For higher-accuracy positions, you also need some sort of a coordinate system to measure the position with respect to. This might be the position along the zodiac or lunar lodges. This might be one of the types of celestial coordinates that are closely analogous to the Earth's latitude and longitude system.

- For some purposes, the useful measure is of the position with respect to the horizon. Then, you need some sort of a coordinate system that gives the altitude above the horizon, as well as the azimuth, which is the angle around the horizon.

- All of these coordinate systems have some point or direction that is the zero from which all positions are measured. This is like the Greenwich meridian serving as the zero for longitude on Earth. In the sky, the zero longitude is often taken to be the spring equinox point, where the Sun is on March 21st. More correctly, the zero point is where the ecliptic crosses the celestial equator with the Sun going north. For the lunar lodges, the zeros for each lodge were defined by the determinative stars.

- For the most accurate positions, the Greeks and Chinese developed a complex device called the armillary sphere, which was a set of nested rings that could rotate and slide to represent the meridian, the celestial equator, the horizon, and the ecliptic.

ARMILLARY SPHERE

ACCURATE PERIODS

- One of the products needed from accurate positions was accurate periods for the planet motion. The great civilizations rose to the challenge.

- The Maya measured the period of Venus to an accuracy of 2 hours out of 584 days. The Babylonians determined the period of the Moon to the remarkable accuracy of half a second out of a month—just $\frac{1}{5}$th of a part per million. Hipparchus wrote a now-lost book giving the length of the year to an accuracy of 27 parts per million, and the Indians improved this to 6 parts per million. The Chinese found the period of Jupiter to within 55 minutes, which is 95 parts per million.

- It's remarkable that such precision can be achieved with essentially no equipment and no modern knowledge. All you need is a calendar with a reliable day count, some means of writing observational reports for an archive, and centuries of waiting.

- The idea is that for some first epoch observation, one of your ancestors wrote down an approximate position on a stated date. Then, you get the date when the target comes back to the same part of its cycle. With your reliable calendar, you can work out exactly how many days there are between the 2 observations. If you can count the cycles accurately, you can simply divide the time interval by the number of cycles and get the period. If the number of cycles is large, then you get an accurate period. If the number of cycles is very large, then you get a very accurate period.

NUMERICAL MODELS

- For various purposes, the planet positions had to be calculated with some sort of a numerical model. Such purposes include predicting eclipses in the future and predicting and postdicting the planet positions.

- The Babylonians developed several complex numerical methods to predict the planet positions. One method is described in what are now called the goal-year tablets, which were written in cuneiform in the 1st and 2nd centuries B.C. The idea behind this method is that each planet has cycles where the motions nearly repeat after some number of years.

- The second series of methods makes use of the steady progression of the planets as they circulate around the ecliptic. By looking at records from the previous year, they could simply make predictions for the next month or year. In reality, due to the planets having elliptical orbits, the motions aren't perfectly uniform. The Babylonian scribes accounted for this by any of several schemes, using moderately complex arithmetic.

- These Babylonian models can be characterized as empirical and numerical.

GREEK GEOMETRIC MODELS

- In parallel, the Greeks were developing planet models that were theoretical and geometrical. These distinctions, theoretical versus empirical and geometrical versus numerical, are key characteristics of Greek science. And they are the great strengths of Greek science for pushing forward, far past the questions in hand.

- For planet orbits, it started with Eudoxus, in Athens, in the generation between Plato and Aristotle. He proposed a geometric model for each planet, where the movement was described by the uniform motion of 3 or 4 nested spheres. The outer sphere rotated once a day, causing the rising and setting of the stars and planets. One of the inner spheres rotated with the period of the planet. Other spheres accounted for the backward, or retrograde, motion of the outer planets.

- The specific scheme proposed by Eudoxus, as best as we can tell, didn't actually work, even by his own standards. Still, Eudoxus's model was the pattern to follow.

- Improvements were made to Eudoxus's model, successively by Callippus, Aristotle, Apollonius, Hipparchus, and Ptolemy. These included adding more spheres and making some of them with offset centers. Furthermore, they started using observations to get specific values for all the model parameters and went on to use their specific geometric models to calculate planet positions.

- By the time of Ptolemy's *Almagest*, any astronomer had all the theory and numbers to work out the positions of all planets (including the Sun and Moon) for times far in the past and far in the future. Ptolemy even published a book, called the *Handy Tables*, that made it easy to calculate the planet positions. Ptolemy's work remained as the definitive exemplar for the next 1500 years.

THE USES OF POSITIONS

- All cultures need positions on the sky for the planets, the Sun, and the Moon. The following is a list of the many uses that ancient astronomers had for planetary positions.
  - Approximate planet configurations were interpreted as part of celestial divination.

  - Detailed planet positions for placement onto the zodiac or lunar lodges were needed for purposes of astrology.

  - The detailed positions of the Sun and stars throughout the day and night were required for ordinary timekeeping.

  - The position of the Sun defines the seasons, which are critical for all hunter-gatherer and farming cultures.

  - The detailed motions of the Sun and Moon are what define the calendar in all civilizations.

* Exact positions of the planets and stars are needed for land and sea navigation.

* Exact positions of the Sun and Moon, plus a good math model of their motions, are required to make eclipse predictions.

* Good positions are needed to work out orbits for the Sun, Moon, and planets, both to predict future positions and to understand the layout of our solar system.

* Workers used the average speeds of planets in the sky to order their orbits, and they used various observations plus geometric models to estimate relative distances within our solar system. This then set the picture and scale for the answers to the question of what our universe is like.

Readings

Carina Software and Instruments, *Voyager.*
Evans, *The History & Practice of Ancient Astronomy.*
Newcomb, *Astronomy for Everybody.*
Ossendrijver, "Ancient Babylonian Astronomers Calculate Jupiter's Position."
Schaefer, "Conjunctions That Changed the World."

Questions

1 Planet massings have often had dire interpretations by ancient astrologers. How will people and governments take the next planet massing of September 8, 2040, when the 5 major planets plus the thin crescent Moon are visible within a 9.5° arc in the evening dusk sky? Who will predict doom, and what type of disaster will be predicted? Will education and history have become broad enough that few will pay attention to the doomsayers?

2 Ancient astronomy has long provided excuses for predicting the end of the world. Doomsayers have long reveled in pointing to particular upcoming dates where some imagined astronomical event will lead to the destruction of most people or our planet. How many ends of the world have you lived through? List and count the dates on which someone predicted that you would die. With this being the modern count for one lifetime, you can get some insight into the power and frequency of doomsaying in ancient times.

3 The Babylonian invention of a part of integral calculus was never used by any other person, was never noticed by the outside world, never had any follow-on improvements, and did not lead to any broader applications—or, at least, no records even hinting at any extensions have survived. Why wasn't such a useful and wonderful discovery widely hailed and used by many?

Activity

1 Go outside at night, spot one or more planets, and follow their motion against the background stars. To start, you can learn where to look for the planets from magazines, planetarium programs, or Internet searches. The planets are usually bright and easy to see, even from inside a city with bad light pollution. You can usually see the planet motion from night to night, especially if there is some nearby background star for comparison. Week-to-week shifts are apparent without much trouble. It would help if you made a brief sketch of the planets with respect to nearby stars. Perhaps even take a ruler (or taut string) to hold at arm's length to make lines between stars for comparing the changing planet positions. Try plotting your measured planet position on a star chart. Look for the elongations of Venus and Mercury and the turnarounds and retrograde motion of the outer planets. Exactly these kinds of observations have been made by countless astronomers throughout the world in ancient times. Watch some pair of planets passing by each other (a conjunction). How would you interpret this?

LECTURE 14

Ancient Timekeeping and Calendars

Ancient astronomers had substantial daily impact on many people through a set of applications from the sky for practical needs. Ancient astronomers became the innovators and standardizers in areas including astrology, mapmaking, direction finding, navigation, timekeeping, and calendars. In this lecture, the focus will be on timekeeping and calendars.

TIME DURING THE DAY

- Timekeeping was important in ancient everyday life, just as it is today. Time during the day could obviously be defined and measured from the Sun. Between sunrise and sunset, time was measured by the position of the Sun. The day hours started at sunrise and ended when the Sun set.

- The length of the day changes throughout the year, so the ancients also changed the length of the day hour. In other words, to fit a given number of hours into the changing length of the daytime, the duration of each hour has to change throughout the year. So, the clock duration of 1 hour in winter is only 70% as long as 1 hour in summer.

- To get some sort of an accurate time, the Sun's position had to be interpolated between the ends of the daylight. The Sun is so bright that it hurts to look at it directly, so the only way to measure the Sun's position is to look at shadows.

- The earliest timekeeping device was a simple gnomon—that is, a stick stuck in the ground. By watching the position of the tip of the gnomon's shadow, the watcher could accurately pull out both the time and the date. For example, the position of the shadow tip at noon will move depending on the time of year, and the direction of the shadow will tell you the time of day.

- The time and date would have to be calibrated for each gnomon, always by watching the shadow positions on previous days. The origins of the gnomon are lost far back in Neolithic times or earlier, but its use has been worldwide.

- The other basic daytime timekeeping device is a sundial. But the sundial is basically just a fancy gnomon. There are many kinds of sundials, but what a typical sundial adds is permanent markings to indicate the time of day, and possibly more.

- Sundials are known at least to the 13^{th} century B.C. in Egypt. The Greeks, Romans, and Chinese had elaborate calculations and models more than 2000 years ago.

- But sundials don't work when it's cloudy. So, people living in cloudy climates have had to come up with other means to keep track of time in some uniform manner.

- A typical solution is a water clock, or clepsydra. The idea is to have a small steady flow of water into a cylindrical pot, such that the rise of the water level is linear with time. If you place a float on the water surface, and a stick with a pointer on the float, then you can read the time from a scale. Many arrangements were used.

- Other sorts of timers were standardized candles or incense sticks that take a given time to burn down. Around 2000 years ago, the hourglass was invented for timing intervals. This reappeared in medieval Europe and came to prominence as the critical timer aboard ships. Mechanical clocks with gears and pendulums became luxury items and were incorporated into civic architecture starting around 1000 years ago, in both China and Europe.

- Water clocks and mechanical clocks had to be reset frequently. And this reset could only be done with the sky. A typical procedure would reset it at every sunrise, because sunrise is an event that can usually be recognized with adequate accuracy even when the sky is cloudy.

TIME AT NIGHT

- At night, only the Moon, planets, and stars are visible. But the motions of the Moon and planets are too erratic for normal timekeeping, so the stars were the only thing left to work with. The stars move uniformly in the sky, so their motions can be viewed like a 24-hour clock rotating around the North Pole.

- As the night goes on, the star Kochab in the Little Dipper swings in a circle around Polaris, marking off time that can be read. This basic method was used in many cultures, with a variety of circumpolar stars. The Pointer Stars in the Big Dipper were popular for this.

- In the Late Middle Ages in Europe, a special navigational instrument called the nocturnal was made for telling the time at night. A person would hold it up at arm's length, view Polaris through the hole in the middle, rotate the handle to fit with Kochab or the Pointer Stars, adjust the dial to the right month, and then read the time.

- An alternative scheme was to define the time at night based on which stars have just risen. This is seen in the very old Egyptian system that used 36 constellations, called decans, spread all around the sky. We've lost the knowledge of which stars were in each decan. The basic idea was to define the time at night by the decan that had just risen.

NOCTURNAL

THE ASTROLABE

- A device called an astrolabe filled all the needs for ancient timekeeping, and much more. Astrolabes are flat bronze plates pivoting on a central rivet, with grillwork showing stars and the zodiac.

- Early versions of this were invented by the classical Greeks, but it became mature with the early Arab astronomers around 700 A.D. It was such a useful instrument that it spread throughout medieval Europe and China.

PERSIAN ASTROLABE

- To use an astrolabe, you hold it by the ring at the top so that the instrument is hanging vertical. There's a sighting rule, called an alidade, which you use to sight in on stars. Then, by reading the position of the alidade on the outermost scale, you can read the altitude of the star.

- The altitude you measure is a function of 4 things: the sky position of your target, the time of day, the day of the year, and your latitude on Earth. So, if you can somehow determine 3 of those quantities, then you can use the astrolabe to calculate the one you don't know. An astrolabe can work in the daytime with the Sun and at nighttime with any of the bright stars.

THE MONTH

- To measure long time intervals, it's very convenient to group days into longer units of time. It's not just coincidence that our longer units are roughly 30 days in length, which is the length of a lunar cycle, or that we give them the generic name of months. The units we call months are either tied to the lunar cycle or have some fixed length with roughly 30 days.

- Most lunar calendars have their months start with the first sighting of the thin crescent Moon in the evening sky. But there are exceptions. The Chinese calendar month starts on the day of the new Moon, when the Moon is invisible because it's too close to the Sun. A small fraction of the many Hindu calendars in India start their months on the date of the full Moon.

THE YEAR

- For longer amounts of time, the solar cycle is the obvious unit, because it's tied to the seasons, which govern many human activities.

- Many cultures kept year counts, and with this, they needed to set a zero year for the start of their year count. Most cultures always picked some real or imagined date far in the past as the zero year. Christianity, and then the Western world, has picked a date sometime close to the birth of Jesus. In addition, many cultures counted the years during the reign of each king.

- The central problem for calendars is that the solar and lunar cycles are not commensurate; that is, you can't fit an integer number of lunar cycles into one solar year. To use approximate numbers, the solar year is 365 days long. But 12 lunar months are 354 days long, while 13 lunar months are 384 days long.

- This means that if you try to come up with a calendar that keeps up with both the Sun and the Moon, the cycles get out of sync. There are 3 primary ways to approach these incommensurate cycles: lunar calendars, solar calendars, and lunisolar calendars.

THE LUNAR CALENDAR

- For a lunar calendar, the idea is that you have each year being exactly 12 lunar months. You forget about even trying to match the solar cycle. The years run together, cycling through the 12 lunar months endlessly. Each year is close to 354 days long.

- A lunar calendar that is in common use is the Islamic calendar, also called the Hijri calendar. The lunar year has 12 months of 29.5 days each, so the lunar year is 11 days shorter than a solar year. This means that the seasons of each Islamic month shift around in the calendar. After 1 year, Ramadan starts around 11 days earlier in the solar year. Approximately every 33 years, Ramadan cycles completely around all 4 seasons.

THE SOLAR CALENDAR

- A second approach to the calendar is to follow the solar cycle. Here, we just forget about trying to match the lunar cycle. The familiar idea of a solar calendar is that each year has approximately 365 days. The months are somehow fit in, but the so-called months have lost all connection with the lunar phases.

- The modern Western calendar is not the only solar calendar. Solar calendars were also prominent in ancient Egypt, India, Iran, and Ethiopia.

- A critical problem with solar calendars is that they don't have exactly the same length as the real solar year; that is, the real solar year is 365.2422 days, and this is a bit different from the effective calendar years of 365 or 365.25 days. This makes for some accumulated error between the calendar and the seasons. For holidays tied to the seasons, it can become embarrassing after a few centuries.

THE LUNISOLAR CALENDAR

- A third approach, called a lunisolar calendar, tries to follow both the lunar and solar cycles. The idea here is that you have each year consisting of either 12 or 13 lunar months. The extra lunar month is added about 1 year in each 3, and this makes the average calendar year come out close to the real solar year. And the months remain faithful to the phases of the Moon.

- This is the most common of ancient calendar systems. Prominent examples are the calendars of the Hebrews, the Greeks, the Chinese, the old Romans, the Sumerians, the Thai, and the old Germanic and Celtic peoples. The Australian Aborigines, American Indians, and sub-Saharan Africans all kept track of both lunar and solar cycles, although they didn't keep track of year counts, and their addition of extra months was always chaotic.

- This is the perpetual problem for all lunisolar calendars: how to work out when to add the 13th month. Without being able to predict and agree on when the extra month is to be added, cultures had large-scale confusion.

- A reasonable solution to is to use some cycle that predetermines what years are to have the extra month. With a good choice of cycle, the average length of the calendar year will closely match the seasonal year.

- The most common of these cycles is what we now call the Metonic cycle, after the Greek astronomer Meton, who introduced it in 432 B.C. This cycle was independently developed by the Babylonians and the Chinese. The Metonic cycle is accurate to 2 hours over 19 years, so it keeps the calendar in sync with the seasons for a long time, getting out of phase by 1 day every 220 years.

Readings

Aveni, *Empires of Time*.
Evans, *The History & Practice of Ancient Astronomy*.
Urban and Seidelmann, *Explanatory Supplement to the Astronomical Almanac*.

Questions

1 How many years will it be until the solar calendar gets out of synchronization with the seasons by 10 days? This was a burning question of high politics from Julius Caesar to the current pope. The issue arises when the effective length of the solar year in a calendar is not exactly correct, so that errors accumulate over time and holidays tied to the calendar come in the wrong season.

2 A hallmark of ancient astronomy is to use the Sun and stars for daily timekeeping needs. Around what year was the divide for when most common people switched from sky time to some mechanical substitute? When did people get clocks and wristwatches available for the masses? In the days before electrification, ship captains required mechanical chronometers for longitude, and rich people might have a pendulum clock, but when did the majority of people have frequent access to a non-celestial clock? Can we take this year as the real end time for ancient astronomy?

Activities

1 Make your own sundial. The simplest sundial involves putting a stick (called the gnomon) solidly into the ground and watching the position of the tip of the shadow. Ideally, the stick is straight and vertical, while the ground is perfectly flat, but this need not be so. For this simplest design, the tip of the shadow will be at the exact same location only for a 1-minute duration for 2 days per year. So, by observing the position of the tip of the shadow, you can simultaneously get the time and the date. But you have to calibrate the sundial. On many days a year, simply put some marks showing the tip position at many times throughout the day. You can generalize this by drawing smoothed curves through your points with marks for each quarter hour or so. Later, you can observe the shadow tip to interpolate between your curves and marks to get the time and date. After making your sundial, place it thoughtfully to allow it getting Sun year-round. Orient your sundial to the north either by looking at Polaris at night, looking at the shadow at a precalculated time of exact local noon, or using a magnetic compass (with corrections for your local magnetic deviation). To calibrate the sundial marks, you can do this empirically over one day, or you can take a template for sundials appropriate for your latitude from an Internet source. With this, you can make your own sundial, with (solar) time accurate to a few minutes.

2 Buy an inexpensive astrolabe replica. Then, take it outside and use it to tell the time from a Sun or star altitude. For your place, with some known qibla, determine the direction to face toward Mecca. The cheap replicas work just as well as the real ones—and maybe better, as you can optimize for your latitude and modern times. One great solution is to photocopy the templates in the back of James Evans's book *The History & Practice of Ancient Astronomy* (see the Bibliography), mount them pasted onto stiff cardboard, and bind them together with a rivet through the center. The astrolabe is on mean solar time, so to get to your watch time, you need to correct for your longitude, the equation of time, and daylight saving time. Also, beware that your astrolabe replica might be for a different latitude than you are.

LECTURE 15

The Lunar Crescent and the Islamic Calendar

Astronomers have always been the keepers of the calendars. And most of the calendars used in times past have been lunar or lunisolar calendars. And most of those calendars start their months each time with the first visibility of the thin lunar crescent low in the west just after sunset. This means that each community must somehow decide whether or not the crescent is visible on 2 or 3 nights out of every month, forever. So, one of the central tasks for ancient astronomers has been predicting and observing the crescent Moon—the subject of this lecture.

THE MOON'S MOTION

- Once every month, as the Moon goes around the sky, it passes close by the Sun. The instant when the Moon is closest to the Sun is the time of the new Moon. Then, the Moon is so close to the overwhelming glare from the Sun that there's no way it can be seen. But over the next day or so, the Moon pulls away from the Sun and can just barely become visible after sunset, low in the western sky. On the evening when the thin crescent is first sighted, the lunar month starts. The ancient astronomers had a difficult task to either observe or predict the visibility of the thin crescent Moon.

- To set up the problem, you first have to understand how the Moon appears on each evening after the new Moon. Consider the view toward the western horizon around sunset on the evening immediately following the instant of the new Moon.

- Before sunset, the Sun is up and the sky is very bright. The Moon is also up above the horizon, but the Sun's glare makes the nearby Moon invisible. Just after the Sun sets, the skylight starts to dim fast. The Moon might still be officially above the horizon, but there's no chance that it can be spotted against the bright twilight before moonset.

- The next night, the Sun will set and the twilight will fade just like it did the previous evening. But this time, the Moon will be much farther from the Sun. The Moon moves an average of 13° per day along the ecliptic, so the Moon will be 13° farther away from the Sun. Just as the Sun sets, the Moon will be fairly high in the sky, about 13° up over the horizon. But the twilight just after sunset will be much too bright to allow for any visibility of the crescent.

- As time goes on, the Sun sinks farther below the horizon, and the twilight dims. At some point, usually around 30 or 40 minutes after sunset, the twilight dims to the point where the crescent can be barely detected by ordinary human eyes. This time of visibility doesn't last long.

- As time goes on, the twilight gets darker. But the dominant effect is then that the Moon gets lower, and the moonlight is dimmed so much by the extra atmosphere that the Moon becomes invisible again, even before it sets. So, the Moon can be seen for only a few minutes. This is the first night of the lunar month.

- On the second night of the lunar month, sunset and twilight proceed the same. But now the Moon is yet another 13° farther along the ecliptic. This means that when the twilight gets dim enough, the Moon is quite high above the murk of the lower atmosphere. So, on the second night of the lunar month, the crescent is obvious to everyone and remains visible for more than half an hour.

PTOLEMY OBSERVING THE SKY

OBSERVING PROBLEMS

- The basic task of going out and seeing whether the thin crescent is visible is easy enough, but a variety of things can go wrong. Maybe the horizon is too high from nearby hills, or the low view to the west is blocked by trees. Maybe the observer is not looking for the few minutes that the crescent was visible, or they were looking in the wrong area of the sky. These are all false negatives, where the observer mistakenly reports that the Moon was not detected.

- More slippery are the false positives, where an observer wrongly claims to see the crescent. There are any of a variety of things up in the sky that can be mistaken for the crescent, including small clouds, very distant, still illuminated by the Sun over the horizon. False positives are very common among people who don't have a lot of expertise.

- Another characteristic problem is how to handle cloudy skies. If you take the lunar month to start with the first sighting of the crescent, then what do you do if the critical night is completely clouded or you have a one-week cloudy spell? One method is to have a fallback based on some calculation, whether crude or sophisticated. Another method is based on the realization that a lunar month really shouldn't be longer than 29 or 30 days. So, if the skies are cloudy on the 30th of the month, then the new month starts anyway.

ANCIENT AND MEDIEVAL PREDICTION ALGORITHMS

- Every culture with lunar months faced the problem of predicting the starts of the months. The astronomers of many cultures have worked hard for a solution.

- The only approach long ago was empirical. For this, the idea was to collect many observations. For each observation, the geometry of the Sun and Moon were calculated and then somehow quantified by 1 or 2 numbers. Finally, some line was drawn to separate the positive and negative sightings. This line then became the rule for predicting visibility.

- In ancient times, many empirical prediction rules were stated. The simplest of the empirical rules is based on the age of the Moon, or time since the exact instant of the new Moon, at the time of sunset. The rule is this: If at the time of sunset the Moon is more than 24 hours after the instant of the new Moon, then the crescent should be visible.

- Another simple empirical rule is very old, and it's now called the Babylonian criterion. This rule states this: The crescent Moon will be visible only if it sets more than 48 minutes after the Sun sets.

- During the Islamic Golden Age, from around 700 to 1200 A.D., science flourished and astronomy was strongly supported by the rulers. Astronomy was critical for 2 of the 5 Pillars of Islam and for various key functions of the government. The crescent visibility problem was central for several of these needs.

- The general need was to regulate the calendar. A very important need was to fix the start and stop dates for Ramadan every year so that everyone would know when to fast during the daytime. Another specific requirement was running the hajj pilgrimage to Mecca.

- Arab astronomers came up with more than 10 detailed algorithms for predicting lunar visibility. These rules placed limits on the longitude difference between the Sun and Moon required for crescent visibility, with the limits being various functions of the lunar latitude and its zodiacal sign. Using these, Muslim astronomers published more than 200 almanacs, handbooks, and books giving tables and explanations for their many prediction criteria.

- About a century ago, there was a revival of interest from historians of astronomy in predicting the crescent. These scholars didn't do anything different or better than their earlier Arab colleagues.

- The critical question for all of these empirical algorithms is how well they predict the first day of the lunar month. Using various old data sets, several researchers have measured that their error rate in predicting the first day of the lunar month is of order 50%. This really isn't acceptable for a calendar.

A MODERN PHYSICS SOLUTION

- The historical and empirical crescent visibility prediction models have failed. There is an entirely new method based on astrophysics. The idea is to construct a physical model for every step of the process: from the light being reflected on the Moon, to its passage through the Earth's atmosphere, and then to the detection by a human eye.

- The framework of the model is getting the geometry of the evening sky exactly right. For the last several decades, detailed and accurate models for the Sun and Moon have been developed that can be reliably calculated through all historic times.

- In addition, workers centered around Richard Stephenson, an astrohistorian at Durham University in England, have worked out the rotation of the Earth back to around 600 B.C. With this, the exact positions of the Sun and Moon can be calculated to excellent precision in the Earth's sky for any minute in ancient times.

- The most critical issue is understanding how much moonlight gets scattered during its passage through Earth's atmosphere. This dimming is called extinction and is quantified by what is called the extinction coefficient. For this, about half comes from the Rayleigh scattering of light off ordinary molecules of oxygen and nitrogen. This contribution can be precisely calculated.

- The biggest uncertainty comes from the extinction caused by varying levels of aerosols in our atmosphere. These aerosols come from sea spray, windblown dust, and pollen, and all the particles usually grow large with absorbed water as the relative humidity rises.

- Constructed by Bradley E. Schaefer, a general aerosol model that corrects for the site's altitude, latitude, relative humidity, and time of year can be used to estimate extinction due to aerosols. This is supplemented with real measures of extinction year-round for 330 sites worldwide, taken over multiple years.

- This model's procedure is straightforward. For the day in question, the program marches in time from sunset to moonset at 30-second intervals. For each time, it calculates the Sun and Moon positions, the Moon's brightness all along the cusps of the crescent, the amount of dimming by the air, the twilight sky brightness, and the probability that the Moon can be seen.

- This physics-based model has some huge advantages over the empirical models. First, the model can be applied to every location and time, with the local conditions fully allowed for. Another major advance is that the probability of detection can be specified, so we can know when we have an uncertain prediction and when the prediction is highly confident.

TESTING THE MODELS WITH OBSERVATIONS

- The nature of science is that we test our ideas against reality; that is, models and rules have to be compared to real measurements that can confirm or deny the predictions. Without this critical step, all you have is speculation, and speculative claims are all too common.

- In the past, the only data set to test models was a collection of crescent Moon sightings from one prolific observer in Athens, Greece, in the late 1800s. This had the disadvantage that lunar visibility models were then tested for only one set of atmospheric conditions. It's difficult to apply any such conclusions to anywhere else in the world. Furthermore, the data set had few non-sightings of crescents, and this hurts in defining the limits of visibility.

- So, some good and large data set is still needed to test crescent visibility models. The best new data set is from a series of 5 Moonwatches, run by Bradley E. Schaefer and LeRoy Doggett. For each Moonwatch, observers were recruited from all over North America to go out on one particular evening and report back whether they'd spotted the crescent Moon. More than 2500 people sent in reports and answered a detailed questionnaire about observing.

- The main product from the 5 Moonwatches is that the probability for spotting the crescent was measured for the whole map of North America. A curve on the map can be defined along which an observer had a 50% chance of spotting the Moon. These curves can then be directly compared to the various model predictions. This is the test that makes for science. For each Moonwatch, a map was created that shows the observed 50% curve as well as the predicted curves for various models.

- The data shows that the ancient and medieval crescent visibility models are wrong the majority of the time.

- Furthermore, the data shows that the algorithm gives the correct answer 90% of the time as to the date of the first visibility. The remaining 10% of the time is correctly identified as yielding a prediction with an uncertain answer. The dominant source of uncertainty is always the exact extinction coefficient, which cannot be predicted or postdicted with exactness. So, all the Moonwatch data proves that the algorithm is a sharp new tool, greatly better than the historical algorithms.

Readings

Doggett and Schaefer, "Lunar Crescent Visibility."
Schaefer, "Lunar Crescent Visibility."
———, "Lunar Visibility and the Crucifixion."
Schaefer, Ahmad, and Doggett, "Records for Young Moon Sightings."

Questions

1 How should a lunar month be started for an observer at high latitude?

2 Should a telescope or binoculars be allowed as an aid for visibility in determining the first day of an Islamic month?

Activity

1 Go outside and catch the first visibility of the thin crescent moon. This was a central task performed by astronomers of many nations for most months for much of the last 2 or 3 millennia. On a selected evening, roughly 1 day after the formal instant of the new Moon, stand outside with a clear and low horizon toward the west around the sunset direction. Start around 30 minutes after sunset, and keep watching the sky for the crescent. If you don't catch it the first night, then look again the next night. Beware of spotting some random contrail or star or plane or small cloud and thinking that you've spotted the crescent. How many hours after the exact instant of the new Moon did you spot the Moon? Find an authoritative Islamic website that announces the start of the Islamic month as based on accepted observations for your country, and compare to see whether its claimed first sighting is reasonable. After trying for many months, can you spot the crescent when the Moon is younger than 24 hours, or 20 hours?

LECTURE 16

Ancient Navigation: Polynesian to Viking

In this lecture, you will learn about direction finding and navigation, a fundamental and often critical need for all ancient societies. The Polynesian navigators were notable for this, starting more than 5000 years ago, when they guided their seagoing canoes on oceanic voyages between Pacific Islands thousands of miles apart. They developed direction finding and navigation by the stars to a high point, allowing for safe landfalls on small islands across vast stretches of open ocean.

FINDING NORTH

- The magnetic compass was invented in China around 1050 A.D., and it made it to Europe only around 1300 A.D. So, everyone earlier was forced to be a folk astronomer.

- It's easy to use the sky to get approximate directions. The Sun rises near the east, is highest around noon toward the south, and sets near the west. The North Star is to the north.

- In the daytime, knowing the direction of the Sun is easy, even if it takes a bit of thinking to interpolate to some estimated time of day. And on a good fraction of cloudy days, the direction to the Sun can still be worked out reasonably from consideration of the light on the clouds.

- At night, you can use knowledge of a few stars or constellations in the same way. They rise in the east and set in the west. The trick is that you have to recognize the stars to know whether they are rising or setting, or when in between. To recognize the stars, you need constellations. You also need knowledge of the time of night and the day of the year.

- For the Northern Hemisphere, the polestar can be used. The direction north is below the North Celestial Pole. For the last 2 millennia, the star Polaris has been pretty close to the North Pole. Polaris is in the Little Dipper, and it's the end of the handle, or the end of the Little Bear's tail. Polaris isn't a particularly bright or distinctive star, so it takes a bit of knowledge to recognize it. To help, you can use the 2 Pointer Stars of the Big Dipper, and these point to Polaris.

- But Earth's axis of rotation wobbles, like a spinning top that has started to lose speed. This wobble is known as precession, and it's very slow. It takes 26,000 years for a single precession wobble of the Earth's rotation to trace a complete circle on the sky. This is why the position of the North Pole shifts with respect to the stars.

- We can roll backward on the clock and the sky to see what this looked like. If we go back more than 2000 years ago, the Earth's north axis was between the 2 Dippers. For approximately finding north, it's adequate to simply look up toward either of the 2 Dippers.

- But for better precision, it can make a big difference whether you are sailing by a north direction based from the Big Dipper or the Little Dipper. This made for a standing debate over whether to follow the Big Dipper or the Little Dipper.

- Navigation is needed both on the land and the sea. On land, celestial direction finding was needed when going across unfamiliar terrain, with no landmarks or trails. Nomads crossing the desert and Eskimos moving around the Artic used celestial navigation. Without direction finding, it's easy to get turned around and wander in circles.

DEAD-RECKONING SAILING

- The first sailing undoubtedly had the first navigation principle simply being to sail along the coast, with all its twists and turns. If your destination was on the same landmass or island as your home port, then this coasting was a guaranteed method of finding your way. And this works even when the skies were cloudy. This coasting strategy is easy, and common.

- But coasting is inefficient, and sailors can be tempted to cut across some body of water to make perhaps huge savings of time. Coasting fails completely when you are going to or from islands or between continents. So, a more sophisticated navigation strategy is required.

- The next step up is to keep track of your position, relative to your start position, by knowing your direction of travel and your distance traveled each day. Adding up these daily movements, you can work out your position. This method is now called dead reckoning.

- For this method to take you to a specific destination, you must have some prior knowledge about where your destination is located in relation to your starting point. For dead reckoning to work, you must use direction finding. And on the open seas, your only hope is up in the skies.

- Ancient Greek merchants had it easy. They could head south from Greece, and sooner or later they would come upon the coast of Africa, a very big target. Then they'd simply follow the coast of Africa toward the east until they reached Alexandria. But much greater accuracy is needed if your target is a small island.

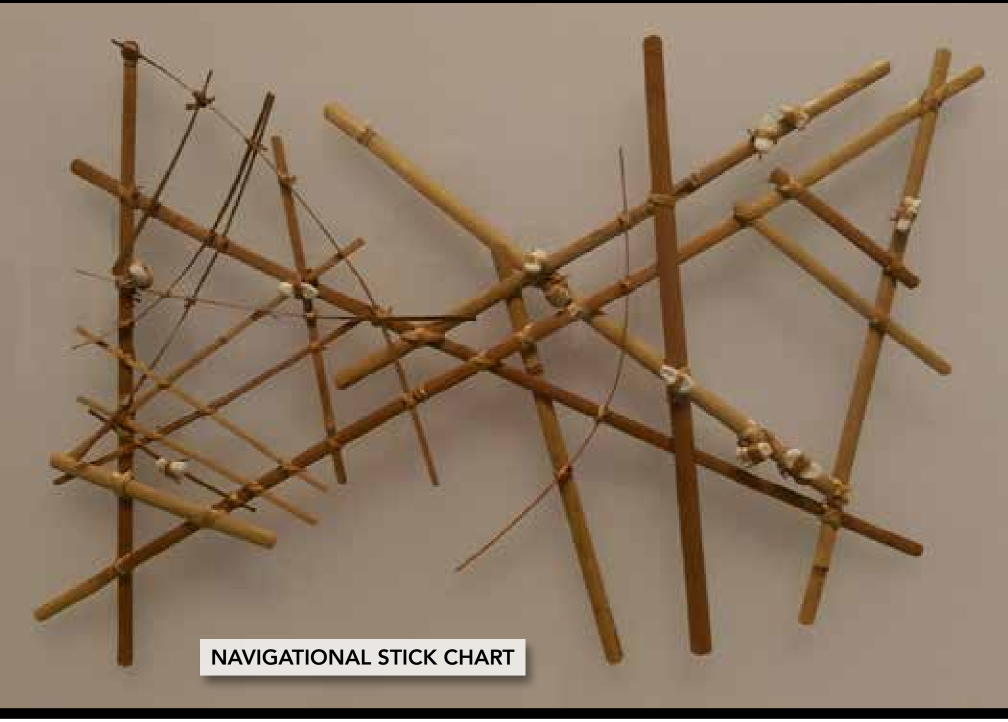
POLYNESIAN NAVIGATORS

- Starting roughly 5000 years ago or more, Polynesians began spreading out to the many islands scattered across vast distances in the South Pacific. The Polynesian navigators were remarkable in their skills. Their navigation was essentially dead reckoning. They aimed their canoes in the correct direction and sailed the correct number of days.

- Their basic directions could only come from the stars. They conceptualized the directions by a star compass. In particular, they memorized many stars and the directions that these stars rise and set. Whenever one star in the desired direction was not visible near the horizon, another memorized star would come along to serve as an alternative definition.

- The Polynesian navigators connected series of stars, stretching along a star path. For teaching purposes, the master navigators constructed stick charts to encode island positions and sailing directions. These stick charts were never taken on real voyages.

- These star-rise directions depended somewhat on the latitude. So, the navigators memorized many particular star paths to provide the direction finding appropriate for each route across the ocean. These



NAVIGATIONAL STICK CHART

star paths are the key and critical element for Polynesian navigation. All you had to do was sail in the direction of the star path and sooner or later you'd make landfall at your destination.

- The star compass wouldn't work on cloudy nights. Fortunately, it's infrequent to have completely cloudy nights. Often, the navigators could get enough of a glimpse of stars that they could still get an accurate direction. When no stars were visible, they would take their cues from the directions of the wind, current, and swells, remembering the angle of attack from the last time they had a star sighting.

- During the daytime, they would have used the Sun. But the Sun's motion is more complicated than it is for stars, because the Sun moves from day to day.

- Dead reckoning over large distances is notoriously difficult, because of the tendency to accumulate errors. So, the Polynesians had one more astronomical tool that was critical for correcting these errors and homing in on their targets over very long trips: the latitude of their destination.

- They noticed that each island has particular stars that pass exactly overhead. By watching the stars pass through the zenith at night, they could see whether they were north or south of their destination. Polynesian navigators memorized long lists of stars and islands, forming a mental and celestial map of the Pacific. This saved them from accumulating errors in their dead reckoning.

- The Polynesian navigators used a variety of other tools that were critical once they got near their target. They could recognize the proximity to land by spotting particular species of seabirds that return nightly to land or by spotting the characteristic clouds that form over islands. The navigators only had to use their astronomy to get within 50 to 100 miles of their target, and then land- and sea-based cues could take over.

- The Polynesians used a general technique called latitude sailing. The idea was that the ship starts going north or south until it reaches the known latitude of the destination and then keeps sailing in the correct direction, east or west, at the correct latitude until they reach the target location.

- Latitude sailing is of little use for many situations. For example, while sailing in the Mediterranean, everything is sort of near the same latitude, and there are plenty of islands and landmarks to use for dead reckoning. But for crossing one of the big oceans, latitude sailing was the only way to guide your landfall.

VIKING NAVIGATORS

- The Vikings were also great navigators across the open seas. From 800 to 1100 A.D., they pioneered routes for island hopping and crossing the north Atlantic. Good navigation was vital for their economy, and it meant life or death for the sailors. Like the Polynesians, the Vikings were dead-reckoning navigators, who used latitude sailing to fine-tune their landfall.

- The Vikings made their long-distance voyages during the summer, to benefit from favorable weather. But they're far to the north, where traveling in summer means that the Sun sets very late, or not at all, with twilight conditions lasting all night. So, the Vikings often could not use stars to determine their latitude. The only alternative was to use the Sun.

- To determine the latitude from the Sun's position in the sky, the Vikings invented and used a Sun compass. The basic idea was simply that of a gnomon, a simple stick pointing vertically out of a round disk. The disk was held horizontally and had curves scratched on it. The idea was to use the Sun's shadow of the stick cast onto the disk to measure the Sun's altitude, and hence the latitude.

- Like the Polynesians, the Vikings also made heavy use of non-celestial clues as they neared their destination. Still, the basics of Viking navigation were direction finding for dead reckoning and latitude sailing for homing in on their destination. These all came from the skies.

LONGITUDE SAILING

- Latitude sailing works, but it's still inefficient. In a variety of situations, once you reach your target latitude, you then don't know whether to sail east or west. And the latitude sailing path was always longer than a straight line path. Furthermore, when you are running along a latitude circle, you don't know when you'll run aground on a shore if you sail at night.

- Mariners from many nations focused on the importance of longitude from around 1500 A.D. on. This turned into a large-scale international enterprise, involving many of the great astronomers of the era.

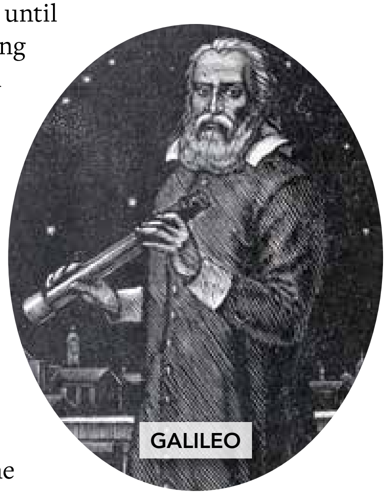
- In essence, measuring longitude requires knowing an accurate time while measuring the altitude of some target in the sky. This is based on the Earth rotating 360° in 24 hours, so it rotates 15° in 1 hour and 1° every 4 minutes. If you measure the altitude of a star or the Sun at some known time, this can be translated into your longitude.

- The measuring of celestial altitudes is easy enough, so the trick is to somehow know the time for your zero of longitude. In the early days, many zero longitudes were used. These are also called prime meridians. In 1884, an international convention adopted Greenwich, near London, as the prime meridian for the world.

- The navigators and mapmakers had to somehow have a way of knowing the accurate time for their home port. A 4-minute error in time would translate into a 1° error in longitude, or around 60 miles east-west.

- All the schemes from the early 1500s up until the mid-1700s involved the exact timing of particular astronomical events, such as lunar eclipses. But lunar eclipses are infrequent. So, for practical navigation, astronomers had to develop accurate predictions for precisely timed events that some mariner could often see on a rocking ship.

- Soon after the discovery of the telescope, Galileo proposed to use the motions of the 4 moons around Jupiter, and many astronomers from 1514 to 1770 made calculations of the Moon passing close by stars.



GALILEO

- The problem of longitude was eventually solved by a clockmaker, rather than by any of the massive astronomical efforts. Around the 1760s, clockmaker John Harrison in England constructed a watch that was robust and accurate, so that it could be carried on a long sea voyage, keeping the time of the home port.

Readings

Evans, *The History & Practice of Ancient Astronomy*.
Finney, "Nautical Cartography and Traditional Navigation in Oceania."
Lewis, *We, the Navigators*.
Morison, *Admiral of the Ocean Sea*.
Schaefer, "Vikings and Polarization Sundials."
Sobel, *Longitude*.

Questions

1 How difficult is it to set up the star paths used by Polynesian navigators? Once you know the direction, then while still on land, set up some trivial sight line to that direction, and simply spend a few nights watching what stars rise in that direction. The difficult part will be in knowing the correct direction to sail, and this can only be learned from empirical experience.

2 Ancient astronomy has a basic suite of 3 techniques in its navigation toolkit: dead reckoning, latitude sailing, and land-finding cues when near the destination. The first 2 can only be done with information from the sky. How many independent inventions of this basic tool kit were made around the world?

Activities

1 Go outside and measure your latitude. This will give you a good feel for the type of activities conducted by old-time navigators and ancient astronomers. Here are 2 suggested methods:

a First, measure the altitude of Polaris above the northern horizon (Θ_{Polaris}). The altitude of the North Pole above your (flat) horizon equals your latitude (λ). Polaris is pretty close to the North Pole, so the altitude of Polaris equals your latitude. So, roughly, $\lambda = \Theta_{\text{Polaris}}$. There are two nonstandard methods for measuring the altitude that readily get an accuracy of better than ½° with little effort. The first of these involves taking a box outside and placing it on a flat table. Sight along the south edge of the table over the box and move the box back and forth until Polaris appears exactly on the line from the table edge to the box top. Then, use a ruler to measure the distance from the edge of the table to the base of the box ($L_{\text{horizontal}}$) and the height of the box (H_{vertical}). The altitude of Polaris (Θ_{Polaris}) is obtained from the equation $\tan \Theta_{\text{Polaris}} = H_{\text{vertical}}/L_{\text{horizontal}}$.

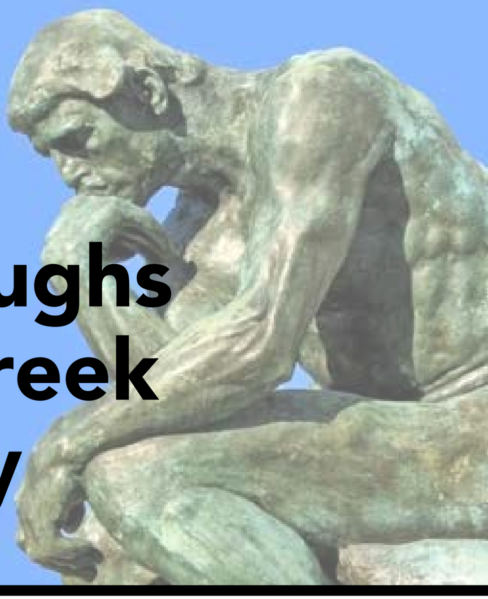
The second method to measure altitude is to use the box top and a door frame with a north view. Hold the box top up to the doorframe, sight along the top to have Polaris appear to skim evenly along the top, hold the box top firmly to the doorframe, and run a pen vertically along the doorframe, leaving a mark on the box top. Take the box top inside and measure the angle between the line and the box top edge. This is most accurately measured by using a ruler to construct a right triangle with your line as the hypotenuse and then measuring the sides, and then using the simplest trigonometry to calculate the angle. This angle is $90° - \Theta_{\text{Polaris}}$.

b The second method to measure your latitude involves measuring the length of the noontime shadow from a vertical pole. You'll need to observe at the time of local noon, which is different from clock noon, depending on the time of the year and your longitude. You could look at some independently known time of local noon, or you could simply keep measuring the shadow length for about 30 minutes and then select the time with the shortest shadow. You can make your own gnomon by erecting a vertical pole in the ground, but it is likely better to use a stop sign pole or similar structure. Make sure that the ground is pretty level. At local noon, measure the length of the noon shadow (L_{shadow}) and the height of the pole (H_{pole}). The altitude of the noon Sun (Θ_{Sun}) is then given by $\tan \Theta_{Sun} = H_{pole}/L_{shadow}$. This altitude depends not only on your latitude (λ), but also on the declination (δ_{Sun}, like a celestial latitude) of the Sun. On the day of the equinox (i.e., around March 21 and September 22), we have $\delta_{Sun} = 0°$, while on the days around the solstices, we have $\delta_{Sun} = 23.4°$ (for June 21) or $\delta_{Sun} = -23.4°$ (for December 21). For days in between, to get δ_{Sun}, you can do a simple sine wave calculation, use planetarium software, or look up the value in an almanac. We have $\lambda = 90° - \Theta_{Sun} + \delta_{Sun}$ if the Sun passes south of your zenith and $\lambda = \Theta_{Sun} - 90° + \delta_{Sun}$ if the Sun passes north of your zenith.

2 Muslims are obliged to pray 5 times daily, all in the direction of Mecca (the qibla). So, mosques around the world usually have the main axis of their building pointing toward Mecca. Check out the orientation of mosques. Does the main axis of the building point along the great-circle line to Mecca? You can go to a local mosque or check out the orientation of many of the famous and big mosques throughout the world by using a satellite-imaging package to get an aerial view of the building.

LECTURE 17

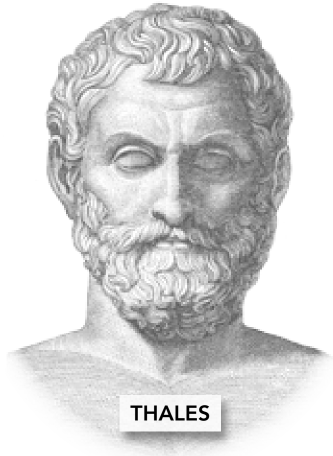
Breakthroughs of Early Greek Astronomy



In 600 B.C., the Greeks were a rather ordinary Early Iron Age society, interested mainly in farming, warfare, politics, and legends. Then, over the next 4 centuries, Greek genius burst forth in all fields. It started by replacing the gods in the sky with physical explanations and then inventing the beautiful system of geometry. Astronomy led the way on both of these. By 200 B.C., the Greeks had worked out plausible ballpark estimates of the sizes, distances, and natures of the Earth, Moon, Sun, planets, and stars. In this lecture, you will discover how this transition has had great importance for understanding the foundations of modern science.

THALES'S ECLIPSE

- The first glimmer of the Greek genius for science is traditionally encapsulated in the story of Thales predicting the total solar eclipse that stopped the 5-year war between the Lydians and the Medes.



THALES

- Herodotus's story of Thales's eclipse also tells us about the state of astronomical knowledge at the time. It tells us that the people still saw the heavens as being run by the gods and that Thales was just daring to order and predict the motions of the gods.

- The exact nature of Thales's prediction has long been controversial for scholars. For the last 2 centuries, astronomers have tried to calculate the time of Thales's eclipse. A critical trouble with this has been working out the exact rotational position of the Earth; that is, the exact length of the day is slightly variable, and over the centuries, small changes will accumulate.

- Uncertainties in this correction translate into uncertainties in the east-west positions of the eclipse centerlines. There's only one eclipse that is a good candidate, and that is one from 28 May 585 B.C. And this is good, because we also hear from Roman encyclopedist Pliny the Elder that the Thales eclipse occurred in a year that translates into 585 B.C.

- Pliny tells us that Thales's prediction was made in the previous year, but what he says is that Thales predicted the eclipse to within the year. That's rather vague—and it's long been regarded as problematic.

- Most of the ways that astronomers can imagine to predict an eclipse would give a particular day or month, or perhaps pair of months. So, we don't know how or why Thales could make a prediction that spanned an entire year.

- The general thinking is to take the report at face value and suppose that Thales must have used some sort of an eclipse cycle; that is, eclipse dates have patterns, and a pattern might have been recognized. Then, with a list of past eclipses, the pattern could be extended to the future.

- With modern calculations, we can work out the solar eclipses visible from the Greek world. Some fraction of the eclipses on the list would have been clouded out. Even if he saw them all, detailed lists show that there was no apparent pattern that Thales could have used.

- Many astronomers and historians have concluded that Thales could not have made any sort of a valid prediction. But this might be too harsh. Perhaps Thales made a good prediction, yet Herodotus did not give an adequate report. Perhaps Thales made a prediction with some sort of a nonstandard method, and his method happened to work. Or perhaps Thales made a prediction on some poor basis, yet he got lucky.

GEOMETRY

- Thales was identified by the classical Greeks as being the first mathematician. He was from Miletus, on the coast of Asia Minor, in what is now Turkey. He certainly went to Egypt, and learned their mathematics. Modern scholars are still debating whether Thales had any knowledge of Babylonian mathematics.

- Egyptian mathematics of the time had an awkward system of fractions. Egyptians could solve simple algebra equations, including the solution of the quadratic equation. For geometry, they could calculate areas of triangles and rectangles. But they got the wrong answer for the area of a quadrilateral, and they could only approximate the area of a circle as the area of a circumscribed octagon.

- The Egyptians aimed at practical problems, getting math answers by intuition and approximation and experiment. All the work was numerical, with scant theory. The scribes solved specific practical problems, with no generalizations.

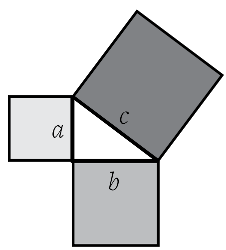
- Thales brought home the humdrum numerical algebra of Egypt. Yet Thales was soon presenting geometric proofs of general theorems, including Thales's theorem and the intercept theorem.

- Thales was doing something new in the world. He constructed logical proofs giving universal truths. He was rising above the specific cases of the Babylonians and Egyptians, and he generalized to cover all cases.

- This theoretical construct is immensely powerful for pushing forward to theorems that no empiricist could have imagined. This is the step that turned mathematics into a beautiful and wonderful logical structure of immense power.

- Once Thales had shown the way, his genius was immediately recognized broadly throughout Greece. He had students who started using his deductive geometry to make advances. Scholars around the Greek world continued making stunning advances in geometry theory.

- Pythagoras, who flourished around 530 B.C., founded his own school of mathematics and philosophy. Pythagoras was the first to prove what is now called the Pythagorean theorem, which says that the sum of the squares of the sides of a right triangle is equal to the square of the hypotenuse ($a^2 + b^2 = c^2$, with a, b, and c being the lengths of the sides).



- Around 300 B.C., Euclid wrote *The Elements*, which collected all the scattered theorems of geometry into a single book. Euclid's book contained essentially all of geometry, remaining definitive and exhaustive until the 1800s.

- Archimedes was an astronomer, mathematician, physicist, and inventor who lived in Syracuse, on Sicily, who solved many now-classic geometry problems and calculated a good approximation of pi.

- With all this work on geometry, the Greeks had a strong tool to build the rest of their science.

TAKING THE GODS OUT OF THE SKY

- Before Thales, the Greeks thought that they lived on a flat Earth, with a sky full of gods, and that all of nature was just some personal aspects of the gods. With such a worldview, there's little that can be done for understanding or advancement.

- Thales was the first person that we know of to break with this worldview. Thales tried to explain natural phenomena without reference to myths or legends. For example, he speculated that the Earth was floating on a vast ocean and earthquakes were caused by waves in that ocean; that is, Thales replaced Poseidon with waves.

- Anaximander succeeded as the master of Thales's school in Miletus sometime before 546 B.C. He made the Sun and Moon into massive bodies far away from Earth. This replaces the chariots of Apollo and Selene with large physical objects.

- Anaxagoras was born on the coast of Asia Minor and moved to Athens around 480 B.C. He became a protégé of Pericles. Plato tells us that Anaxagoras discovered the true causes of lunar phases, lunar eclipses, and solar eclipses. For his model, he had to take the Earth, Moon, and

Sun to be spherical bodies. The rest was just logic deduced from a geometrical model of what happens as the Moon goes around the Earth. This is quintessential Greek science.

- In 450 B.C., the Athenians put Anaxagoras on trial for impiety against the Greek gods; that is, he was charged with taking the gods out of the sky. Pericles spoke in his defense, but Anaximander was still forced to go into exile for the rest of his life.

- Fifty-one years later, the great Greek philosopher Socrates was also put on trial, again with the official charge being impiety. He was found guilty and was soon executed by drinking poisonous hemlock.

- The great Greek philosopher Aristotle wrote extensively on science of all types. In 350 B.C., he wrote a book called *On the Heavens*, in which he championed the spherical Earth, the crystalline spheres for the planets, and his own new model for how the spheres worked. In 322 B.C., he was officially charged with impiety. Rather than face trial and execution like Socrates, he chose to go into exile and died soon after.

NATURE OF THE EARTH, MOON, AND SUN

- The early Greeks—including the great Thales—thought of the Earth as flat. The classic Greeks attribute the realization that the Earth is spherical to either Parmenides or Pythagoras, both around 500 B.C. By the time we get to Aristotle, around 350 B.C., he is reporting 3 proofs that the Earth is round. There was no looking back from this, and the idea spread widely through Eurasia.

- For the size of the Earth, in 350 B.C., Aristotle tells us that certain mathematicians had obtained a circumference of 400,000 stadia. Sometime around 250 B.C., Archimedes tells us in his book *The Sand Reckoner* that some unnamed astronomer got 300,000 stadia for the circumference. Both of these figures are a bit large, but they aren't too far off.

- Around 250 B.C., Aristarchus of Samos came up with a remarkably insightful method to calculate the sizes and distances for both the Sun and Moon. With simple observations plus a good geometric model, Aristarchus laid out the basic size of the solar system.

- Around 240 B.C., Eratosthenes made a famous measure of the circumference of the Earth. In a wonderful analysis, he made a geometric model of the Sun, Earth, and shadows. His circumference of the Earth was 250,000 stadia, which is about right.

- It took a while, but the Greeks finally got the size and shape of the Earth right. With this, the sizes and distances of the Sun and Moon were then determined. And all this was done by 200 B.C.

PLANETARY ORBITS

- The planets had long been regarded as gods, and also as simple points of light on the sky. Around 350 B.C., Eudoxus was the first person to go past this. He constructed a geometrical model for the orbits of planets. Eudoxus's configuration of spheres wasn't even internally consistent, but his basic setup provided the ideal scenario for the next 1800 years.

- Callipus and Aristotle both made modifications, and the system was up and running. To get things to work, Aristotle had to construct a system that had 47 interconnected spheres.

- Around 200 B.C., Apollonius of Perga added epicycles, which are rotating spheres whose centers are anchored on another rotating sphere. The idea was to explain the backward motions of the planets, which is called retrograde motion.

- By 200 B.C., a pretty sophisticated view of planetary motion had been developed by the Greeks. This was all done as a geometrical model. So, they had a complete and reasonable view of the size and nature of the entire solar system.

Readings

Aratus, *Phaenomena*.
Dicks, *Early Greek Astronomy to Aristotle*.
Evans, *The History & Practice of Ancient Astronomy*.
Evans and Berggren, *Geminos's Introduction to the Phanomena*.

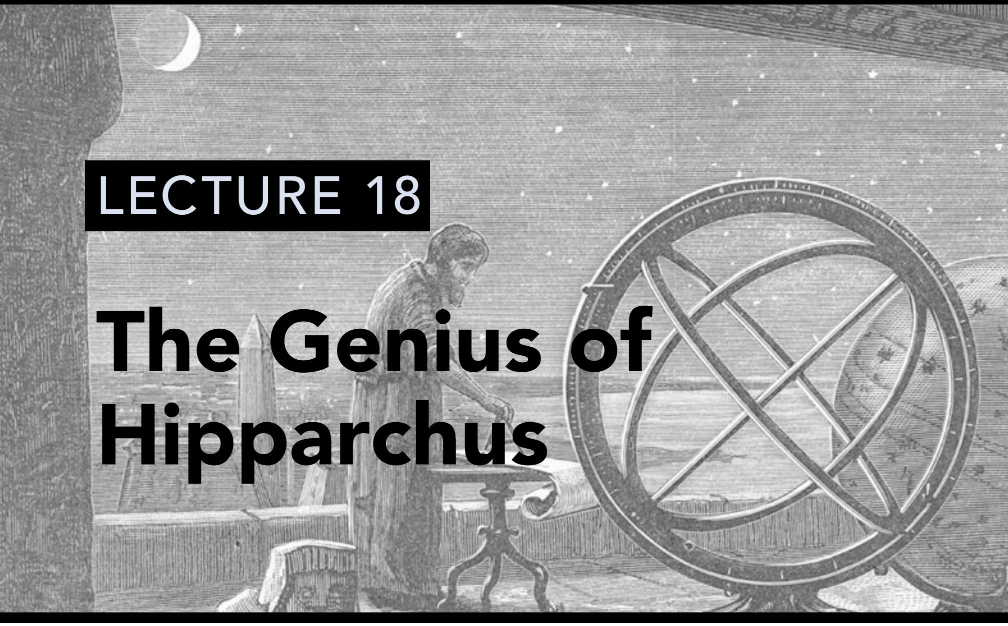
Questions

1. What trait or trend made for the fast flowering of the Greek genius? Why did this happen with the Greeks, and why did it happen from 600 to 200 B.C.?

2. Why did other cultures throughout the world not show a similar overpowering genius?

Activity

1. The early Greeks struggled with knowing the shape of the Earth. But by the time of Aristotle's book *On the Heavens*, he puts forth 3 proofs that the Earth is essentially spherical. Thinking like the Greeks, come up with simple observational proofs that the Earth is spherical.



LECTURE 18

The Genius of Hipparchus

Hipparchus, the subject of this lecture, was born around 190 B.C. in Bythnia, a region of modern Turkey near the Black Sea and the Bosphorus. He lived most of his adult life on the island of Rhodes, just off the southwest coast of Turkey. Ptolemy's great book the *Almagest* attributes a number of astronomical observations to him on Rhodes from 147 to 127 B.C. Hipparchus wrote 14 books, only one of which has survived to modern times. The contents of these books gave him the status of the greatest astronomer in antiquity. Perhaps his best achievement is the discovery of the motion of the stars that is now called precession.

HIPPARCHUS'S MATH

- Early Greek geometry had all sorts of theorems and relations between angles and lengths in triangles and circles. But no one had put this together into anything that we would call trigonometry until Hipparchus. He calculated chord lengths for a series of angles with increments of 7.5°. The chord lengths are closely related to the sines of the angles.

- This advance is critical for turning astronomy into a computational science. Previously, there had been few calculations based on the characteristic geometric models of Greek science. With Hipparchus's trigonometry table, calculations could be made for any angle, not just some special case. So, astronomers could start looking in detail at models and comparing them with real observations.

- Hipparchus made another geometry proof. He proved that the stereographic projection for a sphere onto a plane had the consequence that any circle on that sphere gets projected into a circle on the plane. This theorem is the basis for constructing the astrolabe instrument.

- Before Hipparchus, motions of the Sun and Moon were really only known in a qualitative way. Earlier Greek astronomy used strict geometric proofs, but they put in schematic numbers, often not realistic, or they put in no numbers.

- Hipparchus insisted on precision. This is new to science. And this is one of its fundamental tools.

SUN AND MOON POSITIONS

- Early Greek models insisted that the celestial spheres all turned at exactly uniform speeds. But a big problem arose, because the Sun and Moon both change speeds as they circle in the ecliptic.

- The problem can be easily seen by the unequal lengths of the seasons. This was first noticed by Callipus in Athens in 330 B.C. If the Sun moved around the ecliptic uniformly, then each season should last about 91 days. The Greeks have good measures of the exact dates of the equinoxes and the solstices.

- Hipparchus measured that the seasons varied in length from 88.125 to 94.5 days. This was called the solar anomaly. This set up a conflict on how to reconcile the observations with the philosophic principle of uniform circular motion. In modern times, we do this with Kepler's discovery that planet orbits are elliptical.

- In Greek times, a solution apparently came from Apollonius of Perga around 200 B.C. One way to solve the problem was to slightly offset the center of the Sun's circle from the position of the Earth. Another way was to construct an epicycle, where some additional circle of motion was attached to the inner circle that was centered on the Earth. Both circles kept to the uniform-circular-motion requirement. Apollonius proved that these solutions were equivalent.

- But Apollonius stopped there. He had geometrically demonstrated a model that qualitatively gave the right behavior. But he put in no numbers and tested no predictions.

- It was Hipparchus who put the quantitative into the geometric model of Apollonius. Hipparchus did this for both the Sun and Moon. His lunar and solar models were actually rather accurate. For any day of any year, he could derive the position of the Sun to better than $1/60^{th}$ of a degree.

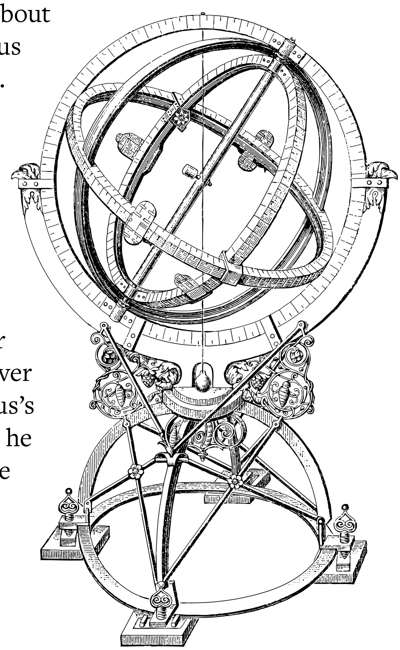
- So, no one could detect any deviation from his model. His lunar model was incorporated into the Antikythera mechanism. His models remained the best up until the 16^{th} century.

STAR CATALOG

- Pliny the Elder tells us the story of how Hipparchus came to make his famous catalog of all the visible stars. He says that Hipparchus saw a new star up in the sky. Modern astronomers think that this was a normal but infrequent nova eruption. Pliny says that Hipparchus started to wonder whether there were other new stars, whether other stars might die, and whether the fixed stars actually moved around a bit.

- Instead of philosophizing, Hipparchus measured the position and brightness of all visible stars. With this star catalog, he could see whether any new star appeared, and he could prove it because it was not in his complete catalog. Hipparchus could see whether any star vanished over time, and he could look for small movements in the star positions.

- Modern astrohistorians argue about exactly what instruments Hipparchus had and whether he invented them. Ptolemy implies that Hipparchus used an armillary sphere. They also argue about what coordinate system Hipparchus used for recording his measured star positions; that is, he might have used coordinates where the central plane was either the celestial equator or the ecliptic. They also argue over how many stars were in Hipparchus's catalog. The default answer is that he had close to 1000 stars, which is the number of stars readily visible from his latitude of Rhodes.



ARMILLARY SPHERE

- We don't have an exact answer to the number of stars in Hipparchus's catalog because his catalog has been lost. Many ancient authors who had seen the catalog tell us some of the details. For example, Ptolemy had a copy. But over time, the copies were somehow destroyed and lost.

- This star catalog started 2 big shifts in Greek astronomy.

  1. Hipparchus collected large amounts of exacting quantitative measurements—in this case, exhaustively getting the exact positions and brightnesses of all the stars. By making precise measurements, you can then produce models with realistic parameters and test already existing models. The concept of measuring things with exactness was not known previously to the Greeks, but it's a fundamental tool for science.

  2. Hipparchus started to study the stars in their own right as physical objects—to understand the nature of the stars themselves. This might be the first example of general basic research. He was aiming to catch and prove more "new stars," and he ended up discovering the motion of the stars called precession.

PRECESSION

- Hipparchus discovered precession by a painstaking comparison of his own observations with old observations. Hipparchus's book on precession has been lost, so we can really only use the very detailed account in Ptolemy's *Almagest*.

- Hipparchus discovered and confirmed precession by 2 methods. Both of these are essentially measures of star positions with respect to the equinox.

- Hipparchus's first method was to measure the relative position of Spica and other bright stars with respect to the position of the equinox. Ptolemy tells us that Hipparchus measured the longitude of Spica with respect to the Moon at the middle of a lunar eclipse.

- This trick makes use of the fact that the Moon at mid-eclipse is exactly 180° away from the Sun. With this, Hipparchus could calculate the longitude of Spica with respect to the Sun. He got the position of the Sun with respect to the equinox from his own theory on the motion of the Sun. Then, he calculated the longitude of Spica with respect to the equinox. Spica was 6° west of the equinox.

- It so happens that a Greek named Timocharis made a similar measure around 290 B.C. in Alexandria. Hipparchus's analysis of Timocharis's datum has Spica being 8° west of the equinox. Instead of writing off Timocharis's datum as being an error, Hipparchus took this to mean that the stars were shifting with respect to the equinoxes.

- Ptolemy tells us that Hipparchus noticed the same thing with a number of other stars. So, he generalized this to say that the sphere with stars fixed to it was slowly rotating. This is precession.

- Ptolemy tells us about Hipparchus's second method for discovering precession. This comes from measuring 2 types of years: the average time it takes for the Sun to go completely around the sky, going from equinox to equinox, which is called the tropical year; and the time it takes for the Sun to return to exactly the same position with respect to the fixed stars, which is called the sidereal year.

- Hipparchus measured the tropical year as 5 minutes smaller than 365.25 days and the sidereal year as slightly larger than 365.25 days. With the Sun as a pointer, he could determine the position of the fixed stars relative to the equinox. That the 2 years had different lengths demonstrated that the fixed stars were shifting slowly with respect to the equinoxes. This is precession.

- Hipparchus's measured value for precession is substantially smaller than the modern value. Almost 3 centuries later, Ptolemy added some more observations and still derived a precession rate that was substantially small. The modern rate has the fixed stars going completely around a full circle at close to 26,000 years.

- In modern times, we understand the why of precession. Both the Sun and the Moon provide gravitational tugs on the bulged shape of the Earth, which forces a very slow precession on the Earth's rotation. The physics is the same as that of a top, in which the axis of rotation changes its direction by going around in a circle.

- The tilt of the Earth's rotation remains at close to the 23° value, but the direction changes. In other words, the 23° angle remains the same, but the polestar changes. Nowadays, we understand that it's the Earth's axis that is slowly turning. But in the days of Hipparchus, where the Earth was considered to be fixed in space, it would look like something is turning the outer sphere on which the fixed stars are pinned.

- Another consequence of precession is that the stars are always shifting around with respect to the equinoxes and the equator. This means that the stars and constellations on the celestial equator are always changing.

- During one whole precessional cycle of 26,000 years, the position of the equinox will move through the 12 zodiacal signs with a little bit more than 2000 years in each sign. This depends on choices of exactly where to draw the edges of the constellations. For approximately the past 2000 years, the spring equinox has been in the constellation of Pisces.

- It's possible that Hipparchus's discovery of precession was turned into a new religion—called Mithraism—that dominated the Roman Empire for centuries. Mithraism was centered around the god Mithras and is one of the ancient mystery religions, in which its practices and teachings were kept secret and never written down.

Readings

Evans, *The History & Practice of Ancient Astronomy*.
Ptolemy, *Ptolemy's Almagest*.
Ulansey, *The Origins of the Mithraic Mysteries*.
Weinberg, *To Explain the World*.

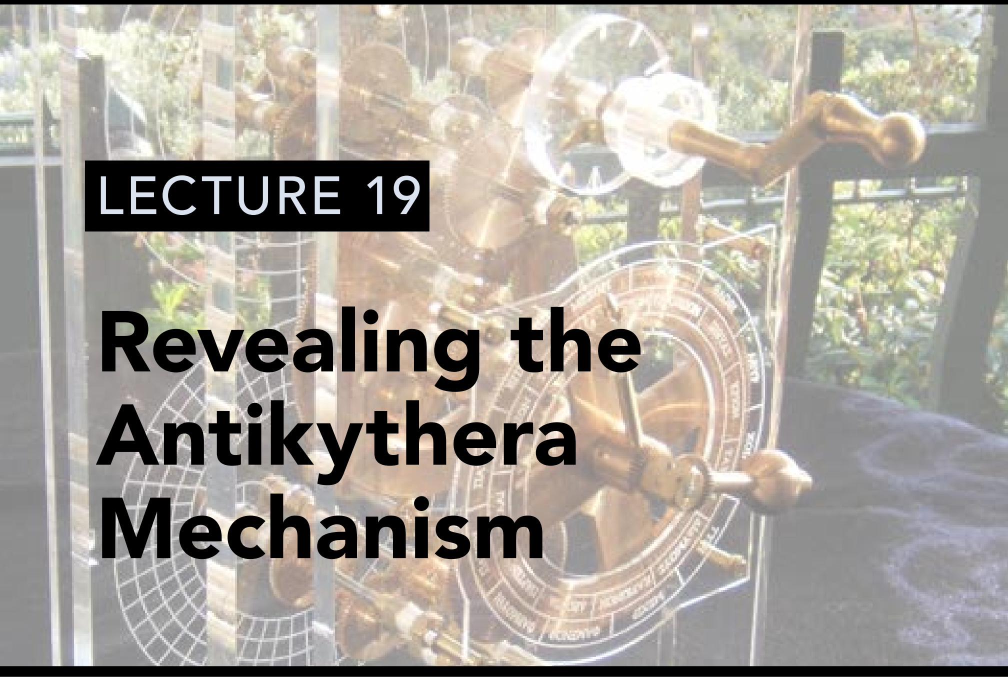
Questions

1 Were the Greeks doing science? This all depends on how you define "doing science," so carefully state what your definition is. Also consider alternative definitions.

2 David Ulansey presents the plausible claim that Hipparchus's discovery of precession was canonized as the central secret of the Mithraic mystery cult that dominated the Roman Empire. But we have no surviving written testimony as to the innermost secret, so we might characterize Ulansey's idea as unproven. But what would it take to provide a proof that would be commonly accepted? What sort of modern discovery—for example, by archaeologists or by document experts—could provide good evidence, pro or con, for Ulansey's claim?

Activity

1 Hipparchus's *Commentary* says that the North Pole has no star at its position, but there were 3 nearby stars, such that the 3 stars plus the North Pole position nearly forms a square. When was this observation made? The exact position of the North Pole moves somewhat over Hipparchus's long lifetime (roughly 190 to 120 B.C.). For this activity, you'll need to get either a star chart that goes down to 6.5 magnitude that plots the path of the poles through the centuries or a planetarium program that can show the sky with ancient star coordinates. From these, point to the position of the North Pole from 170 B.C. to 120 B.C. Can you spot a trio of (presumably faint) stars that form 3 corners of a square, with the North Pole at the fourth corner? Can you then deduce whether Hipparchus's observation is from early or late in his life?



LECTURE 19

Revealing the Antikythera Mechanism

A true pinnacle for all of Greek astronomy is represented by the Antikythera mechanism. Yet it’s also remarkable that we know anything about the Antikythera mechanism at all. This lecture will tell the story of its discovery and the subsequent work that went into figuring out what it was, when it was made, where it came from, and who made it.

DISCOVERY

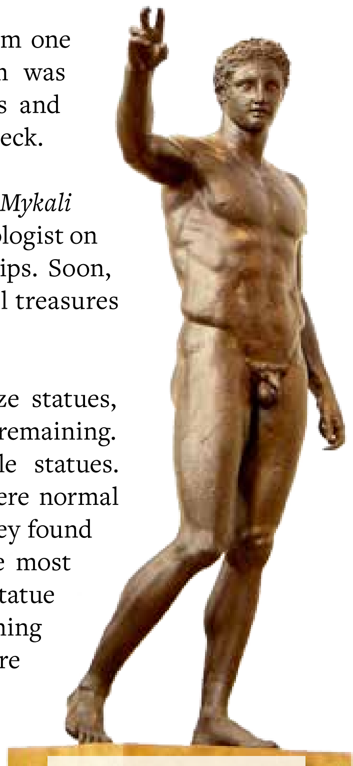
- Antikythera is the name of 1 of 2 islands in the middle of the passage between the Greek mainland and Crete. It is only about 2 by 4 miles in size. The larger island of Kythera lies to the northwest. This is the natural choke point for ships going from the Aegean Sea in the east to the wider Mediterranean in the west.

- If a storm arises, a natural reaction of sailors would be to get their boat into the lee of Antikythera. And in 1900, this happened to a pair of boats that carried 6 sponge divers, all from the Greek island of Symi, near Rhodes.

- After weathering the storm, divers from one boat discovered that the sea bottom was filled with marble and bronze statues and amphora—all part of an ancient shipwreck.

- The Greek government troopship *Mykali* sailed on 24 November with an archaeologist on board, and with 3 smaller support ships. Soon, divers were pulling up many wonderful treasures from the wreck.

- Overall, the divers found many bronze statues, usually broken up with only parts remaining. The divers also recovered 36 marble statues. They found many amphorae, which were normal stock on an ancient merchant ship. They found glassware and lamps. At the time, the most spectacular find was a well-preserved statue showing a Greek youth holding something round in his hands. The artifacts were taken to the National Archaeological Museum in Athens.



ANTIKYTHERA EPHEBE

- No one visited the shipwreck site again until 1953, when Jacques Cousteau and Harold "Doc" Edgerton came for a few days in the research ship *Calypso*. They returned again in 1976, but this time they spent a month dredging the site. They pulled up bronze coins, gold jewelry, and gemstones. The coins, in particular, proved important for dating when the wreck occurred.

THE ANTIKYTHERA MECHANISM

- But the sponge divers in 1901 had already discovered the most remarkable artifact in ancient astronomy. This object now goes by the name of the Antikythera mechanism.

ANTIKYTHERA MECHANISM FRAGMENT

- The sponge divers pulled up every bit of bronze that they could find. Many of these were just fragments of statues, and many were just congealed bronze blobs.

- In May 1902, the Greek Minister of Education and his wife were examining the impressive statue of the Greek youth with the globe. Lying around the statue were scattered fragments of bronze. He saw that one of these fragments had what looked like part of a gear on it. He found other fragments nearby and was able to piece together a plate with the whole gear showing.

- There was Greek writing inscribed on the bronze that read "ray from the Sun." Speculation immediately was that it might be some sort of a navigation instrument or something like an astrolabe. The newspapers quickly picked up the excitement and published 7 articles in the next few days, but little was done after this initial realization.

- Then, from 1951 to 1974, a long set of investigations was made by the British historian of science Derek J. de Solla Price. On one of the bronze pieces, he could read inscriptions on 2 concentric circles divided into 12 segments, the 2 sets of segments a bit offset by a rotation. What he read were names of zodiacal constellations and Greek month names.

- He was also able to make partial readings of one plate that was apparently on the front of the box. What he read were lists of the visibility of stars. For example, 3 lines in a row read, "The Hyades rise in the morning, Gemini begins to rise, Altair rises in the evening."

- Such lists were well known in Greek astronomy as parapegmas, which were almanacs used for charting the seasons. A version of this is presented with the weather signs as given by the archaic Greek author Hesiod and by the classic Greek poet Aratus.

- They were also known as inscribed stones put up in public places, with one hole for every day of the solar year. A peg would be placed in a hole and moved along once a day. A parapegma like this served as a sort of calendar and a predictor of both star visibility and the weather. This meant that the Antikythera mechanism was some sort of an astronomical calendar device.

- Critically, in 1971, Price was able to get X-ray pictures of the bronze fragments all corroded together. This allowed him to see inside the mass and recognize interior gears and count their teeth.

- Price had the wonderful insight to realize that these gears could give the Metonic cycle. This cycle was first noticed by Meton of Athens in the 5th century B.C. Meton's cycle consists of 19 solar years, which, it turns out, correspond closely to 254 lunar orbits.

- Price thought that the Antikythera mechanism was made to model the motions of the Sun and Moon; that is, by turning the main crank, the user would change the Sun and Moon positions on a dial in the front, all with good astronomical accuracy.

- Price was able to lay out the basic setup for the gears and how the front and back faces looked. He began calling the Antikythera mechanism an early computer for the calendar and for positions of the Sun and Moon. All this was described in a paper in 1974. But scholars wondered how to test his claim, or how to advance on it.

PENETRATING X-RAY TOMOGRAPHY

- In 2005, a broad group of Greek and British scholars used the new technology of X-ray tomography, which is similar to a CAT scan, to get a 3-dimensional image of the density of the bronze, all through the inside of each hunk of corroded metal.

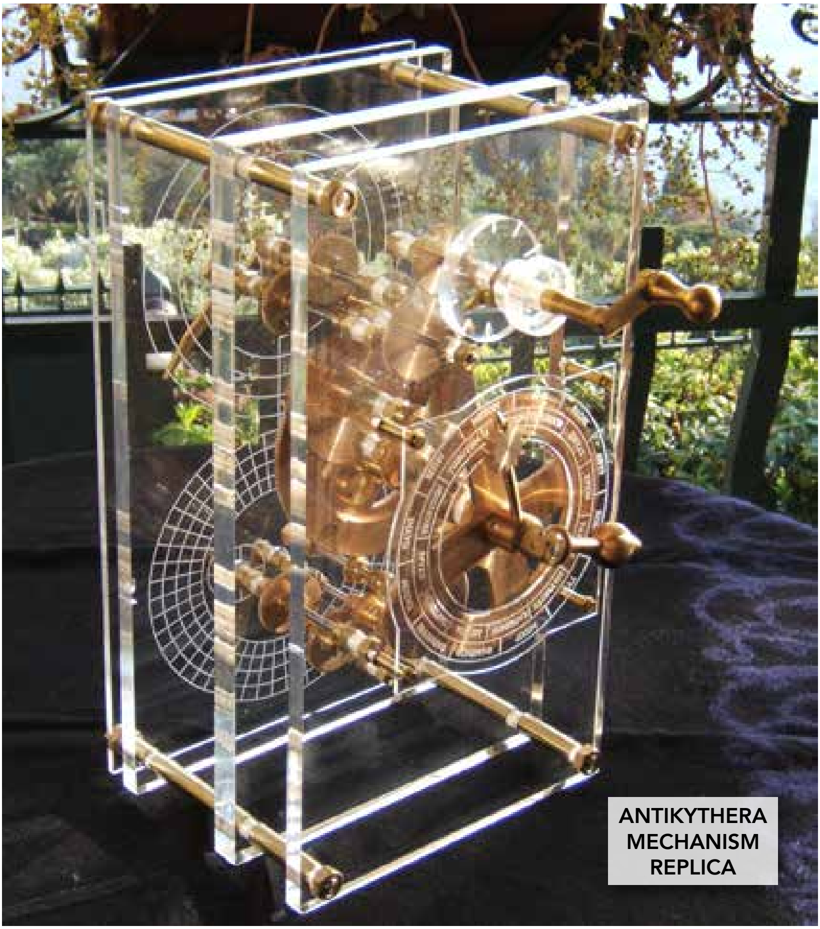
- The team was able to confirm the broad picture that Price had put forth in 1974. They were able to see a total of 30 gears hidden inside the fragments; get good counts on the number of gear teeth; and read inscriptions, even on the interior surfaces.

DESCRIPTION OF RECONSTRUCTED MECHANISM

- With real tooth counts and gear trains, the team could work out the astronomy that was built into the Antikythera mechanism. And some of the team members built working replicas. There are still some arguments about the exact gear trains, mainly for areas of the mechanism with missing parts.

- The picture we have now is that the Antikythera mechanism was a wooden box that was roughly 13 by 7 by 3.5 inches thick. On one side was a crank that the user could turn forward or backward in time. Inside were at least 30 gears. The front face had a fixed circle with the zodiacal signs going around. This showed the position on the sky along the ecliptic. A series of pointers, much like the hands on a clock, rotated around.

- A total of 7 pointers pointed to the positions of the Sun, the Moon, and the 5 planets. There was a small ball, one hemisphere colored white and the other hemisphere colored black, that rotated to show the phase of the Moon. The rear face had 2 dials, each spiral shaped, with 4 wraps of the spiral. These tracked the Metonic cycle, predicted eclipses, and kept track of the Olympic Games.



ANTIKYTHERA MECHANISM REPLICA

DATE OF CONSTRUCTION

- What we have is a remarkable artifact. It shows incredible sophistication, both in its geared construction and in its astronomical accuracy. This would've required a genius to make. Starting with Price in 1974, an ongoing discussion has been mulling over the possibilities of who this genius was. There is pretty good evidence, but not quite enough to get a consensus in the community of astrohistorians.

- The first issue is to get the date that the Antikythera mechanism was built. The artifacts of the shipwreck and recovered pottery and amphoras places the shipwreck within about a decade of 70 B.C., and the making of the Antikythera mechanism must be before the shipwreck.

- We have a starting limit for the design based on the gear train. The gears incorporate the lunar model attributed to Hipparchus. We don't know when in his lifetime Hipparchus constructed his model, but around 130 B.C. would be a good estimate. The Antikythera mechanism must have been designed after around 130 B.C.

- So, the range of dates for the design and construction is within about a decade of the interval between 130 and 70 B.C.

PORT AND CITY OF ORIGIN

- The location of the wreck—at a choke point in the route between the Aegean and the larger Mediterranean—strongly suggests that the ship was either going to or coming from the Aegean area.

- Based on evidence from archaeologists, who can recognize where artifacts were made based on the styles, the ship came from Asia Minor, with stops in Rhodes and perhaps other islands in the Aegean.

- Given the route of the ship, the origin of the computer is likely in Asia Minor, apparently from near Pergamon or Rhodes. So, this is where we should look for the most likely base of the maker.

- To determine the city of origin for the Antikythera mechanism, we must look at the mechanism itself, not the ship or its other contents. The Greek inscriptions show that it was made in the Greek world.

- The month names on the back-side dials point to northwest Greece, or perhaps Corinth, and the back dial also has pointers for the Rhodian Games. The parapegma was used only for latitudes below 37° north, which eliminates all candidates except Rhodes. In addition, the lunar gears incorporate a special and unique function that uses Hipparchus's lunar model, which also points strongly to Rhodes. Although the most likely place for the construction of the Antikythera mechanism is Rhodes, this is not proven.

WHO MADE THE MECHANISM?

- The design of the Antikythera mechanism required a world-class astronomer from approximately 130 to 70 B.C., apparently from around Rhodes. We know of only 2 world-class astronomers in the Greek world during this time interval—Hipparchus and Posidonius—and it turns out that both of them were from Rhodes.

- Posidonius was considered by the Greeks of the time to be the greatest all-around scholar of their age. He was an astronomer, a politician, a philosopher, a geographer, and a historian. Critically for the question at hand, Posidonius worked on the theory of the motions of the Sun, Moon, and planets and had created a flat working model of the Sun, Moon, and planets; that is, he was making devices like the Antikythera mechanism.

- But we can also make a good case for the builder being Hipparchus. We know from the Bythnian coin that he was making sky globes, and we know from Ptolemy that Hipparchus was making things like armillary spheres.

- We don't have enough information to choose between Hipparchus and Posidonius, and given the high level of craftsmanship, it's also possible that the work was carried out by someone whose name has not survived but worked with Hipparchus or Posidonius.

Readings

Anastasiou, Seiradakis, Evans, Drougou, and Efstathiou, "The Astronomical Events of the Parapegma of the Antikythera Mechanism."

Freeth, "Decoding an Ancient Computer."

Freeth, et al, "Decoding the Ancient Greek Astronomical Calculator Known as the Antikythera Mechanism."

Nikoli and Seiradakis, "The First Newspaper References to the Antikythera Shipwreck Discoveries."

Price, "Gears from the Greeks."

Questions

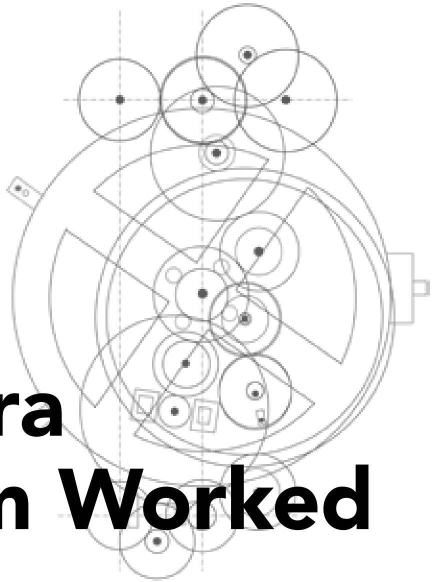
1 Who do you think built the Antikythera mechanism?

2 Authoritative and detailed accounts of the discoveries from 1900 to 1902 are found in the papers by Derek de Solla Price as well as by Magdalene Nikoli and John H. Seiradakis (see Bibliography for the references). But look at the many differing versions of this story on Wikipedia and in many newspaper articles, where you'll see that they are getting many facts wrong. What does this tell you about the accuracy of Internet resources for modern history? Can this accuracy rate be extended to the reliability of Internet information on all of ancient astronomy?

3 When reading and writing history, historians have a natural tendency to want to come to definite conclusions. And these get amplified when results are reported in the press or on the Internet. But sometimes the evidence is ambiguous or not decisive. Is this the case for identifying the maker of the Antikythera mechanism? Is there enough evidence to reach an unambiguous conclusion?

LECTURE 20

How the Antikythera Mechanism Worked



The Antikythera mechanism is the most remarkable artifact in all of ancient astronomy—and arguably in all of ancient science. The main reason for this is because it incorporates the best model of the solar system and represents the highest pinnacle of ancient astronomy. In this lecture, you will learn about the technical details of how the Antikythera mechanism works, so that you can better understand why it represents the epitome of ancient astronomy.

THE BASIC GEARING

- In 2005, new X-ray tomography of the bronze fragments showed incredible details of the many gears and inscriptions hidden deep inside the clumps of bronze. They revealed an intricate set of gear trains and instructions.

- The team of researchers was able to make a reasonable reconstruction of the gear trains. This confirmed the limited analysis that Derek J. de Solla Price was able to make in 1974.

- The basic gear train starts with a hand crank on the right side, which turns the basic year cycle, with the Sun pointer attached on the front face. This front face tells the position of the Sun on the zodiac and tells the day of the solar year. The notes attached to this face make a parapegma, which gives the visibility of stars and the predicted weather.

- This same basic shaft is connected to 2 other gear trains, both of which are used to calculate Moon positions and cycles. One of the trains feeds into the top spiral of the back face. On this is a pointer moving through all 235 lunar months of the Metonic cycle.

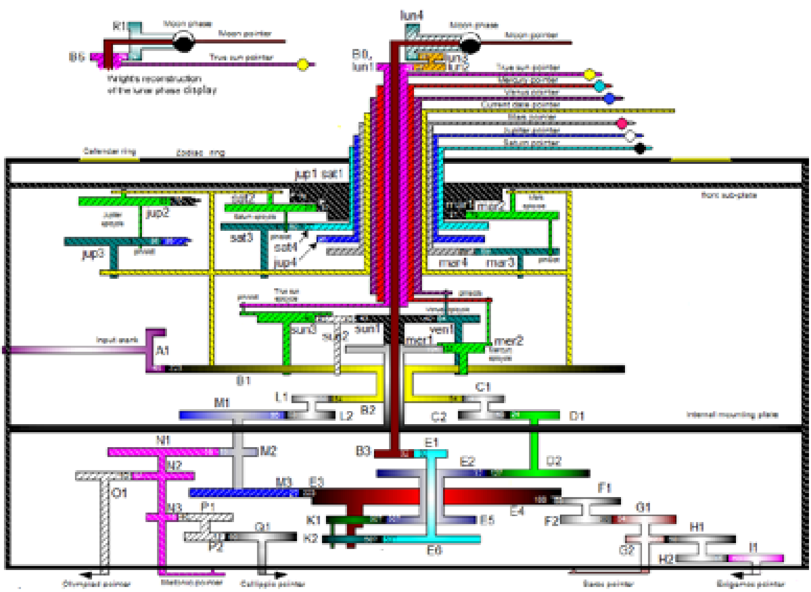
- This is essentially a lunar calendar, telling you the month names and when to put in extra months. In the Metonic cycle of 19 years, 7 of those years will need an extra month. On the back of the mechanism, a pointer shows to an extra month when needed.

- The other train feeds down to the bottom spiral on the back face. On this is a pointer that moves through all 223 lunar months in the Saros cycle. This tells the user dates of upcoming possible eclipses, both solar and lunar.

- The 2 trains then feed back to the central shaft to a pointer on the front face that shows the position and phase of the Moon. Critically, the device is the first use of a pin-and-slot gear that is an ingenious way to implement Hipparchus's theory of the Moon. Using simple gears wouldn't have allowed for variable speeds, but using the pin-and-slot gear did allow for a variable speed, thereby showing the variable speed of the Moon.

- Other side gear trains go off to show various calendar cycles. These include identifying the years of the 4 Panhellenic Games, including the original Olympic Games. There's evidence that the positions of all 5 planets were also shown on the front face, but the gears haven't been found in the shipwreck.

- There are more than 30 gears, in complicated configurations. The gears perform complex calculations that mirror the Greek geometric model for the solar system. In all history before 1300 A.D., no one ever made any other geared mechanism involving more than 4 gears in a very simple configuration. These simple geared mechanisms were odometers attached to chariots, in both China and around the Mediterranean.



- The gears were all made from bronze. The teeth were simple triangular shapes, making fabrication easier. The teeth were positioned uniformly with remarkable precision. The hand crank was connected to a gear with 48 teeth on it. This was connected to another at right angles. This second gear has either 223 or 224 teeth and attaches to the central shaft, the one onto which the Sun pointer is firmly attached.

- One turn of the front pointer corresponds to the Sun going through 360° all the way around the zodiac and also through 365 days of the solar year. To get this one full year of motion, the user has to turn the crank by 4 ⅔ turns.

THE SOLAR MODEL

- The position of the Sun is the central measure in the Antikythera mechanism. This is shown on the front face. The pointer for the Sun points simultaneously to 2 dials. One of the dials is the day of the solar year. For this, the scale shows the months of the Egyptian civil calendar, which was a solar calendar. The other main outer dial is the position of the Sun along the zodiac. The one Sun pointer works for both because the Sun is always at almost the same position on the same day of the solar year.

- Only ⅕ of the front dial has survived. This is actually enough to figure out most of what is going on, but a schematic version of the dials, with the lost portions put back in by pretty confident extrapolation, can help us understand them.

- The outer dial shows 12 30-day months. The month names are from the Egyptian calendar as transliterated into Greek.

- The inner dial on the front side is labeled with zodiac signs, as a way to measure the Sun's position along the ecliptic. The 12 zodiac signs are in order and labeled. Each sign has 30 smaller divisions. That means the ecliptic is divided into 360 degrees. As the pointer moves around, it indicates both the day in the Egyptian solar year and the position of the Sun on the ecliptic.

- Within a simple scheme, the pointer would move uniformly around the evenly spaced marks on the dials. This would represent a uniform motion of the Sun in the sky. The Greeks had a philosophical preference, almost a requirement, for uniform circular motion.

- But ancient astronomers were long aware that the Sun does not move uniformly around the sky. In some parts of the sky, the Sun moves a bit faster, and in other parts, it moves a bit slower. This is called the solar anomaly because of the somewhat unequal length of the seasons, and it was first pointed out by Callipus in 330 B.C.

- The Babylonians had a numerical scheme in which the Sun moved uniformly at a faster rate over half of the orbit and then at a slower rate uniformly throughout the other half. This is called system A by modern historians. Hipparchus had developed a detailed geometric model that worked with uniform circular motion by slightly offsetting the center of the circle from the Earth.

- In 2010, a trio of researchers, led by James Evans from the University of Puget Sound, found that the Antikythera mechanism does indeed have a correction for the solar anomaly. Because of this, it looks like the maker of the Antikythera mechanism adopted the numerical scheme of the Babylonian system A.

THE LUNAR MODEL

- The device has many gears going into the lunar model. The majority of the gears are devoted to showing the lunar motions accurately. This all feeds into one shaft that is inside the main solar shaft. Coming out on the front face, the pointer goes around, showing the Moon's position in the zodiac.

- The maker put a spherical bead onto the lunar pointer so that it could spin around. The bead was black all over one hemisphere and white all over the other hemisphere. The user could only see one face of the bead. At times, only the white hemisphere would show, corresponding to a full Moon phase. By varying the part of the bead showing, the user could see all of the lunar phases. The rotation of the bead was governed by yet another small gear.

- This lunar gear train was the first instance of an ingenious technique called a pin-and-slot mechanism. The effect of this was to mimic the epicycles as taken by the Greeks for their orbits; that is, the lunar anomaly, caused mostly by the elliptical shape of the Moon's orbit, makes the Moon speed up and slow down as it moves through the sky. If not corrected for, then the Moon could be up to 5° out of position. So, the maker was working hard to get the device's accuracy to much better than 5°.

- The gears incorporate a particular set of parameters for the lunar orbit. These correspond to Hipparchus's lunar model.

THE OTHER CYCLES

- The Sun and the Moon positions are clearly the main focus of the Antikythera mechanism. But the device includes much more. The whole back face is taken up with other cycles directly calculated from the Sun and Moon gears.

- One dial on the upper side of the back face is divided into 4 parts, each part having the name of 1 or 2 of the Panhellenic Games. With this, the Antikythera mechanism moves past being simply an astronomical and calendar computer and into the social realm of current events.

- The dial for the Saros cycle, over 223 months, ran off the lunar gears. But having a dial with 223 labeled units would be pretty tight, so the designer decided to wrap up the Saros dial into a spiral. In some months, the Saros dial indicated with a letter that there might be a solar eclipse or a lunar eclipse that month. These always followed the usual half-year eclipse season pattern.

- The back side also has a large lower dial, which is also a wrapped spiral. The sliding pointer went around 4 complete turns once every Metonic cycle. This 19-year cycle is when the Sun and the Moon have both made an integer number of revolutions, so the solar years and the lunar months get back in synchronization.

- This famous cycle, discovered by the Babylonians and by Meton of Athens, is used to legislate the adding of extra months in many lunisolar calendars. The Antikythera mechanism provided a solution to the practical problem of months faced by all lunisolar calendars.

THE LOSS OF THE MECHANISM

- This mechanism appears to have been a one-shot invention, created without much precedent and leaving no descendants, implications, or records. The new technology apparently died with the inventor, leaving no imprint on the rest of the world. The ideas of complex gear trains and mechanical computers were born and died with the Antikythera mechanism.

- A new technology can get lost if there is not a critical mass of people around who understand and can work with the device, if the needed support technologies become unavailable, or if the society has no driving need.

- However, none of these issues seem to be a problem at the time the mechanism would've been used, so it remains a mystery why the Antikythera mechanism was completely lost to mankind after the time that the ship sank in the lee of the storm-swept isle of Antikythera.

Readings

Carman, Thorndike, and Evans, "On the Pin-and-Slot of the Antikythera Mechanism."

Evans, Carman, and Thorndike, "Solar Anomaly and Planetary Displays in the Antikythera Mechanism."

Freeth, "Decoding an Ancient Computer."

Freeth, Jones, Steele, and Bitsakis, "Calendars with Olympiad Display and Eclipse Prediction on the Antikythera Mechanism."

Freeth, et al, "Decoding the Ancient Greek Astronomical Calculator Known as the Antikythera Mechanism."

Questions

1. How could the genius have made the leap to designing and building the Antikythera mechanism?

2. Why was the newly invented technology lost so quickly?

3. Farmers throughout Europe have long been randomly digging up buried hordes of coins, hikers have come across "ice men" that used to be frozen in the now-disappearing glaciers, and scholars have recognized palimpsests of lost great manuscripts. The Antikythera treasure is just the most prominent example of lost discoveries/inventions/writings coming to light against long odds. Imagine some important astrohistory artifact that has a plausible chance of being recovered by archaeologists, or whomever, in the upcoming years. What would you most hope for? What search strategies might you think of to optimize discoveries, and how would you trade this off versus time and expense?

Activity

1 The Antikythera mechanism gear teeth were placed with a typical accuracy of ¼ of a degree around the circumference. That is not easy. For a gear with 32 teeth, any good Greek geometer can lay out an accurate division. But 2 of the critical gears had 53 teeth. How can you do that? As a challenge to you, divide up some perfect circle into 53 teeth positions. You can test your work by numbering your marks, photocopying it onto a transparency, and then flipping and rotating it on top of the original. Line up various pairs of marks, and then see how far off your count is around the circle.

LECTURE 21

Achievements and Legacy of Ptolemy

Ptolemy is often viewed as the greatest astronomer of ancient times. His premier book, the *Almagest*, was indeed the greatest astronomy book, summarizing most of the world's knowledge of astronomy as a science for the next 14 centuries. In this lecture, you will learn about Ptolemy—specifically as the primary force in astronomy between the time of Hipparchus and Copernicus.

PTOLEMY'S BACKGROUND

- Ptolemy, whose full name was Claudius Ptolemaeus, lived in Alexandria, the intellectual center of the eastern Mediterranean. He wrote in Greek and was a Roman citizen. Only approximate dates for his lifetime are known, for his birth around 100 A.D. and his death around 175 A.D. He reports his own observations, which stretch from the years 127 to 141 A.D. Little else is known about Ptolemy personally.

- Ptolemy's fame is mainly based on his astronomy book, now called the *Almagest*, which was written within a few years of 150 A.D.

- Ptolemy wrote 2 other books that are each the greatest in their fields. The first is now called the *Tetrabiblos* and is considered the bible of astrology. This book provides an exhaustive and comprehensive account of ancient astrology. The dominance of his book served to fix Ptolemy's version of astrology for the entire rest of Western culture up until the 1800s.

- The second book is called *The Geography*. After giving a full treatise on cartography, Ptolemy then gave a gazetteer listing the latitudes and longitudes of 8000 named locations around the world. Ptolemy's book was the primary basis for mapmaking and geography up until the 1400s, and even later in most areas around Europe.

- In these 3 books, Ptolemy wrote the exhaustive and comprehensive systems of knowledge for the fields of astronomy, astrology, and geography. There's nothing like them anywhere in the ancient world. Ptolemy's 3 books remained as the definitive sources of knowledge in their respective fields for more than 1300 years.

THE *ALMAGEST*

- Ptolemy's *Almagest* gives a complete view of the entire science of astronomy, and it takes a wide array of specialized knowledge of both the astronomy and the historical conventions to understand it.

- Still, Ptolemy has a logical organization and good explanations. He gives details of his proofs, cites his sources, and quotes his raw data. He has little philosophizing, but instead gives pointed calculations.

- We know that there's a lot in the *Almagest* that goes back to prior workers: Ptolemy is frequently telling us of the old observations he's using and gives full recognition to the observers, and he often makes long discussions that he's directly attributing to earlier astronomers. But the majority of the *Almagest* is new and innovative work of Ptolemy.

- The *Almagest* consists of 13 parts, each called a book. The first book sets out the basics of his universe, with a round Earth at the center and the heavens going around as spheres. The last half of the first book gives introductory material on various geometry theorems relating to the skies.

- The second book lays out the effects of the observer's latitude on the length of the day as well as the rise and set times of the Sun.

- Next, the *Almagest* talks about the motion of the Sun, highlighting the solar anomaly, in which the motion of the Sun appears to speed up and slow down throughout the year. This is the place where Hipparchus's solar model with an epicycle added in is introduced. This solar model is central to all the later books.

- The next 2 books discuss the motion of the Moon, including its changing speed, and give a detailed model grounded in observations.

- Then, Ptolemy uses the solar and lunar models to work out eclipses and lunar phases.

- Book 7 tells about Hipparchus's precession and tells how to measure star positions with an armillary sphere. Divided between books 7 and 8, Ptolemy gives the full star catalog of 1028 stars. The *Almagest* continues with the visibility of stars and how to construct a sky globe.

- The last 5 books present detailed models of the orbits of the 5 planets, all complete with epicycles.

THE PTOLEMAIC SYSTEM

- The main point of the *Almagest* is to present in exacting detail the system of the world and the orbits of the Sun, Moon, and planets. Famously, his system has the Earth as being motionless at the center and everything else going in circles around us. This is called the Ptolemaic system. This is also called the geocentric system, with the Earth ("geo") at the center.

- An alternative idea is that the Earth goes around the Sun. This is called the heliocentric system, with the Sun ("helios") at the center. The Greek astronomer Aristarchus had already proposed a heliocentric system around 250 B.C.

- After Aristarchus, Greek astronomers were aware of both the geocentric and heliocentric possibilities, and the community decided to go with the Earth at the center. And after Ptolemy's *Almagest*, the Earth-centered system became frozen in place.

- In modern times, it's fashionable to deride Ptolemy for having the wrong model. Ptolemy has become the stereotyped deluded intellectual, frozen in his archaic mindset. The Earth-centered model is wrong, but only with hindsight and modern knowledge.

THE *ALMAGEST* STAR CATALOG

- The heliocentric system in the *Almagest* has attracted much research from astrohistorians into the fine details of Ptolemy's system, and it has attracted much comment as a failed system from popularizers and philosophers.

- But there's another area in the *Almagest* that has attracted a lot of detailed research: the star catalog. The analysis and controversies have been going on continuously for the last 4 centuries.

- Ptolemy's star list has 1028 stars, although 2 of them are duplicates. Each star is identified by its constellation and a brief description of its position within the figure. The listing for each star then gives 3 numbers: the celestial longitude, the celestial latitude, and the brightness expressed as a magnitude.

- The celestial longitudes and latitudes are for a coordinate system that is much the same as the longitude and latitude system used on the surface of the Earth. In the case of Ptolemy, he's using the ecliptic coordinate system, where the zero-latitude circle is the ecliptic, the yearly path of the Sun. The pole of this ecliptic coordinate system is 23° from Polaris, in the middle of one of the coils of Draco the Dragon. The zero longitude is defined by the position of the Sun at the time of the spring equinox.

- Ptolemy and all the Greeks used this ecliptic coordinate system because they were interested in the motions of the Sun, Moon, and planets. In the Sun's case, it moves through the sky always with an ecliptic latitude of zero. In this case, the motion is easy to express by one number, the ecliptic longitude. If the equatorial coordinate system had been used, then the motion could only have been expressed as an awkward 2-dimensional equation.

- Similarly, for the Moon and planets, their motions are largely parallel with the ecliptic, so their motions are easiest to be viewed as a 1-dimensional problem in ecliptic longitude, with only small perturbations in the latitude. This is expressed in astrology, where only the ecliptic longitude is used to place a planet on a horoscope.

- The ecliptic coordinate system has another huge advantage for the Greeks after the time of Hipparchus. The reason is that the precession motion appears as a simple rotation of the sky sphere around the ecliptic poles. This means that the apparent motion of the stars has a direction that is exactly parallel to the ecliptic. The use of the ecliptic coordinates, then, greatly eases calculations.

- To precess star positions—for example, from the time of Hipparchus to the time of Ptolemy—all you have to do is add a constant to the ecliptic longitude. The alternative is to use the equatorial coordinates, and then to precess stars, you must perform a complex trigonometric calculation where both latitude and longitude change.

- Although not familiar to modern people, it is much easier to work in the ecliptic system for many of the kinds of problems highlighted by ancient astronomers.

- There's a lot of discussion among astrohistorians as to whether some Greeks, Hipparchus in particular, might have used equatorial coordinates, but there is not enough information to resolve this question.

- To modern amateur and professional astronomers, the use of ecliptic coordinates seems odd and archaic. That's because we're usually addressing questions, such as pointing a telescope, for which use of the equatorial coordinates makes it easy, whereas any use of ecliptic coordinates would be unworkable.

- Nowadays, the motions of the planets are a solved problem, so few people are working on questions for which ecliptic coordinates offer any simplifications. The optimal choice of coordinate system depends on the typical uses and the questions being asked. In modern times, the equatorial coordinate system dominates by far. But in ancient times, the ecliptic coordinates made the most sense.

- The last column in Ptolemy's star catalog was the magnitude of the star, which is an arcane way to describe the apparent brightness of the star. The brightest 15 or so stars in the sky are grouped together and labeled into a category called stars of the first magnitude; the faintest visible stars were called stars of the sixth magnitude.

- The first place that this magnitude system appears is in the *Almagest* star catalog. And there are no words of explanation about anything on magnitudes. Based on a statement by Pliny the Elder around 79 A.D., the origin of this magnitude system is always attributed to Hipparchus.

- The magnitude system has long been confusing because, counterintuitively, the brighter the star, the smaller the magnitude number. The magnitude system is also confusing because it's not linear; rather, it's logarithmic.

- Since the 1800s, the magnitude has gone from a crude classification into 1 of 6 bins to a precisely calibrated continuous logarithmic scale. Today, we can pull out a lot of physics from good measures of star magnitudes, determining the nature of the unresolved stars themselves.

- But before the 1700s, the only use for magnitudes was star identification. There are many stars in the sky, and often the positions alone are not enough to uniquely identify the star being talked about. By adding the magnitude into the listing for each star, many of the ambiguities can be worked out.

- The thousand stars in the *Almagest* were placed into 48 constellations, and these then made up the 48 classic constellations of the Greeks. Ptolemy further separates out various small groups of stars that are not part of any constellation. Ptolemy orders his constellations mostly going from north to south.

- In all, the *Almagest* star catalog is a wonderful tour de force. Up until the 1500s, it represented the entirety of knowledge about the stars. In modern times, we now have better star catalogs, but the *Almagest* is still the best and virtually only source for knowing the ancient skies.

FEW ADVANCES

- From the time of the Antikythera mechanism to the time of Ptolemy, no advances in astronomy were made. After a 2-century hiatus, Ptolemy pushed far past the previous heights of Greek astronomy as represented by Hipparchus and the Antikythera mechanism.

- Ptolemy left no students. No Greek researchers followed up on Ptolemy's system. Later Greek writers just popularized and rehashed the *Almagest*. Up until the end of the Roman Empire, the Greek astronomy knowledge was around, but fading.

- After the Romans, the Greek knowledge was lost from Europe. Some of the Greek astronomy was retained by the Byzantines, but they did little with it, and mainly just served to pass on some Greek texts to the Arabs. Only with the Arabs during the Golden Age of Islam was the memory of the Greek astronomy preserved and revered. But little in the way of advances on the *Almagest* came anywhere until Copernicus in 1543.

Readings

Evans, *The History & Practice of Ancient Astronomy.*
Grasshoff, *The History of Ptolemy's Star Catalogue*.
Ptolemy, *Ptolemy's Almagest*.
Schaefer, "The Great Ptolemy-Hipparchus Dispute."
———, "The Latitude of the Observer of the Almagest Star Catalog."

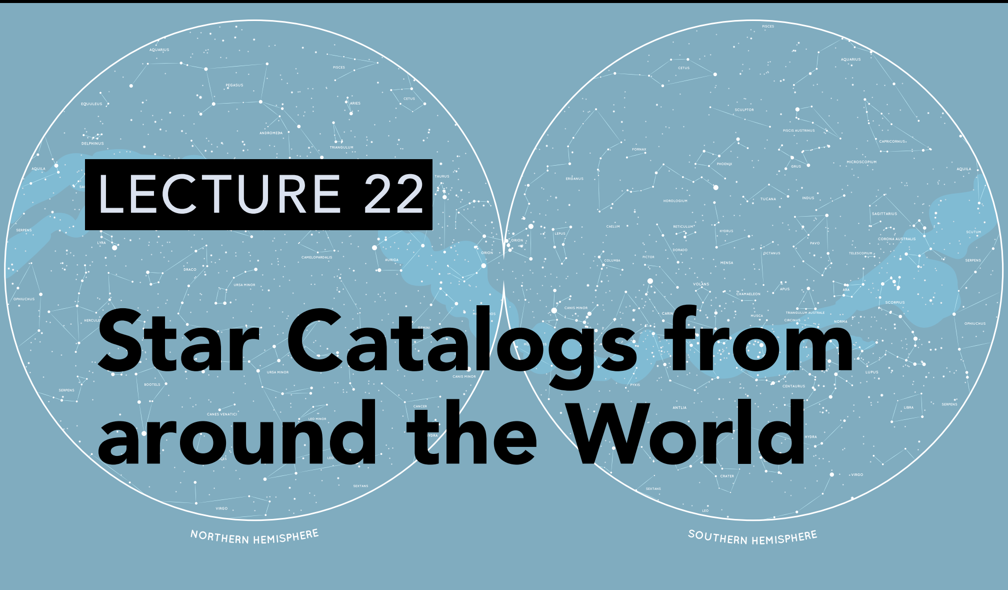
Questions

1 Was Ptolemy the greatest astronomer in antiquity?

2 Was Ptolemy's *Almagest* the greatest book of ancient astronomy?

3 Very few science books ever are innovative definitive syntheses of entire fields with avid readership over centuries. Ptolemy has 3: the *Almagest* (for astronomy), the *Tetrabiblos* (for astrology), and the *Geography* (for geography). Each of these was exhaustive and comprehensive, representing the culmination of knowledge in the field. All 3 of Ptolemy's books remained the best in the world for more than 1300 years. Can you name any other such books in any science?

4 Why did the Greek genius in astronomy apparently completely turn off from around 70 B.C. to 150 A.D.? And why did the Greek genius completely turn off again after the brilliant flare of Ptolemy c. 150 A.D.? Do your answers have any relevance for modern policy?



LECTURE 22

Star Catalogs from around the World

Hipparchus and Ptolemy both created catalogs containing about 1000 stars. These can be viewed as a good part of the peak of Greek astronomy. They fit into a larger picture of world astronomy, where a variety of other people made star catalogs. Star catalogs tell us a lot about the overall state of astronomy for various times and cultures, so they're a great way to get a measure of the ancient knowledge of the sky. In this lecture, you will discover a variety of ancient star catalogs.

GREEK STAR CATALOGS

- The Greeks made 2 star catalogs. The first was by Hipparchus, around the time of 130 B.C. This catalog survived for at least a few centuries but has now been lost. The second was by Ptolemy, around 150 A.D. Ptolemy's star list appears in the *Almagest*, with 1028 stars.

- To construct the catalogs with accurate star positions, some sort of a calibrated sightline is needed, with scales for the 2 coordinates. Hipparchus solved this by his invention and construction of what we now call an armillary sphere. Around 280 years later, Ptolemy made his own armillary sphere in Alexandria.

- Armillary spheres allow for astronomers to measure angles between stars within a latitude/longitude coordinate system. The inner sightline points to the 2 stars in turn, and the angles are read from pointers on a large graduated circle. The markings on the circle were at ¼° intervals, and the real accuracy approaches this. Something like an armillary sphere is the only way to get positional accuracy to better than about 1° in positioning stars all around the sky.

- They also needed some way to calibrate the longitudes. This was done by setting some standard stars and measuring their longitudes with respect to the Sun. The longitude of the Sun with respect to the position of the equinox was taken from Hipparchus's model for the solar motion. This then gave the longitude of the standard stars with respect to the equinox. Finally, by measuring their thousand stars with respect to the standard stars, they would get all the stars' longitudes.

THE FARNESE ATLAS

- The oldest surviving, and best, representation of the ancient skies appears on a marble statue called the Farnese Atlas now in a museum in Naples, Italy. The statue stands 7 feet tall and shows the Titan, named Atlas, holding the skies on his shoulder. This statue was unearthed in

Italy and was acquired by the Cardinal Farnese in the early 16th century. Art historians say that the statue is a 2nd-century A.D. Roman copy of a now-lost Greek original, made before 1 B.C.


FARNESE ATLAS

- The heavens are depicted as a globe 26 inches in diameter showing most of the constellation figures of the Greek sky. The globe also shows many coordinate circles, which give us an accurate coordinate grid.

- Because the positions of the constellation figures on the sphere match the sky, an accurate date can be derived for the origin of the star positions used to make the globe. The key is precession, as discovered by Hipparchus. The date 125 B.C., with an error margin of 55 years, gives the epoch of the star positions to within one lifetime.

- Measurements prove that the placement of the constellation figures onto the globe had an average accuracy of better than 2°. The original sculptor probably didn't work from a list of star coordinates, so there has to be something like an accurate star globe that the artist could copy exactly from.

- To get 2° accuracy, the only way to do it is with a star catalog as the original source. And to get this accuracy, the star catalog had to have been made with something like an armillary sphere.

- Because we have enough information to uniquely identify the date of the observations as being within a lifetime of 125 B.C., we can infer that it was Hipparchus whose star catalog is represented on the Farnese Atlas. The constellation figures follow Hipparchus's descriptions, and he was renowned through the Greek world for his sky globes.

STATE OF ASTRONOMY IN 200 A.D.

- The height of Greek astronomy can be represented by the works of Hipparchus and Ptolemy, and by their 2 star catalogs, plus the Antikythera mechanism. But Greek astronomy never advanced beyond this level.

- The state of Greek astronomy by 200 A.D. was a high one, but Greek astronomy had become stagnant. Nevertheless, Greek knowledge became widely distributed around Eurasia and North Africa. The Romans and the Indians received the Greek work and spread the word. But after 200 A.D., as Europe slipped into the Dark Ages, Greek astronomy was slowly lost to the Western world.

- The state of Chinese astronomy in 200 A.D. was also relatively high. Their first all-sky star catalog was close to 2 centuries before Hipparchus. Chinese astronomers discovered precession in 320 A.D., more than 4 centuries after Hipparchus. And they discovered the inequality of the seasons in 570 A.D., 9 centuries after Callipus in Athens.

- The Chinese had a well-regulated lunisolar calendar and a complex system of astrology, and they could accurately predict the positions of the planets with numerical methods. They knew the shape of the Earth and the cause of eclipses. They measured the size of the Earth first in 725, a full millennium after the first Greek measures. In all, the Chinese of 200 A.D. were quite sophisticated, but not near to the Greeks at their height. Even by 1600, the Chinese had not risen to the level of the Greeks in astronomy.

- The state of astronomy elsewhere in the world in 200 A.D. was still stuck at a level far below the Greeks or Chinese. Outside of the Eurasian milieu, everyone else thought that they lived on a flat Earth. The skies and all of nature was run by gods and demons and spirits. They all had only crude lunisolar calendars. They had no year counts and no astronomical records, even from oral traditions.

- Their most complex astronomical tools were gnomons for telling time and various rock alignments pointing to the seasons. They all had constellations with associated lore, but this was just for telling stories around the campfire.

- In 200 A.D., the whole world outside of Eurasia was still at the level of the Greeks in 600 B.C. The rest of the world kept at this level of astronomy, with few advances, up until contact with European travelers starting around 1500 A.D.

ISLAMIC STAR CATALOGS

- In 200 A.D., the Arabs had little astronomy past the basics. They had imported the lunar lodge system from China, and they had their own lunisolar calendar and constellations. Only around 700 A.D., with the fast advance of the armies of Islam, did the Arabs get in touch with books and knowledge of the Greeks.

- With enlightened rulers, the Arabs prized knowledge, and this led to the Golden Age of Islam, in which many of the top scholars were astronomers, although all had very wide interests. The motivation was for the many practical applications required by the Islamic religion. So, they made much good work and research into lunar crescent visibility, calendars, timekeeping, and direction finding. The astrolabe epitomizes these applications, all brought to a peak by the Arabs.

- In the first part of the Golden Age of Islam, Arab scholars simply worked hard to recover and understand the Greeks' work. Around 1000 A.D., Islamic astronomers had gotten to the point where they were making some tweaks on the parameters in Ptolemy's model. They used their own observations along with the old observations in the *Almagest* to derive an improved rate of precession. They determined that precession moved the stars by 1° in longitude in 70 years, which is close to the modern value. This is all good work, but not really innovative. And they never got past the level of the Greeks.

- In the later part of the Golden Age of Islam, Arab astronomers made 2 star catalogs.
  - Around 960 A.D., Persian astronomer al-Sufi published his own catalog of 1028 stars. Al-Sufi's catalog copied the stars and the star positions exactly from the *Almagest*, but a constant was added to Ptolemy's ecliptic longitudes to precess the positions up to the epoch of al-Sufi. He reports his own observed magnitudes for all 1028 stars. According statistical tests, about ⅓ of the magnitudes were copied from (or somehow influenced by) the *Almagest*, leaving around ⅔ that were independently observed and reported by al-Sufi.

  - Ulugh Beg, who came to rule a vast region in central Asia from his capital in Samarkand, noted errors in the positions of stars as given in the *Almagest*. Then, he gathered a group of scholars and built an observatory in Samarkand. They reobserved all the star positions mentioned in the *Almagest*, creating a catalog of their own. It's unclear how much was done by the ruling sultan and how much by the scholars. But all the magnitudes were straight copies from the *Almagest*.

CHINESE STAR CATALOGS

- The early Chinese tell us that their first star catalog was made by the great astronomer Shi Shen, who is dated to the late Chou dynasty, perhaps around 350 B.C. We know from the book *Shi Ji* that this catalog was in place by at least 100 B.C. Parts of his catalog are preserved in a book called the *Kaiyuan Zhanjing*, written during the Tang dynasty in 729 A.D. These show 809 stars in 120 constellations. The Chinese never really indicate the brightness of any star, much less in a quantitative manner.

- The surviving tables only give the coordinates for the 120 primary or determinative stars of each constellation. The Chinese always report these positions in equatorial coordinates, as the celestial longitude within the lunar lodge, and the angular distance from the North Pole. The given star positions have an accuracy of better than 1°, and books from the 7th century A.D. tell about the earliest Chinese astronomers using an armillary sphere designed to return equatorial coordinates.

- By the time of the early Han dynasty, around the 2nd century B.C., 2 more star catalogs had been produced: the catalog of Gan De, with 118 constellations, and the catalog of Wu Xian, with 44 constellations. Unfortunately, there are uncertainties by up to 2 centuries as to the dates of each of the 3 original Chinese star catalogs. Still, we're left with the Chinese having 3 good star catalogs with accurate positions for many hundreds of stars before the time of Hipparchus in the West.

- Over the next millennium, Chinese astronomers constructed further star catalogs in the years 120, 270, 635, 725, 1036, 1052, 1070, 1080, and 1092 A.D. Over the next millennium, Chinese astronomers made many star maps and star globes.

- Globes depicting the stars in the sky date back to 436 A.D. as made by the astronomer Qian Lezhi and back to 117 A.D. by Zhang Heng.

- The earliest surviving star map dates back to around 660 A.D. It was discovered inside a walled-up cave far out in the Gobi Desert on the Silk Road, in the Dunhuang cave complex. Found in 1907 by archaeologist Aurel Stein, the map is a roll of thin paper with 1339 stars in 257 constellations.

DUNHUANG STAR MAP

✦ The stars from the 3 original star catalogs are designated by red, white, and black colors. The star positions are consistent with being placed according to a Mercator projection away from the pole and a stereographic projection around the pole. The positional accuracy is about 2°.

TYCHO'S STAR CATALOG

- In the late 1500s, in northern Europe, Danish nobleman Tycho Brahe was proving himself to be one of the all-time great observers in astronomy—by achieving remarkably high accuracy and by working at observational questions that sharply distinguished between competing hypotheses. All of this was original to Tycho and is very modern in outlook.

- Part of Tycho's genius was in constructing many astronomical instruments, including armillary spheres, crafted with high precision and often made on a rather large scale.

- In a blatant attempt to copy the *Almagest* star catalog, Tycho started making his own catalog of all stars visible from Denmark. In 1592, Tycho first published a catalog of 777 stars in his book the *Progymnasmata*. By 1597, Tycho had observed more stars and then published a new combined catalog with 1004 stars.

- For Tycho's reported star magnitudes, statistical data shows them to be consistent with no copying from any earlier catalog. For Tycho's measured positions, he was achieving the remarkable positional accuracy from $1/40^{\text{th}}$ of a degree when he was young to $1/100^{\text{th}}$ of a degree in his prime.

Readings

Evans, *The History & Practice of Ancient Astronomy.*

Ptolemy, *Ptolemy's Almagest.*

Schaefer, "The Epoch of the Constellations on the Farnese Atlas and Their Origin in Hipparchus' Lost Catalogue."

———, "The Thousand Star Magnitudes in the Catalogues of Ptolemy, Al Sufi, and Tycho Are All Corrected for Atmospheric Extinction."

Stephenson, "Chinese and Korean Star Maps and Catalogs."

Questions

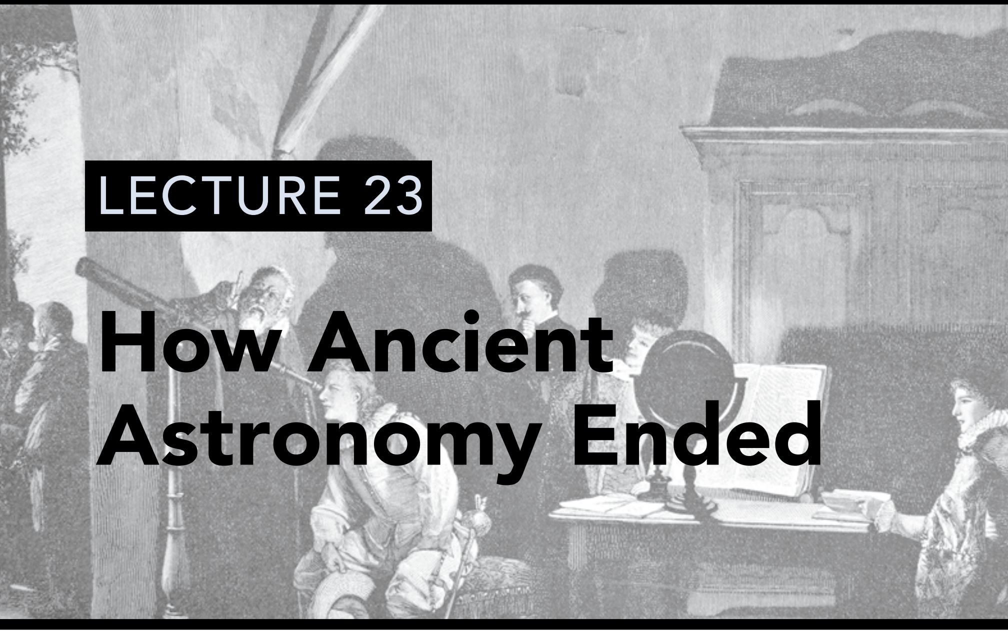
1 When you look at popular literature on the astronomies of cultures outside of Eurasia for before the year 1600 A.D., you generally read rosy stories highlighting their achievements, with the implications that these are impressive/important and that the culture is “advanced.” But Bradley E. Schaefer’s analysis shows that these cultures never got much past the Neolithic Stone Age level in any aspect. For example, they were all still at the flat-Earth level. So, why are these analyses so different?

2 Outside of the regions connected to the Greek and Chinese cultures, even up until 1600 A.D., can you think of any astronomical instrument, tool, or equipment that was anything past something like a few sticks or stones somehow put together?

Activities

1 Examine and compare various early star charts. With the usual Internet searches for images, you can easily find star charts for al-Sufi’s catalog (which really has the positions from the *Almagest*), Tycho’s catalog (in Beyer’s *Uranometria*), and Hevelius’s catalog (from 1690). How similar are they? How different are they? Why are they different? After all, they’re just looking at the same sky.

2 Find a copy of the Dendera zodiac. Spot all the Hellenistic zodiac signs, mixed in with the older Egyptian constellations. Can you identify other constellations that have heritage from the Greeks or Mesopotamians? Does this look like the accuracy of placement requires a star catalog made with an armillary sphere? Despite much speculation, only a few of the Egyptian constellations have been confidently identified with stars in the sky. Beware of poor renditions on some of the reproductions. Also be aware that some of the figures are actually just the gods associated with the 5 planets. And be wary of the various fringe speculation that the Dendera zodiac stimulates.



LECTURE 23

How Ancient Astronomy Ended

This lecture will set the scene of the transition from ancient astronomy to what can generally be called modern astronomy by surveying the state of astronomy around the world in 1500. As you will discover, astronomy led the way. Most of the key breakthrough figures were in astronomy, and it was astronomers who founded the methods and ideals for all of modern science.

OUTSIDE EURASIA

- Outside of the Eurasian milieu, in 1500, all the various cultures had received little or no astronomy from Greek or Chinese sources. All these peoples have a basic set of knowledge and skills and tools that can be considered the early astronomy tool kit.

- Outside of Eurasia, their astronomies were all fundamentally similar in nature. There was indeed a wide range of local variants, and the names for things in the tool kit were always different. Still, the early astronomy tool kit has many nearly universal features.
    - These calendars all had lunar months with seasonal names, and the solstices were tracked. But the insertion of extra months was ill-defined and chaotic. No year counts were kept, nor were records of events by year kept. For timekeeping, the Sun and star positions were tracked, but only with something like a gnomon. The most sophisticated item in the early astronomy tool kit was the gnomon plus a few sticks or stones to indicate directions.

    - Everyone had many constellations, always depicting their gods, heroes, legends, animals, and workaday tools. The stars and constellations were used as seasonal markers, for measuring the time at night and for determining directions. Everyone knew the constellations, which were made more memorable by telling stories around the campfire.

    - The shape of the Earth often received little attention. The default vision was of a flat body with some sort of a dome covering the sky, where the gods dwelt. In this view, the cause of eclipses was not yet known. Also, the planets were just moving lights, and they might be personified.

- Using the early astronomy tool kit, the sky and all of nature were still controlled by the whims of gods and ancestral heroes. Because only the gods could touch the heavens, sky events could only be trying to tell us the will of the gods—and maybe our futures. Eclipses, comets, and meteors were breaks in the regular order, so they were almost always taken as very bad omens. Everyone read signs in the skies.

- This basic early astronomy tool kit was worldwide, including all of Eurasia, up until 600 B.C. The fact that this pattern was so widespread plausibly suggests, though it does not prove, that the basic elements of this early astronomy tool kit are very ancient.

- Some advances on this basic tool kit had been made in some non-Eurasian cultures. For example, the Maya and Aztecs developed sophisticated calendars, plus an intricate astrology system, and were able to measure and predict the positions of the planets and eclipses.

INSIDE EURASIA

- Inside Eurasia, by 1500, many cultures had risen or recovered to the level of the Greeks. The spherical shape and diameter of the Earth had been long known by everyone. The cause of eclipses was realized to be simply shadows. The sizes and distances of the Sun, Moon, and planets were approximately known. The positions of the planets around the ecliptic were known and could be predicted with moderate accuracy, either by geometrical or numerical methods.

- All the visible stars were catalogued with good positions. Everyone was using well-regulated calendars that kept accurate dates and year counts, each keeping up with the Sun or Moon or both. There was widespread availability of sundials, water clocks, astrolabes, compasses, astronomical tables, and even complex geared clockwork mechanisms.

- The dominant concern of the astronomers was always for practical applications. A common high-level issue was calendar reform, making corrections in the calendar. For example, in Europe, the calendar reflected concern over the date of Easter.

- A prominent practical application throughout Eurasia in 1500 was astrology. All cultures had their own versions of astrology, and these were always complex. Astrology was accepted by virtually everyone in principle, but it's unclear what fraction of the people actually based real decisions on the stars. The needs of astrology kept astronomers working hard to get better and better positions for the planets.

- The state of astronomy throughout Eurasia in 1500 was that it had not reached the level of the astronomy of the ancient Greeks at their peak. There's virtually nothing that would not be easily familiar to Ptolemy. And many fringe areas of Eurasia had received only a small fraction of the knowledge of the Chinese or Greeks.

- In Europe in the 1500s, the intellectual situation was weighed down by long-dead authorities. A Renaissance had started in Italy and spread throughout Europe, putting forth humanism in the arts, literature, and philosophy.

- Part of the basis for this broad movement was also a recovery of the great classic books of the Greeks. These Greek books came to represent the height and breadth of knowledge and philosophy. Dominating this were the works of Aristotle, who was taken to be definitive. With this sweeping acceptance of Aristotle as the prime authority, Aristotelian physics gained primacy.

- In astronomy, Ptolemy's *Almagest* was recovered and became the final authority. But with the voyages of the early Portuguese and Spaniards, the age of discovery began widening the horizons of the Europeans.

COPERNICUS

- Ancient astronomy started to change in the second half of the 1500s. This all started in 1543 when Polish astronomer Nicholas Copernicus published his book titled *De Revolutionibus Orbium Coelestium* (*On the Revolutions of the Celestial Spheres*).

- Sometime before 1514, Copernicus started working on the revolutionary idea that the Sun was immobile at the center of our solar system and that the Earth was just 1 of 6 planets in orbit around the Sun, with only the Moon still going around the Earth. This basic scenario is called the heliocentric model. Critically, his idea was a significant switch from Ptolemy's geocentric model, which has the Earth as the center of the solar system.

- Many modern scholars point to the publication of Copernicus's book in 1543 as the start of the Scientific Revolution, because this is the first time that the authority of Aristotle or Ptolemy was challenged directly.

COPERNICUS

- It was replacing the geocentric model in favor of a heliocentric model that opened the way to start questioning other claims of Aristotle and Ptolemy. And people began questioning other Greek classics. Once minds were freed from the bounds of the old books, new discoveries could be made. And discoveries were made, at ever-increasing speed.

- But Copernicus was still operating in the tradition of Ptolemy. This means that Copernicus adopted without question the assumptions, philosophy, and methods of the Greek astronomers. In short, it's quite plausible to say that ancient Greek astronomy culminates with Copernicus.

STARTING THE CHANGE

- After Copernicus, the key astronomers are Tycho Brahe, Johannes Kepler, and Galileo Galilei. Brahe was a Danish astronomer working in the last 3 decades of the 1500s. Kepler worked in the last decade of the 1500s and in the first 3 decades of the 1600s, at various cities in central Europe. Galilei worked in northern Italy in the first 3 decades of the 1600s.

- The mindsets of Tycho, Kepler, and Galileo were all completely different from those of Ptolemy and Copernicus. Tycho and Galileo were no longer focused primarily on geometric derivations; rather, they were studying precise measurements and how to account for those measurements. And they were thinking about experimental tests of their ideas.

- Ancient astronomy, as viewed in Europe around the 1500s, was epitomized by the books of Aristotle and Ptolemy. Ptolemy presented a model solar system with the Earth stationary and everything else on spheres traveling with uniform circular motion.

- The books of Aristotle contained many teachings on astronomy and physics. Aristotle advanced and championed a geocentric solar system. He also required that the planets travel with uniform circular motions. Aristotle stated that everything above the atmosphere must be "perfect" and unchanging. And Aristotle's physics had the speed of falling bodies being proportional to their weight.

- In European universities and science, as well as in the culture and theology, the primacy of Aristotle was only barely challenged. Aristotle's work was the basis and core of the university curriculum. Aristotle's philosophy had been Christianized and adopted into theology, so for some people, an attack on Aristotle would be tantamount to an attack on the Christian Bible, as well. For astronomy in Europe in the 1500s, Ptolemy's *Almagest* had a similar air of unchallenged authority.

- Aristotle and Ptolemy had both presented detailed claims and models that are open to experimental testing. Prior to Tycho and Galileo, no one had bothered to do such testing—to let nature tell you what is really going on. This is the essence of modern science. Historically, with an ever-increasing pace, astronomers found that reality disagreed with both Aristotle and Ptolemy on many and important issues.

- Many discoveries made by Tycho, Kepler, and Galileo refuted Aristotle and Ptolemy. For example, Tycho and Kepler both proved that the distant heavens were changeable, in contradiction to Aristotle's dogma. Galileo performed an experiment to test Aristotle's laws of motion and proved Aristotle's physics wrong.

- The success of Kepler's laws of planetary motion at reproducing many and exacting observations made by Tycho proved that his laws were correct. With that came the proof that the Earth and planets went around the Sun. Aristotle and Ptolemy were both wrong. Furthermore, the shapes of the planet's orbits were not circular and their speeds were not uniform, in direct contradiction to central claims of Aristotle and Ptolemy.

- In the space of a few decades, Tycho, Kepler, and Galileo racked up many proofs that Aristotle and Ptolemy were both often wrong on many points. So, the old, failed ideas needed replacing.

THE START OF MODERN ASTRONOMY

- Waiting since 1543, Copernicus's heliocentric model now started to replace Ptolemy's geocentric model. This only started once there came reasonable evidence to support this switch. This was the Copernican revolution. The whole affair took a long time. The pace of research was slower back then; it also took a while to come up with many proofs.

- Aristotle's failed physics was replaced by Galileo's physics. The huge advantage of Galileo's physics was that it matched experiment. It took a while for Galileo's physics to blossom into the awesome physics of Isaac Newton.

- The new ideals of modern science started replacing the ideals of the Greek astronomers. Copernicus hadn't made this change, but Tycho, Kepler, and Galileo all led the way into a completely different mode of thinking.

- Tycho invented the idea that large amounts of high-precision data should be collected as a way to test competing hypotheses. Kepler invented the idea that physics can be applied to the heavens. Galileo invented the scientific method of experimentation. After this, there was no looking back.

- So, in the decades around 1600, Copernicus's heliocentric model replaced Ptolemy's geocentric model, Galileo's experimental physics replaced the physics of Aristotle, and the modern astronomy mindset of astrophysics replaced the ancient astronomy mindset.

- This was the start of the Scientific Revolution, characterized by an exponential growth of science knowledge and discoveries in all fields. The effects on philosophy and society are enormous. This exponential growth in knowledge continues to today.

Readings

Galilei, *Sidereus Nuncius, or the Sidereal Messenger.*
Gingerich, *Copernicus.*
Kuhn, *The Structure of Scientific Revolutions.*
Sobel, *A More Perfect Heaven.*
———, *Galileo's Daughter.*

Questions

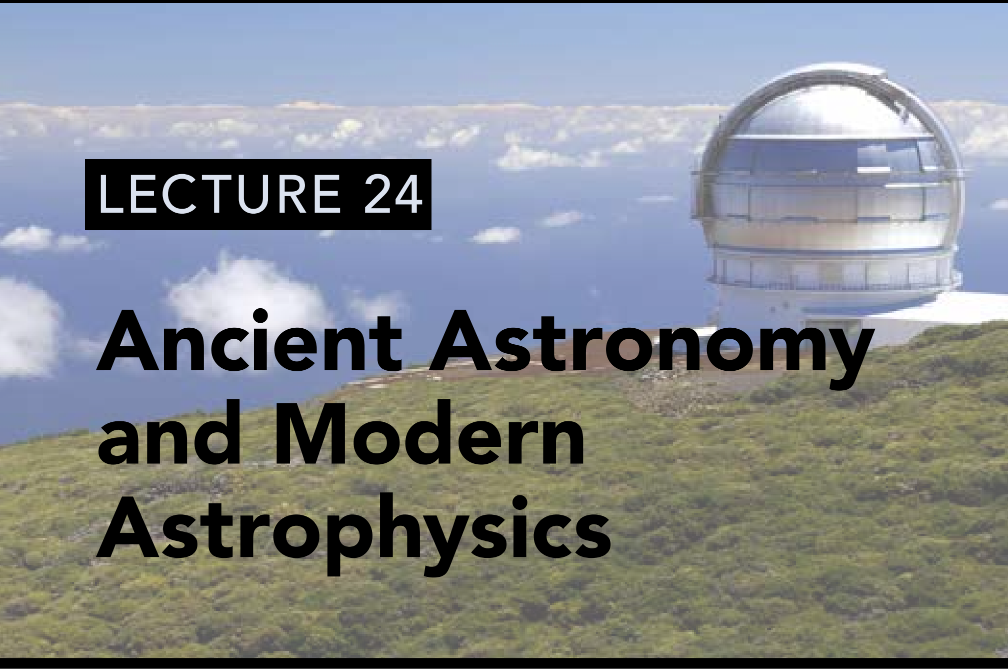
1 Throughout this course, you have learned about a variety of astronomy points that are shared by all cultures. Make a list of these astronomical universals. Any universal property of all human cultures must arise from something very deep. For each item on your list, see if you can work out why it is a universal.

2 When we look back at ancient astronomy, it is often like we are looking at a mirror up in the sky. What we are seeing reflects on our current world. We can see events in the past that mirror ongoing events in our own time. We can learn good and bad ideas from the results and consequences in olden times, usually without the burden of our own modern preconceived notions and agendas, so history might be able to provide some guidance to the thoughtful student. Look back through the course material and topics, seeing what situations have parallels in our times. Then, consider whether it is wise to make an application to modern policy.

3 The Needham question is "Why did modern science, the mathematization of hypotheses about Nature, with all its implications for advanced technology, take its meteoric rise only in the West at the time of Galileo [but] had not developed in Chinese civilisation or Indian civilisation?" For astronomy, this same question applies: Why did the exponential growth of astronomy knowledge and research come only in Europe, starting with Copernicus and Galileo, with no similar exponential growth in either China or India or elsewhere?

Activity

1 Repeat Galileo's Leaning Tower of Pisa experiment. Simultaneously drop 2 items of greatly different weight from some height and watch whether they hit the ground simultaneously. If Aristotle's physics is correct, the heavy object will fall much faster than the light object and will hit the ground long before the other ball. Is Aristotle's prediction true?



LECTURE 24

Ancient Astronomy and Modern Astrophysics

Ancient astronomy is more than just the precursor to modern astronomy. As you will learn in this lecture, the sky records and observations of the ancient astronomers are used by modern astronomers as data that yield results for modern astronomy. The modern astronomer is doing modern science. Usually, the trick is that the ancient data is very old, and the long time interval amplifies some effect of interest. And sometimes, the goal is simply getting firsthand information about what a long-past event looked like.

HALLEY'S COMET

- Edmund Halley was a British astronomer working in the decades around 1700. He was highly influential in many ways. He proposed to use the transit of Venus to measure the distance to the Sun, and this turned into a multinational program that dominated astronomy until the late 1800s. He also persuaded Isaac Newton to write the book *The Principia*, which has defined all of physics—up until some additions were made a century ago.

- Halley is best known as the namesake of Halley's Comet, which comes around every 75 years. He did not discover the comet, because the Chinese and Babylonians had been watching it for more than 2 millennia.

- Halley was simply trying to calculate orbits for various bright comets from long-past history, following the agenda laid out by Newton in his *Principia*. Most of these comets were from centuries past, so Halley was using large amounts of pre-telescopic observations of the positions of the brightest comets as they moved through the sky. With the theory and math methods from the *Principia*, Halley found the orbital parameters for each of the ancient comets.

- In 1705, Halley noticed that 4 of these ancient comets had rather similar orbits. These were the comets in the years 1456, 1531, 1607, and 1682. Then, he noticed that these comets were separated by time intervals of close to 75 years.

- Halley was thinking about the situation within the paradigm of Newtonian mechanics, where any one comet had a set orbit and would repeatedly follow along the same track time after time. In this paradigm, it was easy for Halley to realize that these 4 old comets were actually just 1 comet coming around 4 times. This discovery was only possible because long-dead astronomers had carefully recorded their measured positions.

- This wasn't the discovery of Halley's Comet, or of comets, or of comet orbits. But it put all this together into one easily understood package. Halley's Comet became the poster child for Newton's new mechanics.

- Halley's discovery was another step in the march to take the supernatural out of the sky. Halley's discovery showed that comets obeyed Newton's laws of physics. And they became predictable, at least in principle. Comets suddenly became a lot less fearsome.

DISCOVERY OF PROPER MOTION

- In 1718, Halley discovered that some stars are slowly moving across the sky when viewed against the background stars. Astronomers now call this proper motion. Stars are independent bodies spread throughout our galaxy, each moving on its own path. If a star happens to have its motion, relative to our Sun, moving across the line of sight, then it will look like the star is moving.

- For stars shuffling around our Milky Way, closer stars will appear to move the fastest. These closer stars also must be the brighter stars.

- Halley was of the modern idea that stars are just floating around space, so proper motion is to be expected. During a study of star positions, he noticed that his modern positions were substantially different from the ancient positions for 3 of the brightest stars, based on their positions from Ptolemy's *Almagest*.

- Halley saw that Sirius, Arcturus, and Aldebaran were each more than ½° off. That's more than 1 Moon diameter. He thought this was too large to be simply some triple error by Ptolemy. So, Halley correctly realized that he was watching stars move through space.

- This was the discovery of proper motion. It was only possible because the ancient data was a very long time back. In such a case, very old measures of moderate accuracy are greatly better than waiting some decades to collect new observations with better accuracy.

- Halley's discovery contributed to the replacement of Aristotle and Ptolemy. The old Greeks had the planets and stars attached to crystalline spheres, and with this, individual stars could not move around independently. But with Halley's proper motion, the crystal spheres were shattered.

EARTH'S ROTATION AND THE MOON'S ORBIT

- In 1695, Halley started the modern analysis of the ancient records of solar and lunar eclipses. The oldest ones he had available were the 22 lunar eclipses in the *Almagest*, of which the oldest was from a Babylonian record dating back to 721 B.C. Halley also had a few eclipses reported in medieval times.

- By using these very old times, he could work up the most accurate periods for the Sun and Moon. After all, that's the same reason Ptolemy used the old Babylonian records that were ancient for him. Halley found some irregularity, which he interpreted as the Moon going faster and faster in its orbit around the Earth.

- The simple picture would be that the Earth and planets go around our Sun in an invariant orbit, our Moon goes around our Earth always with the same orbital period, and our Earth rotates around its polar axis in a constant day.

- With Newton's law of gravity, everyone realized that there will be some subtle jostling of the planets on each other, but detailed calculations showed that these were negligibly small—for the immediate purposes of the time.

- In 1754, the great philosopher Immanuel Kant realized that the tides on Earth are making a drag that must slow down the Earth's rotation. Soon enough, people realized that Newton's law of the conservation of angular momentum means that the Earth's lost angular momentum mainly goes into the Moon's orbit, slowing and expanding it.

- So, Earth's day should be getting longer, and so should the Moon's orbital period.

- We're talking about effects that are impossibly small to measure from cycle to cycle, even with the best of modern technology. But these very small changes will accumulate, cycle to cycle. So, if you can collect enough cycles, then the effects can become observable.

- The effects are observable in the ancient observations despite their moderate accuracy. This is the key idea. This is what turns ancient astronomy data into the basis for modern astronomy discoveries.

- To measure the length of the day, you just need times of local noon from ancient data. The trick is that we have to somehow connect their noontime to a modern standard clock. For this, we can use times of solar or lunar eclipses, or lunar occultations of stars.

- We have good records of many eclipses from 721 B.C. up until the discovery of the telescope. The oldest observations are from the Babylonians. As the oldest, these are in many ways the most valuable. We have more than 100 useful solar and lunar eclipse timings from 721 to 47 B.C.

- One difficulty with using ancient eclipse data is trying to understand the ancient time and calendar systems. Fortunately, historians have these well worked out. Often, the times are quoted with both good precision and good accuracy.

- It's also difficult to know how much of the Sun was covered during a solar eclipse. This uncertainty creates larger errors in knowing the rotational position of the Earth at the known time of eclipse. Modern scholars argue over how and whether to include the less reliable reports. A related problem is that often the location of the observer is not specified, and this also contributes to the uncertainty.

- Putting all this together has been a vast process, extending since the time of Halley. With this, we have pretty good measures of the Earth's rotation and the acceleration of the Moon's orbit.

- The rich knowledge we have of how our Earth and Moon are changing speeds is all possible only because Babylonian, Greek, Chinese, Arab, and medieval European astronomers left detailed records of eclipses.

SUPERNOVAS

- Another area where ancient data has had even more remarkable implications are the few precious recorded sightings of the exploding stars known as supernovas. For ancient observers, a supernova appears as a sudden "new star" in the sky. It brightens from nothing to peak in about 2 weeks, stays near peak brightness for a few weeks, and then starts fading.

- We now know that these explosions are from stars at the end of their lives. There are 2 mechanisms that create supernovas, and these are both of very high and broad importance. Roughly 10% of modern astrophysics is aimed at questions with supernovas at their center.

- Just a century ago, astronomers had no idea that there was anything outside our own Milky Way galaxy, nor did they have any idea of what powers the stars. With the use of spectroscopy, we were just starting to break out of the dominance of positional astronomy, turning astronomy into astrophysics. We had spotted occasional supernovas, but they looked largely the same as ordinary novas.

- Various astronomers began recovering remarkable records from pre-telescopic times, including the accurate positions and brightness measures in the book by Tycho on the "new star" of 1572 and the book by Kepler on the "new star" of 1604.

- Furthermore, the Chinese records of the "new star" of 1054 A.D. were pulled out, and this explosion was connected with the weird gas cloud given the name of the Crab Nebula. In 1929, Hubble measured the expansion of the Crab Nebula and realized that the gas cloud was a remnant of a titanic explosion seen by the Chinese.

- With this historical information, plus remarkable insight, this was all put together into 2 short papers in early 1934 by Hubble's colleagues Walter Baade and Fritz Zwicky, who invented the concept of supernovas, invented the name "supernova," realized that supernovas are caused by the collapse of massive stars, invented the concept of a neutron star, and explained the mysterious cosmic rays as being made by supernovas.

- A substantial part of the supernova idea came only because the historical observations were in hand. Another realization came with it: that these supernovas left behind vast clouds of ionized gas, expanding at the rate of many thousands of kilometers per second.

- This realization came because Tycho, Kepler, and the Chinese recorded good positions in the sky for their "new stars," and when modern astronomers looked much later at these same positions, they saw expanding gas clouds.

- By watching these clouds expand, they could date the expansion as coming from near the recorded time for the "new star." Nowadays, we call these supernova remnants. The critical connection between supernovas and supernova remnants came from history.

- Historical records also provided a remarkably valuable fact about the age of each supernova remnant. Today, we know that the Crab remnant was born in 1054, Tycho's was born in 1572, and Kepler's was born in 1604. Two other supernova remnants have exact historical ages: the supernova of 1006 A.D. on the Lupus-Centaurus border and the supernova of 1181 A.D. in Cassiopeia.

- These 5 ages are the touchstone of astrophysics for these remnants. The remnant age is the critical issue for all analysis of supernova remnants.

- All of these issues were pushed to the forefront yet again with the discovery of the Crab pulsar in the middle of Crab Nebula. It was speedily realized that this was the neutron star long predicted by Baade and Zwicky. The pulsar is most easily visible in the radio band, so radio astronomers timed the pulses and found that the spinning neutron star is actually slowing its rotation.

- There is a lot of detailed physics involved, and the key point was its known age. As X-ray astronomers watched the cooling of neutron stars, their only foundation has been the pulsars with known ages.

- Modern astronomers are still finding a wide variety of uses for the ancient data on supernovas.

Readings

Stephenson, "Historical Eclipses and Earth's Rotation."
——— , "Historical Evidence Concerning the Sun."
Stephenson and Green, *Historical Supernovae and Their Remnants*.
Stephenson and Morrison, *Historical Eclipses and Earth's Rotation*.
Xu, Pankenier, and Jiang, *East Asian Archaeoastronomy*.

Questions

1 Our cell phones are now filling many of the functions of ancient astronomy (including navigation, timekeeping, calendars, storytelling, mapmaking, direction finding, prayer times, star charts, planet positions, and astrology). Our culture has divorced itself from the sky and is largely losing contact with nature in general. What our culture has gained is high accuracy and widespread availability. Is this a worthwhile trade?

2 To put things in perspective, compare the utility and importance of ancient astronomy to the utility and importance of ancient physics, ancient biology, and ancient chemistry.

Activity

1 Go outside and see for yourself that stars move through the sky. Ptolemy's *Almagest* states that around 150 A.D., the stars Alpha Librae, Arcturus, and Zeta Ursae Majoris were exactly colinear. Go outside on a clear night, take a string held taut and stable in your hands, carefully align it so that the string occults Alpha Librae and Zeta Ursae Majoris, and then see whether Arcturus really fits on this line with one eye closed. On the basis of this one ancient report, would you be willing to say that you've (re)discovered the proper motion of stars?

List of Constellations

NOTE: The constellation names (but not the proper names) have been translated where possible.

The names of asterisms that might or might not be given the status of full constellations are in square brackets.

The ordering is that used in the *Almagest*, with a few extra added.

Some constellations are given multiple names, and it is unclear whether these are 2 different images for the same stars or just a different name.

The equals sign is used when the same stars have different names.

The comma is used for constellations that make up different parts of the Greek constellations. Some of the MUL.APIN constellations cross over between more than one Greek constellation.

Parenthetical additions are for clarification.

An asterisk indicates that the Greeks took the constellation from the Mesopotamians.

The star identities for some of the MUL.APIN constellations are not well known.

****IAU (1922)**	***Almagest* (150 A.D.)**	**Aratus (c. 275 B.C.)**
* Little Bear	Little Bear	Lesser Bear (Cynosura) = Wain
* Great Bear	Great Bear	Greater Bear (Helice) = Wain
Dragon	Big Snake	Dragon
Cepheus	Cepheus	Cepheus
Herdsman	Boötes	Boötes = Arctophylax
Northern Crown	Northern Crown	Crown
Hercules	Kneeler	Engonasin = Kneeler = Phantom
Lyre	Lyre	Tortoise = Lyre
Swan	Bird	Bird
Cassiopeia	Cassiopeia	Cassiopeia
Perseus	Perseus	Perseus
* Charioteer	Charioteer	Charioteer
Serpent Bearer	Ophiuchus	Ophiuchus
Serpent	Snake of Snake Holder	Serpent
Arrow	Arrow	Arrow
* Eagle	Eagle	Eagle = Stormbird
Dolphin	Dolphin	Dolphin
Small Horse	Figurehead of a horse	
Pegasus	Horse (Pegasus)	Horse
Andromeda	Andromeda	Andromeda
Triangle	Triangle	Deltoton
Ram	Ram	Ram
* Bull	Bull	Bull
* Gemini	Gemini	Twins
* Crab	Crab	Crab
* Lion	Lion	Lion

**International Astronomical Union

Homer and Hesiod (c. 750 B.C.)	MUL.APIN (1370 ± 100 B.C.)
	Wagon of Heaven, Hier of Sublime Temple
Great Bear = Wagon	Wagon, Fox
	Hitched Yoke, Pig
Boötes	SU.PA, Ewe
	Dignity
	Standing Gods of Ekur, Sitting Gods of Ekur, Dog
	She-goat, Lamma, Ninsar, Erragal
	Panther
	Horse
	Old Man
	(Shepherd's) Crook
	Zababa
	Eagle
	Dead Man
	Field, Swallow
	Stag, Rainbow, Deleter
	Plow, Wolf
	Hired Man
	Bull of Heaven
	Great Twins, Little Twins
	Crab
	Lion, King

**IAU (1922)	*Almagest* (150 A.D.)	Aratus (c. 275 B.C.)
* Virgin	Virgin	Maiden
* Scales	Claws (of Scorpion)	Claws
* Scorpion	Scorpion	Scorpion
* Archer	(Centaur) Archer	Wielder of the Bow
* Sea Goat	Sea Goat	Aegoceros
* Water Bearer	Water Bearer	Hydrochous
* Fish	(Two) Fish	Fishes
Whale	Whale	Monster of the Sea = Cetus
Orion	Orion	Orion
River	River	River
Hare	Hare	Hare
Big Dog	Dog	Dog
Little Dog	Procyon	Procyon
Keel + Stern + Sails	Argo	Argo
* Water Snake	Water Snake	Hydra
Cup	Cup	Cup
* Crow	Crow	Raven
Centaur	Centaur	Centaur
* Wolf	Beast	Beast
Altar	Incense Burner	Altar
Southern Crown	Southern Crown	[Ringed Circle]
* Southern Fish	Southern Fish	Southern Fish
Berenice's Hair	[Berenice's Hair]	
* [Pleiades]	[Pleiades]	Pleiades
* [Hyades]	[Hyades]	[Hyades]
[Arcturus]	[Arcturus]	[Arcturus]
		[Water]

Homer and Hesiod (c. 750 B.C.)	MUL.APIN (1370 ± 100 B.C.)
	Furrow
	Scales
	Scorpion, Lisi, Nabu, Sarur, Sargaz
	Pabilsag (Centaur archer), Bark
	Goatfish
	Great One
	Anunitu
Orion	True Shepard of Anu, Lulal and Latarak
	Rooster
Sirius, Orion's Dog	Arrow
	Bow
	Eridu, Ninmah, Harrow
	Snake
	Raven
	EN.TE.NA.BAR.HUM, Numusda, Sullat and Hanis
	Mad Dog
	Fish
	Lion Tail, Frond of Eru, Abundant One
Pleiades	Stars
Hyades	Jaw of the Bull
[Arcturus]	

Timeline

B.C.

c. 14000 years ago	Great Bear came across the Bering Strait
10,900	Younger Dryas meteor impact event (maybe)
c. 5000 to c. 2000	Dolmens throughout Eurasia astronomically aligned
4500 to 1900	Age of Taurus
4100	First iron (i.e., meteoritic) grave goods in Iran
3400	First iron (i.e., meteoritic) grave goods in Egypt
3300 to 1200	Bronze Age in Anatolia (Stone Age before, Iron Age after)
3200 ± 500	Creation of Chinese lunar lodge system
3150 to 600	Bronze Age in Egypt (Stone Age before, Iron Age after)

c. 3100 to c. 1600	Stonehenge construction
c. 3100 to c. 2000	Newgrange construction
c. 3000	Maeshowe construction start
c. 3000	Recumbent stone circles in Scotland
2600 to 1800	Cardinal orientation of pyramids in Egypt
c. 2554	Great Pyramid oriented to $\frac{1}{20}°$ precision
c. 2500	Stonehenge, sarsens, and trilithons erected
2300	Omens start appearing in Mesopotamia
2134 as the traditional date	Hsi and Ho beheaded for not predicting eclipse
26 Feb 1953	Conjunction at start of Hsia dynasty
1900 to 100	Age of Aries
c. 1800	Compilation of omens in Mesopotamia
1750 ± 640	Creation of Indian lunar lodge system from Chinese system

c. 1700	Mesopotamian Prayer to the Gods of the Night lists constellations
26 Dec 1576	Conjunction at start of Shang dynasty
1500	Earliest known sundial
1400 to 1100	Evidence for many Mesopotamian constellations
1370 ± 100	MUL.APIN observations made
c. 1330	King Tut's tomb with meteoritic iron knife and more
1130 ± 80	Year of observations reported by Eudoxus
c. 1100	Oracle bones in Shang dynasty record stars, eclipses, and lunar lodges
28 May 1059	Conjunction at start of Chou dynasty
c. 750 ?	Homer and Hesiod mention 7 stars, clusters, and constellations
721 to 47	Babylonian eclipse records
687 to 281	Surviving and dated MUL.APIN tablets
c. 600 to 200	Greek flowering of astronomy

585	Thales's eclipse stops a 5-year war (the prediction is problematic)
c. 500	Zodiac finished in Babylon
500 to 200	Natal horoscopes start in Babylon
c. 450	Anaxagoras explains lunar phases, eclipses, and the Sun
27 June 432, sunrise	Meton's timing of summer solstice and 19-year Metonic cycle
413	Nicias's eclipse stops evacuation of siege of Syracuse
c. 400 to 200	Chinese "imperial constellations" invented
c. 400	Fen Yeh (field allocation) geo-astrology
366	Eudoxus's *Phaenomena* describes all Greek constellations
357	Dion's lunar eclipse (no fear after Anaxagoras's explanation)
350 to 100	Shi Shen's star catalog
350 to 50	Babylonian planet models (with calculus!)
350	Aristotle wrote *On the Heavens*

330	Callippus in Athens discovers "solar anomaly" (variable speed)
290 to 100	Greeks adopt Babylonian zodiac and astrology
275	Aratus's *Phaenomena* (poetic version of Eudoxus's book)
c. 250	Archimedes makes sky globes with planet motions
c. 250	Aristarchus of Samos speculates on Sun-centered solar system
204	Idean Mother brought to Rome for use against Hannibal
200 ± 600	Creation of Arabic lunar lodge system
c. 200	Eratosthenes in Alexandria measures radius of Earth
c. 200	Saros cycle (18 years and 11.33 days)
c. 200	Apollonius of Perga adds epicycles
200 B.C. to 400 A.D.	Greek eclipse records
136 ± 8	Hipparchus discovers precession and makes a star catalog
130 to 70	Construction date of Antikythera mechanism

125 ± 55	Farnese Atlas star data
c. 100	Chinese zodiac (12-year cycle of animals)
fl. 100	Ssu-ma Chien, the grand historian, treatise on all Chinese astronomy
c. 100	Hellenized astrology ported to Egypt
100 B.C. to 2500 A.D.	Age of Pisces
c. 78	Posidonius makes flat model of solar system (seen by Cicero)
c. 70	Hellenized astrology ported to Rome (by Posidonius)
67	First Mithraic rites recorded by Cilician pirates
23 September 63	Birth of Octavian (with very propitious natal horoscope)
46	Julius Caesar reforms to make Julian calendar
44	Caesar's comet (used as propaganda by Octavian)
12	Halley's comet appeared (*not* the Star of Bethlehem)
17 April 6	Molnar's Star of Bethlehem as a natal horoscope

5	Comet seen by the Chinese (*not* the Star of Bethlehem)
4	Herod the Great dies (date known from lunar eclipse)
2	Venus-Jupiter occultation (*not* the Star of Bethlehem)

A.D.

7 April 30 and 3 April 33	Crucifixion candidate dates
54	Comet on the death of Emperor Claudius
60	First comet of Nero
64	Second comet of Nero (suicide of Seneca)
c. 80 to 90	Gospel of Matthew written down (with narrative on the Star of Bethlehem)
c. 100 to 300	Hellenized astrology ported to India
150	Ptolemy's *Almagest*
218 to 222	Roman Emperor Elagabalus makes meteorite worship supreme
320	Chinese discover precession

434 to 1280	Chinese eclipse records
570	Chinese discover inequality of seasons
c. 600	Indian astronomy imported into China
605	Kaaba restored; Muhammad places Black Stone as cornerstone
700 to 1500	Heyday of astrolabes
725	I Hsing in China measures radius of Earth
800 to 1100	Viking Age with oceangoing navigation
827	Arab astronomers near Baghdad measure radius of Earth
830 to 1020	Arab eclipse records
830 to 1150	Chaco Canyon occupancy
c. 850	Dorset people find the Cape York meteorite
960	Al-Sufi star catalog
c. 1050	Compass invented for navigation in China
1054	Crab supernova

1265 to 1600	Medieval European eclipse records
c. 1300	Compass makes it to Europe
after 1300	Astronomical clocks and orreries throughout Europe
1437	Ulugh Beg's star catalog
1456, 1531, 1607, 1682	Returns of Halley's Comet known to Halley
1492 to 1493	Christopher Columbus's first voyage
1502 to 1504 (29 Feb 1504)	Columbus's fourth voyage (lunar eclipse)
1514 to 1770	Lunar-distances method being worked on
1543	Nicholas Copernicus published *De Revolutionibus*
1572	Tycho's supernova in Cassiopeia
1577	Tycho's comet
c. 1580	Jesuits arrive in China, bringing Western star knowledge
1582	Pope Gregory XIII reforms calendar to Gregorian calendar

1589 reportedly	Galileo's Leaning Tower of Pisa experiment
1590, 1596	Plancius invented many far-southern constellations
1592, 1597	Tycho's star catalog
1604	Kepler's supernova in Ophiuchus
1609	Kepler published his first 2 laws
1610	Galileo makes many great discoveries with his telescope
c. 1600 or 1610	End of ancient astronomy

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Aratus. *Phaenomena*. Translated by G. R. Mair. Cambridge, MA: Harvard University Press, 1921. The most characteristic book of early Greek astronomy. Tells the Greek knowledge of the stars and planets and how they move, plus the signs that relate the weather to the skies. Aratus’s poem was a runaway best seller with high popularity for both the Greeks and Romans, has 27 known published commentaries, and is even quoted in the New Testament (Acts 17:28).

Aveni, Anthony F. *Empires of Time: Calendars, Clocks, and Cultures*. London: Tauris Parke Paperbacks, 2000. Covers the world with comprehensive and in-depth looks at timekeeping and calendars—for the Western tradition, tribal societies, the Maya, the Aztec, the Inca, and the Chinese. Fun reading. Aveni is both an astronomer (originally) and an anthropologist (by long practice), and this is valuable for getting the facts right and for keeping a broad picture.

Barthel, Peter, and George van Kooten, eds. *The Star of Bethlehem and the Magi: Interdisciplinary Perspectives from Experts on the Ancient Near East, the Greco-Roman World, and Modern Astronomy*. Leiden, South Holland, Netherlands: Brill, 2015. Conference aimed at testing and publicizing Molnar's solution, with the latest work on the Star of Bethlehem from a wide variety of disciplines.

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———. "On the Orientation of Old Kingdom Egyptian Pyramids." *Journal for the History of Astronomy* 32, *Archaeoastronomy Supplement* no. 26 (2001): S1–S20. http://adsabs.harvard.edu/abs/2001JHAS...32....1B. Measures of many pyramid orientations and ventilation shaft elevations, plus a summary of the evidence from the hieroglyphic texts.

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Carina Software and Instruments. *Voyager*. http://www.carinasoft.com/voyager.html. Classical planetarium program showing the sky in any direction as viewed from any location at any time. Voyager was used extensively in developing this course, partly because the positions in ancient times compare well against the definitive Jet Propulsion Laboratory ephemerides. However, all the many planetarium programs do a wonderful job, even back to historical times. Voyager is for a Mac or a computer running Windows. Other excellent planetarium software (including some that also run under Linux) are Stellarium (free at http://www.stellarium.org/), Starry Night (http://astronomy.starrynight.com/), and Cartes du Ciel (free at http://www.ap-i.net/skychart/en/start).

Carman, Christian C., Alan S. Thorndike, and James Evans. "On the Pin-and-Slot of the Antikythera Mechanism, with a New Application to the Superior Planets." *Journal for the History of Astronomy* 43 (2012): 93–116. A reasonable way to incorporate the planets into the Antikythera mechanism with just 4 gears per planet. The pin-and-slot mechanism is a unique innovation that accounts for the lunar anomaly as expressed with the epicycle of Hipparchus's lunar model.

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Katasterismoi and Hyginus's *Poetical Astronomy*. Often, the stories are contradictory, demonstrating that the old myths are not some canonical block of lore. Good commentary from Condos.

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Espenak, Fred. *Mr. Eclipse*. http://www.mreclipse.com/MrEclipse.html. One-stop shopping for all eclipse information, going far in the past and far into the future. Fred Espenak has for 3 decades provided the definitive eclipse calculations, exhaustive explanations and advice on eclipses of all types, and detailed instructions on how to view eclipses. Espenak's definitive ephemeris calculations are mirrored at http://eclipse.gsfc.nasa.gov/eclipse.html.

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Hadingham, Evan. *Early Man and the Cosmos*. Norman, OK: University of Oklahoma Press, 1984. A fun romp through archaeoastronomy, myths, and observations of prehistoric sky watchers. Emphasis on Britain, North American Indians, and the Maya. While extensively discussing now-long-discarded ideas, Hadingham usually gets it right and tells the reader why the old claims have been rejected.

Hawkins, Gerald. *Stonehenge Decoded*. New York: Dell, 1965. Hawkins started the enduring worldwide obsession with Stonehenge, and this is the book that launched the whole industry of archaeoastronomy. We now know that all of Hawkins new claims are wrong. The only surviving claim is the old one that the main axis points toward midsummer sunrise, and this is likely wrong, too, with the intended pointing of the main axis in the opposite direction, toward the midwinter sunset.

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Johnson, Dianne. *Night Skies of Aboriginal Australia: A Noctuary.* Sydney: Sydney University Press, 2014. Scholarly view of all aspects of Aboriginal astronomy, with examples from throughout Australia and copious citations. Chapter 2 gives Aboriginal worldview and cosmology.

Krupp, E. C. *Echoes of the Ancient Skies: The Astronomy of Lost Civilizations*. New York: Harper & Row, 1983. In a fun style, this book collects many stories on city orientation, solstice alignments and celebrations, grave and tomb orientation, stone circles, and cardinal alignments. Like most popular books on archaeoastronomy, all claims are presented equally with little critical evaluation, so the reader is presented with many claims that are now long refuted that all appear valid.

Kuhn, Thomas S. *The Structure of Scientific Revolutions*. Chicago: University of Chicago Press, 1962. Wonderful paradigm for how scientific revolutions proceed. Readable but scholarly book, highlighting the Copernican revolution. For fair warning, philosophers of many stripes (and political scientists and economists) have put forth many tweaks, metaphysical musings, and rants to Kuhn's thesis. Real historians and scientists ignore the metaphysics and realize that Kuhn has grasped a large part of the reality.

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Lewis, John S. *Rain of Iron and Ice: The Very Real Threat of Comet and Asteroid Bombardment*. New York: Basic Books, 1996. Readable, popular, and scary account of the stories and statistics of meteor falls and impacts from old history and how they affect humans in big and small ways. This definitive argument has the historical death rate by meteors being much higher than conceived of popularly. From available reports from the Yuan and Ming dynasties in China alone, the total casualties are more than 10,000 people spread over 6 events.

Magli, Giulio. *Mysteries and Discoveries of Archaeastronomy: From Giza to Easter Island*. New York: Praxis Publishing, 2009. Fun and chatty exploration of the many sides of archaeoastronomy and ancient astronomy lore from around the world. Topics bounce around a lot, with somewhat of a concentration on the Egyptian pyramids. Magli is often not judicious, including many strongly rejected claims in an apparent effort to include anything ever proposed.

Molnar, Michael R. "Astrological Omens Commemorated on Roman Coins: Capricorn." *Celator* 8, no. 4 (1994): 6–15. Analysis of the natal horoscope of Augustus Caesar, showing why at least 2 widely separated astrologers during Octavian's youth identified him as soon to be the ruler of the world. Molnar has a long history of work on the natal horoscopes of great kings around the edge of the Mediterranean, a body of work that is unique and valuable because it is reproducing the ancient astrological interpretations by using the rules as given in the relevant ancient texts.

———. *The Star of Bethlehem: Legacy of the Magi*. New Brunswick: Rutgers University Press, 1999. Molnar's epochal convincing solution is that the Star of Bethlehem is the natal horoscope for 17 April 6 B.C. For the first time since Kepler, a really new idea was put forth. The basis is that

Magi were acting as astrologers (not astronomers), so the known rules of ancient astrology had to be used in detail. No one had done this previously. Molnar's solution has been sweeping the scholarly world.

Monroe, Jean Guard, and Ray A. Williamson. *They Dance in the Sky: Native American Star Myths*. Boston: Houghton Mifflin Company, 1987. This is a storybook, not a scholarly treatise. The myths associated with the constellations of the Native American Indians are many and varied, as each tribe has different stories for the same stars. Many stories have been long lost, and even so, this book can only scratch the surface.

Morison, Samuel Eliot. *Admiral of the Ocean Sea: A Life of Christopher Columbus*. Boston: Little, Brown, and Company, 1942. Full and correct story of Columbus at Salamanca. Definitive biography of Columbus. Wonderful detail on Columbus's navigation methods, as well as his mostly horrible attempts to measure latitude and longitude.

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Nikoli, Magdalene, and John H. Seiradakis. "The First Newspaper References to the Antikythera Shipwreck Discoveries." In *From Antikythera to the Square Kilometer Array: Lessons from the Ancients*, 12–15 June 2012, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=170. PDF available at http://adsabs.harvard.edu/abs/2012aska.confE..10N. The true story of the discovery from primary sources. Shows that many tertiary web pages get many facts wrong.

Ossendrijver, Mathieu. “Ancient Babylonian Astronomers Calculate Jupiter’s Position from the Area under a Time-Velocity Graph.” *Science* 351, 29 January (2016): 482–484. Everyone was startled when Ossendrijver discovered that a Babylonian cuneiform tablet recorded a mathematical method to calculate the position of Jupiter that was certainly doing what would be called calculus. A nice piece of work, and a real eye opener about the remarkable astronomy of ancient times.

Pearson, Mike Parker, and the Stonehenge Riverside Project. *Stonehenge: Exploring the Greatest Stone Age Mystery*. London: Simon & Schuster, 2012. One of the premier archaeologists of Stonehenge tells all about the details of the modern excavations, all in a chatty and definitive manner. These excavations are in the area outside of the Stonehenge ditch, often miles away. There are still many recent surprises that tell a lot about the basic stones of Stonehenge.

Price, Derek de Solla. “Gears from the Greeks: The Antikythera Mechanism—A Calendar Computer from ca. 80 B.C.” *Transactions of the American Philosophical Society* 64 (1974): 1–70. A readable paper that starts with all the historical details and technical details. This tour de force is the culmination of 23 years of work and has all the key insights. Until 2006, Price’s claims were largely disregarded due to lack of convincing evidence. The 2006 work on 3-dimensional X-ray tomography showed that Price was right in the overview and in many of the details.

Ptolemy, Claudius. *Tetrabiblos*. Edited and translated by F. E. Robbins. Cambridge, MA: Harvard University Press, 1964. Available online at http://www.sacred-texts.com/astro/ptb/ or at https://archive.org/stream/manethowithengli00maneuoft#page/n299/mode/2up. The bible of ancient astrology, written around 160 A.D., is a dense summary of all the rules. If you want to see how ancient astrology really worked, you can’t get better than Ptolemy.

———. *Ptolemy’s Almagest*. Translated and annotated by G. J. Toomer. Princeton, NJ: Princeton University Press, 1998. Definitive translation of the *Almagest*. Frequent resource book for astrohistorians for considering almost anything in the Western tradition up to 1600 A.D. Ptolemy's writing is very dense, being filled with calculations, derivations, tables, and numbers. You'll have to work hard to understand anything much, and it will require some technical and astronomical knowledge.

Ramsey, John T., and A. Lewis Licht. *The Comet of 44 B.C. and Caesar's Funeral Games*. Atlanta: Scholars Press, 1997. Definitive and exhaustive story on Caesar's comet. A unique collaboration between a classics scholar and an astronomer.

Ruggles, Clive. *Ancient Astronomy: An Encyclopedia of Cosmologies and Myth*. Santa Barbara: ABC-CLIO Inc., 2005. Definitive encyclopedia covering the whole breadth of ancient astronomy, with an emphasis on archaeoastronomy. Ruggles is 1 of the 2 greatest archaeoastronomers, with the other being Michael Hoskin. Ruggles does not shy away from politely labeling bad ideas as bad, unlike much of the way-too-polite can't-reach-a-negative-conclusion literature throughout archaeoastronomy.

———. *Astronomy in Prehistoric Britain and Ireland*. New Haven, CT: Yale University Press, 1993. A full course on the history, theory, techniques, statistics, and alignments of archaeoastronomy in the British Isles. Definitive and exhaustive.

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———. “Conjunctions That Changed the World.” *Sky and Telescope* 99, May (2000): 28–34. Stories about the mandate of heaven and the conjunctions at the start of the Hsia, Shang, and Chou dynasties; the universal deluges of 1186 and 1524; and the conjunctions of Genghis Khan, Chaucer, and Rudolf Hess. Article timed to coincide with the feared-on-the-internet conjunction of May 4, 2000.

———. “Lunar Crescent Visibility.” *Quarterly Journal of the Royal Astronomical Society* 37 (1996): 759–768. http://adsabs.harvard.edu/abs/1996QJRAS..37..759S. Observations of the thin crescent used to test the ancient and medieval prediction algorithms, which are all found to be poor and biased. The record young crescents are 15 hours after the new Moon by an unaided eye and 12.1 hours for a telescopic view.

———. “Lunar Eclipses That Changed the World.” *Sky and Telescope* 84, December (1992): 639–642. Stories how lunar eclipses changed history. Highlighted episodes are the siege of Syracuse by Nicias in 413 B.C., the fall of Constantinople in 1453, Columbus’s trick in 1504, the siege of Soochow during the Taiping Rebellion by General Gordon in 1863, and the critical attack on Aqaba by Lawrence of Arabia in 1917. The timing of the publication was for a well-placed lunar eclipse in 1992.

———. “Lunar Visibility and the Crucifixion.” *Quarterly Journal of the Royal Astronomical Society* 31 (1990): 53–67. http://adsabs.harvard.edu/abs/1990QJRAS..31...53S. The lunar crescent visibility from 26 to 36 A.D., as viewed from Jerusalem for the lunar months of Nisan, is the critical point for calculating the date of the Crucifixion. Now the definitive paper on the question, it grabbed a huge amount of public attention from all over the world.

———. “Meteors That Changed the World.” *Sky and Telescope* 96, December (1998): 68–75. Stories about how meteors and meteorites have changed history in big ways. This includes the Cape York meteorite, the Idean Mother versus Hannibal, the Red River meteorite, the Black Stone of Emessa with Elagabalus, the Black Stone of the Kaaba, and the Chicxulub dinosaur killer. Five years in advance, the date for publication was chosen so that it would appear in *Sky & Telescope* at the time of the awesomely great Leonid meteor storm.

———. "Solar Eclipses That Changed the World." *Sky and Telescope* 87, May (1994): 36–39. Highlighted solar eclipses are associated with the prophet Muhammad (in the years 569, 632, and 661), with Tecumseh and his brother Tenskwatawa (in the year 1806), with the slave revolt leader Nat Turner (in 1831), and with the great physicist Albert Einstein (in 1919). Two years in advance, the publication was timed for a solar eclipse crossing mid-America.

———. "The Epoch of the Constellations on the Farnese Atlas and Their Origin in Hipparchus' Lost Catalogue." *Journal for the History of Astronomy* 36, (2005): 167–196. http://adsabs.harvard.edu/abs/2005JHA....36..167S. The Farnese Atlas is a large marble statue, now in Naples, showing the Titan Atlas holding a celestial globe on his shoulders. These constellation positions date to 125 ± 55 B.C., pointing to Hipparchus's long-lost star catalog.

———. "The Great Ptolemy-Hipparchus Dispute." *Sky and Telescope* 103, February (2002): 39–44. From Tycho to the present day, astrohistorians have a vehement controversy over whether Ptolemy's 1028 star catalog is copied (without attribution) from Hipparchus's now-lost star catalog. The arguments come from many directions, and they always go many levels deep. There is little in the way of decisive proofs. The conclusion is that Ptolemy's catalog did have some heritage from Hipparchus, but that most of it was Ptolemy's own.

———. "The Latitude and Epoch for the Formation of the Southern Greek Constellations." *Journal for the History of Astronomy* 33 (2002): 313–350. http://ukads.nottingham.ac.uk/abs/2002JHA....33..313S. The constellations have a southern zone of avoidance, or void, with no constellations. The edges of this void can be used to define and constrain the radius and center of the void. With this, the southern Greek constellations were made around the year 700 B.C. from a latitude of 33°.

———. "The Latitude and Epoch for the Origin of the Astronomical Lore of Eudoxus." *Journal for the History of Astronomy* 35, (2004): 161–223. http://adsabs.harvard.edu/abs/2004JHA....35..161S. Analysis of 173 specific lore items used by Eudoxus (as taken from Aratus and Hipparchus) that depend on the date or latitude for their validity. From this, lore must have been collected in 1130 ± 80 B.C. at a latitude of 36.0° ± 0.9°, clearly pointing to a Mesopotamian origin for the lore repeated by Eudoxus, then Aratus, and then Hipparchus.

———. "The Latitude of the Observer of the Almagest Star Catalog." *Journal for the History of Astronomy* 32 (2001): 1–42. http://adsabs.harvard.edu/abs/2001JHA....32....1S. Uses stars around the southern horizon to determine latitude and epoch of the catalog. In the first 3 quadrants, the observer was at a latitude of 32.0° ± 0.8° and an epoch of 500 ± 200 A.D., pointing strongly to Ptolemy as the observer. In the fourth quadrant, the observer was at a latitude of 35.7° ± 1.1° and an epoch of 600 ± 500 B.C., with Hipparchus mildly preferred over Ptolemy.

———. "The Origin of the Greek Constellations." *Scientific American* 295, November (2006): 70–75. Basic story of the development from the ancient to modern set of constellations. "Constellations provide a unique way of gaining insight into a culture (different from, say, pottery styles) because they consider an intellectual aspect of prehistoric society, something that is hard to discern from more typical archaeological sources. Furthermore, the sequence in the uses to which societies put constellations tracks the way one aspect of astronomy was transformed into a modern science."

———. "The Star of Bethlehem is *Not* the Nova DO Aquilae (Nor Any Other Nova, Supernova, or Comet)." *The Observatory* 133, (2013): 227–231. http://adsabs.harvard.edu/abs/2013Obs...133..227S. A widely publicized book in 1999 put forth a claim that the Star of Bethlehem was a particular nova (DO Aquilae), but this claim cannot be valid for several strong reasons from astronomy.

———. "The Thousand Star Magnitudes in the Catalogues of Ptolemy, Al Sufi, and Tycho Are All Corrected for Atmospheric Extinction." *Journal for the History of Astronomy* 44 (2013): 47–74. http://arxiv.org/abs/1303.1833. All of the old star catalogs quote magnitudes that are corrected for extinction. This is startling to astrohistorians, because there is no mention of anything even vaguely like atmospheric dimming before 1723, much less formulating a way to correct for extinction. PDF online contains long technical appendices.

———. "Vikings and Polarization Sundials." *Sky and Telescope* 93, May (1997): 91–94. The Viking sunstones are still a mystery of their navigation. A prominent and wrong proposal is that the Viking navigational aid was some method to measure the polarization of the daytime sky. Another astronomical tool from ancient astronomy is the sundial. These 2 astro-history themes are put together as a polarization sundial. This whimsical idea actually works. Pictures of the only existing polarization sundial and instructions for building one.

Schaefer, Bradley E., Imad A. Ahmad, and LeRoy Doggett. "Records for Young Moon Sightings." *Quarterly Journal of the Royal Astronomical Society* 34 (1993): 53–56. http://adsabs.harvard.edu/abs/1993QJRAS..34...53S. The friendly competition for spotting the youngest crescent Moon has deep implications for debate on criteria on accepting/rejecting claimed sightings of the Ramadan Moon.

Sobel, Dava. *A More Perfect Heaven: How Copernicus Revolutionized the Cosmos*. New York: Bloomsbury, 2012. Tells the story of Copernicus and how *De Revolutionibus* both fits in with the old Greek astronomy and also broke from it.

———. *Galileo's Daughter: A Historical Memoir of Science, Faith, and Love*. New York: Walker & Company, 1999. A best seller telling the story of Galileo's humanity and science. Warning: The majority of the competing books and articles on Galileo have the authors pushing some modern philosophical/political/religious agenda with their "reinterpretations."

———. *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time*. New York: Walker & Company, 1995. Details how the longitude problem was solved by a clockmaker, not by astronomers. Sobel has written a number of critically acclaimed popular astrohistory books, including *Galileo's Daughter* and *Longitude*.

Sofaer, Anna, Volker Zinser, and Rolf M. Sinclair. "A Unique Solar Marking Construct." *Science* 206, 19 October (1979): 283–291. The discovery paper for the Sun dagger on Fajada Butte.

Souden, David. *Stonehenge: Mysteries of the Stones and the Landscape*. London: Collins and Brown/English Heritage, 1997. Overview of Stonehenge as well as its detail in a beautiful picture book. Many good explanatory diagrams.

Spence, Kate. "Ancient Egyptian Chronology and the Astronomical Orientation of Pyramids." *Nature* 408, 16 November (2000): 320–324. Details a widely publicized claim that the pyramids were oriented on the direction toward where Mizar and Kochab are vertically placed. Her claim has been widely attacked in the scholarly community on many strong grounds, with no real chance of her proposed alignment scheme having actually been used by the Egyptians.

Staal, Julius D. W. *The New Patterns in the Sky: Myths and Legends of the Stars*. Blacksburg, VA: McDonald and Woodward Publishing Company, 1988. Myths for each constellation; about a third of the coverage is for non-Western myths from around the world. Highlights of the best astronomical objects in some of the constellations. Drawings are good for seeing the many star pictures.

Stephenson, F. Richard. "Chinese and Korean Star Maps and Catalogs." In *The History of Cartography: Volume Two, Book Two—Cartography in the Traditional East and Southeast Asian Societies*, edited by J. B. Harley and David Woodward, 511–578. Chicago: University of Chicago Press, 1994. http://www.press.uchicago.edu/books/HOC/HOC_V2_B2/

Volume2_Book2.html. Detailed and exhaustive summary of Chinese star measures up to 1600 (the coming of the Jesuits). Easily readable. See Miyajima's article on Japanese sky maps in chapter 13, pages 579–603.

———. "Historical Eclipses and Earth's Rotation." *Astronomy & Geophysics* 44 (2003): 2.22–2.27. http://adsabs.harvard.edu/abs/2003A%26G....44b..22S. Popular, readable, and full description of how to use the ancient observations of eclipses to pull out the variations in the Earth's rotation speed.

———. "Historical Evidence Concerning the Sun: Interpretation of Sunspot Records during the Telescopic and Pretelescopic Eras." *Philosophical Transactions of the Royal Society of London* series A, 330 (1990): 499–512. http://www.jstor.org/stable/53599?origin=ads&seq=1#page_scan_tab_contents. Impressive results in a long program of correcting ancient Chinese sunspot reports for the survival rate of such reports. The way to do this is to compile rates of surviving records for events that do not vary over time.

Stephenson, F. Richard, and David A. Green. *Historical Supernovae and Their Remnants*. Oxford: Oxford University Press, 2002. Authoritative book on historical supernovas. A readable account that is heavy on the details. Stephenson and Green are a wonderful collaboration between world leaders of astronomy from history and supernova remnants, with such cross-disciplinary work being rare and valuable.

Stephenson, F. Richard, and Leslie Morrison. *Historical Eclipses and Earth's Rotation*. Cambridge: Cambridge University Press, 1997. Exhaustive scholarly work on Earth's rotation. Compliment to the popular article in *Astronomy & Geophysics*. Stephenson has written the authoritative and exhaustive works on pulling out modern astrophysics from ancient astronomical records—for each of Earth's rotation, supernovas, and sunspots.

The Solstice Project. "The Sundagger Explorer: Interactive Model of the Ancient Calendar Site in Chaco Canyon, New Mexico." http://accad.osu.edu/~aprice/works/sundagger/index.html. Fully 3-dimensional model of the stones and the sky, all with accurate calculations of the Sun and Moon shadows. While you might not install their full system, their sample video gives a good idea of how the Sun dagger works. Anna Sofaer's Solstice Project is devoted to the Sun dagger at Fajada Butte.

Thomsen, Elsebeth. "New Light on the Origin of the Holy Black Stone of the Ka'ba." *Meteoritics* 15, (1980): 87–91. http://adsabs.harvard.edu/abs/1980Metic..15...87T. Proposes the new idea that the Black Stone is the impactite from the Wabar meteor crater in the Empty Quarter of Saudi Arabia. Refutes all other proposed naturalistic origins for the Black Stone. Her case is strong, but not proven with any high confidence. A critical, necessary test is to get some better dating of the age of the Wabar crater.

Ulansey, David. *The Origins of the Mithraic Mysteries*. Oxford: Oxford University Press, 1989. For centuries, the Mithraic mystery cult was one of the main religions in the Roman Empire. Ulansey puts forth the reasonable idea that the central mystery of Mithraism is actually just Hipparchus's precession. Precession proves that some high power outside the known universe is actually taking the whole universe and turning it, so that this new übergod is worthy of a new religion. Traditional scholars of Mithraism dislike this book.

Urban, Sean E., and P. Kenneth Seidelmann. *Explanatory Supplement to the Astronomical Almanac*. 3rd ed. Washington, DC: United States Naval Observatory, 2012. The definitive and authoritative source giving full and very detailed information on calendars, timekeeping, eclipses, and the positions of everything up in the sky. Not for the casual reader.

Weinberg, Stephen. *To Explain the World: The Discovery of Modern Science*. New York: HarperCollins Publishers, 2015. Exciting history of the Western tradition for physics and astronomy from the Greeks to Isaac Newton, both in very broad overviews and in very detailed technical notes. Part of the thesis is that the ancient Greeks were not doing science. The author is a Nobel Prize–winning physicist, and you might recall his excellent book *The First Three Minutes*. Weinberg has many historians in an uproar of rage. They accuse him of applying modern values as to the nature of science, of having the gall to define what progress is, of ignoring all the dead ends and sideshows that fill history, and of failing to be impressed by the subjects of the historian's writings. Weinberg gleefully admits to all these faults. But for some of the interesting and critical questions, Weinberg is certainly correct.

White, Gavin. *Babylonian Star-Lore: An Illustrated Guide to the Star-lore and Constellations of Ancient Babylon*. London: Solaria Publications, 2008. Good summary of the Babylonian sky. The "A–Z Gazette of the Stars and Constellations" pays good attention to primary sources. The constellations and stories are largely unfamiliar to people now, but they were on the path to the Greek constellations, with these being on the path to the modern constellations.

Wilk, Stephen R. *Medusa: Solving the Mystery of the Gorgon*. Oxford: Oxford University Press, 2000. Fun romp through old mythology from the Greeks and many cultures worldwide. Provides new and credible explanations for many aspects of the Medusa legend, drawing from astronomy, ornithology, architecture, and forensic medicine. Wilk's explanations are much better than previous claims, and his ideas have the great virtue of being plausible.

Xu, Zhentao, David W. Pankenier, and Yaotiao Jiang. *East Asian Archaeoastronomy: Historical Records of Astronomical Observations of China, Japan, and Korea*. Amsterdam: Gordon and Breach Science Publishers, 2000. Exhaustive list of all surviving ancient oriental observations of eclipses, comets, and much more. The ancient astronomers in China, Japan, and Korea spent vigils at all times, all year round, watching the skies from their imperial palaces, waiting for signs from heaven as part of the mandate of heaven doctrine.

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