Theories of the Universe

From Babylon to the Big Bang

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Introduction
Astronomy for All

There are certain events which sear into the mind at an early age: a violent thunderstorm; a damaging flood or fire; others' grief in response to tragedy; a display of wanton cruelty; a total solar eclipse; the birth and death of family members; the starry sky on a moonless night. You never forget these things. And their collective message is that you, an individual human, are quite puny compared to the mighty forces that run the Universe. So you're drawn to efforts to understand what those forces are. That's a major avenue to both religion and science, the two principal fields of human endeavor which lay claim to validity outside the merely here-and-now.

This class is a history of humanity's theories about the Universe – seen mainly from a 20th-21st century perspective. That last qualifier is necessary because it's definitely a science class – but science has become, in Horace Judson's words, "our century's religion". So the story of each is bound up with the other. At the beginning (-2000 BCE) and end (2000 CE), that will be evident; in between, not so much. Astronomy 1610 is the story of how all that came to be.

We'll start with some accounts of how the world began, and how it is constituted. Early famous examples (Enuma Elish, Genesis) are usually called "myth", to contrast them with modern accounts which are sometimes called "science". As we will see in Chapter 1, they don't seem all that different. Tiamat and Marduk, Yahweh and Lucifer, Adam and Eve, yin and yang, protons and electrons, order and disorder, particles and fields, quantum and continuum physics. The world seems only to make sense when you consider such pairs, and the relations between them.

In today's culture, knowledge of the constellations is rare and considered an oddity. Believe it or not, it's even rare among professional astronomers. But it must have been universal in years past. Whenever traveling, you needed to find your way using the Sun by day, and the stars by night. For seafaring people, this would be even more critical, because there are no markers at sea, and getting lost could be fatal. Everyone must also have known that there are "wandering stars", and of course seven of them became very famous: Sun, Moon, Venus, Jupiter, Mars, Mercury, and Saturn – more or less in descending order of importance. The regular motions of these objects are the world's natural markers of ***time***... and whoever had a great understanding of time could be quite important in society. Just for starters, you could be a great farmer, sailor, astronomer, astrologer, or priest. Or even all these things (the age of specialization had not yet arrived). If your society valued written records, and had the foresight to write them on permanent media like clay, then your understanding of these processes would be even deeper, because you might then have access to many centuries of astronomical observations. And we, 40 centuries later, might have access to yours.

This pretty much describes the "Babylonians", who are the starting point of our narrative, for several reasons:

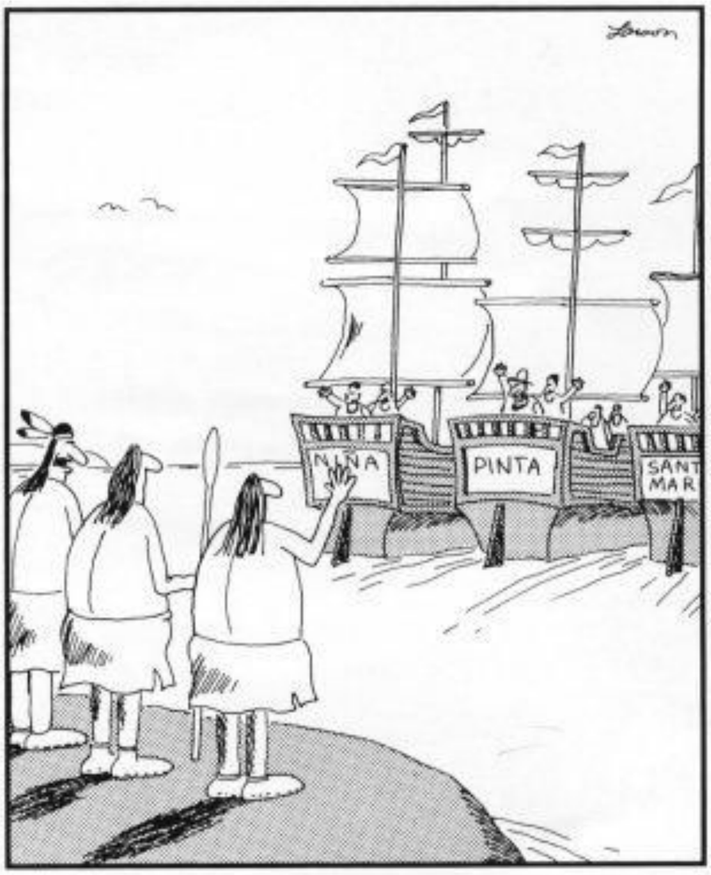
(a) because their achievements were so impressive;

(b) because the Greeks knew about their work and built upon it; and

(c) perhaps most important, because their clay tablets are still available for us in museums and libraries.

But astronomy must have been comparably important in many other cultures, not just the one we select – based on proximity to the Balkan peninsula, and their happy selection of clay as the writing-medium of choice.

Chinese astronomy is a good example. Chinese astronomers have closely patrolled the skies for eruptive objects ("guest stars") for at least 2000 years, and their records are now a great resource for study in the fields of supernovae and novae. Their idea of a "patrol" is pretty impressive; some accounts say that four astronomers were on duty at all times, watching the four corners of the sky (E, W, N, S) for unusual events – and with severely adverse personal consequences, possibly death, if they missed anything important. Today we have patrols which snap one picture every four days (and frequently can't report the data for weeks, because the digital data is too vast to analyze automatically). And our version of capital punishment for mistakes is that you're denied tenure and have to go to work on Wall Street.



"Did you detect something a little ominous in the way they said, 'See you later'?"

Likewise on the other side of the globe, where the Maya developed a famously complex and accurate calendar system, based on centuries of observation. State functions appear to be in several cases correlated with astronomy in many Mesoamerican societies, with certain sacrifices and architecture guided by astronomical events. The astronomer-astrologer-priest (often the same guy) would have been the local authority on such matters. The Maya left written records[1], but unfortunately for us,

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[1] These are the famous *codices*. A codex was a book written on wood or bark cloth – durable for at least a few centuries. Much of our knowledge of Mayan astronomy comes from the Dresden codex (these things get named for the libraries where they now reside).

many were destroyed in the book-burnings of the Spanish priests who accompanied the conquistadors.

Indigenous cultures in North America did not leave written records, so we don't know much about their science and skylore. Many tribes seemed to have a cosmology based on a principle of *four:* four directions, four worlds (such as in Hopi conceptions, where our current "World Complete" is the last[i]), four stages of life (infancy, childhood, adulthood, and old age), and four parts to the heavens (such as the Lakota sun, moon, sky, and stars). For many tribes (including, among others, the Hopi and the Zuni), the important directions were apparently not N-S-E-W, but rather the sunrise/sunset points on the horizons, especially at the extrema (winter and summer solstices). These might be more useful for time-keeping, especially in a culture enjoying sunny skies and clear horizons.

Probably all cultures used astronomy to devise a calendar; how else could you do it, and how could you live without a calendar? Pueblo peoples used a mixture of stellar and lunar calendars, which the Zuni reconciled through the yearlong rite of Sayatasha's Night Chant, which delineates the Zunis' origin and necessary rituals. The Anasazi constructed particular sun-viewing sites, and many native peoples participated in elaborate ceremonies on the solstices. The Hopi would send a young man with offerings to a shrine marking the precise direction of the winter solstice, and then have him run back to the village in order to coax the sun to make haste towards summer. By contrast, a young man or child sent to the summer-solstice shrine would meander slowly home, in hopes that the coming of winter would be similarly lethargic.

For the migratory Navajo, the stars offered the timekeeping and navigation that the Sun and Moon did for their more sedentary peers. Time was marked by the stars' journey across the sky, and the seasons – most importantly, when to sow and harvest crops – were marked by the “heliacal” rising and setting of certain constellations. Thus Navajo art often highlights important constellations, while Pueblo art emphasizes the Sun and Moon.

“Anthropologists! Anthropologists!”

It's surely true that in our world ruled by electric lights, smartphones, warm houses, water on tap, burger joints, fear of darkness, and food that is genetically modified (or at least from California), general knowledge about astronomy has deteriorated a lot. Still, one can easily go overboard with the “wisdom of the ancients” theme. The grand prize goes to stories about the wisdom of the Dogons, an indigenous tribe in Mali (still around). Some anthropologists visited the tribe in the early 20th century, and learned from village elders that Sirius was an important star in their culture. Fair enough – it's the brightest star in the sky. The elders went on to say that Sirius has a companion star which is extremely faint and orbits Sirius with a period of 50 years. Of course this was a major discovery of the 1920s – the first discovery of a *white dwarf* star (by Alvan Clark and Walter Adams) and correct explanation (by Subramanyan Chandrasekhar).

So even without telescopes, relativity, and quantum theory (all of which are needed to detect and explain a white dwarf), those doggone Dogons managed to do pretty well! Wisdom of the ancients, you know. When you look at the actual dates of the French interviews (1930s) and hypothesize that just *maybe* one science-savvy visitor in the 1920s had a long chat with the Dogons (or at least the one interviewed by Marcel Griaule, the anthropologist who is the sole source for this claim), the story loses most of its punch.

But in addition to the wisdom-of-the-ancients seduction, there's also the wisdom of the aliens. Robert Temple wrote a very popular book called *The Sirius Mystery,* which recites this story and concludes that the Dogons were visited not by a Frenchman who reads newspapers, but by talkative Sirius-based extraterrestrials, who naturally knew a lot about that particular binary system. (Personally, I wish they had gone on to discuss other binaries; it would save me a lot of time in my own research.) The book goes on to describe a few other visits – Easter Island, Egypt, Mesoamerica – which enabled those cultures to produce their famous exploits in architecture, science, and engineering. How else to understand those exploits? If only they had visited Europe, or China! Apparently those generous aliens, aware of the correlation between scientific acumen and melatonin, decided to visit only the cultures which needed help.

Chapter I

Ancient Astronomy

1. Myth and Science

The term "myth" is often used nowadays to denote something which is widely believed but definitely *false.* People say "oh, that's just a myth"... or "urban legend" or "old wives' tale". It's almost always a pejorative; the literary scholar Max Muller even called myth "a disease of language". But the great myths of history surely bear no relation to tales about alligators in New York City sewers. Nearly all myths are essentially ***stories***, and stories are perhaps the principal vehicle by which humans learn about their world. That's pretty much obvious when it comes to human behavior. Consider these great heroes of history, who in our minds are the epitome of humans' finest qualities:

Job – patience

Abraham – loyalty
Jesus – love and forgiveness
Eve – curiosity
Athena – wisdom
Daedalus – invention

Odysseus – bravery and resolve
Gilgamesh – bravery and power

Buddha - wisdom

Krishna – love
Moses – leadership
Hercules – strength
Prometheus – courage
Helen – beauty

Solomon – justice
The Good Samaritan – empathy

And some on the darker side:

Narcissus – pride
Judas – greed
Cain – envy

You know all these people, don't you? Most come from "myths", but their impact on us is much greater than that of the "scientific" works of Immanuel Kant, Jeremy Bentham, and John Rawls. These stories play a big role in how we learn about the heights and depths of human behavior.

Is it a lot different with the material world – the world of physics? Many would say emphatically yes. In the years after Newton, many physicists and philosophers thought that the world was a vast machine operating according to known or soon-to-be-known precise laws: ***Determinism.*** Many of the French *philosophes* (e.g., Rousseau, Condorcet . . . "the perfectability of society") thought that as soon as we learn the laws of human behavior – along the model of Newton's laws – we could fashion a perfect society.[2] That chimera didn't last long, but in the late 19th century, after Helmholtz, Faraday, and Maxwell discovered and codified the laws of energy

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[2] And they were pretty sure that Louis XVI and Marie Antoinette were not a part of that perfect society.

and electromagnetism, scientific determinism became popular again. Lord Kelvin gave a famous speech in 1900, in which he suggested that the end was in sight for theoretical physics, because present theory was consistent with all known experiments, except for two: blackbody radiation and the Michelson-Morley experiment. Surely these anomalies would clear up after a little more work. Well, the former gave rise to quantum theory, and the latter relativity, the two great revolutions of the 20th century. Both starkly inconsistent with the "absolutism" of classical physics.

Nowadays we have randomly decaying nuclei, string theory, 10-dimensional space, dark energy, Schrodinger's cat, etc. Black holes are no longer reliable (they evaporate), and even the vacuum itself is packed with virtual energy. Everywhere you look, you find not determinism but probabilities. In the present landscape of physics, it's impossible to even *imagine* how you could construct a deterministic physics. And that's not even considering the biggest problem of all: living things.

In modern physics we have particles, waves, and space. These concepts are impossible to define in isolation. What matters are the stories we weave around these concepts, and those stories are called ***physics.*** Electrons acquire their meaning in relation to protons, and both acquire their meaning in relation to charge. Charge acquires its meaning in relation to... what? cat's fur? electrons? space? And what is space?

Myth and science. The appendix contains two famous accounts of the creation of the Universe: Enuma Elish, about 4000 years old (see page 93); and Genesis (see page 95), about 2500 years old. John Hawley wrote a similarly complete account of Genesis-à-la-Big Bang (following page). Like the Book of Revelation, it even manages to squeeze out a prediction about the future, with one important difference: *but maybe not.*

A New Genesis

In the beginning there was neither space nor time as we know them, but a shifting foam of strings and loops, as small as anything can be. Within the foam, all of space, time, and energy mingled in a grand unification. But the foam expanded and cooled. And then there was gravity, and space and time, and a universe was created. There was a grand unified force that filled the universe with a false vacuum endowed with a negative pressure. This caused the universe to expand exceedingly rapidly against gravity. But this state was unstable, and did not last, and the true vacuum reappeared, the inflation stopped, and the grand unified force was gone forever. In its place were the strong and electroweak interactions, and enormous energy from the decay of the false vacuum. The universe continued to expand and cool, but at a much slower rate. Families of particles, matter and antimatter, rose briefly to prominence and then died out as the temperature fell below that required to sustain them. Then the electromagnetic and weak interaction were cleaved, and the neutrinos were likewise separated from the photons. The last of the matter and antimatter annihilated, but a small remnant of matter remained. The first elements were created, reminders of the heat that had made them. And all this came to pass in three minutes, after the creation of time itself. Thereafter the universe, still hot and dense and opaque to light, continued to expand and cool. Finally the electrons joined to the nuclei, and there were atoms, and the universe became transparent. The photons freed at that time continue to travel even today as relics of the time when atoms were created, but their energy drops ever lower. And a billion years passed after the creation of the universe, and then clouds of gas collapsed from their own gravity, and stars shone and there were galaxies to light the universe. And some galaxies harbored at their centers giant black holes, consuming much gas and blazing with great brightness. Still the universe expanded. And stars created heavy elements in their cores, then exploded, and the heavy elements went out into the universe. New stars form still and take into themselves the heavy elements from the generations that went before them. More billions of years passed, and one particular star formed, like many others of its kind that had already formed. Around this star was a disk of gas and dust. And it happened that this star formed alone, with no companion close by to disrupt the disk, so the dust condensed, and formed planets and numerous smaller objects. And the third planet was the right size and right distance from its star so that rain fell upon the planet and did not boil away, nor did it freeze. And this water made the planet warm, but not too warm, and was a good solvent, and many compounds formed. And some of these compounds could make copies of themselves. And these compounds made a code that could be copied and passed down to all generations. And then there were cells, and they were living. Billions of years elapsed with only the cells upon the planet. Then some of the cells joined together and made animals which lived in the seas of the planet. And finally some cells from the water began to live upon the rocks of the land, and they joined together and made plants. The plants made oxygen, and other creatures from the seas began to live upon the land. Many millions of years passed, and multitudes of creatures lived, of diverse kinds. And a kind of animal arose and spread throughout the planet, and this animal walked upon two feet and made tools. And it began to speak, and told stories of itself . . . and at last it told this story. But all things must come to their end, and after many billions of years the star will swell up and swallow the third planet, and all will be destroyed in the fire of the star. We know not how the universe will end, but it may expand forever, and finally all the stars will die and the universe will end in eternal darkness and cold.

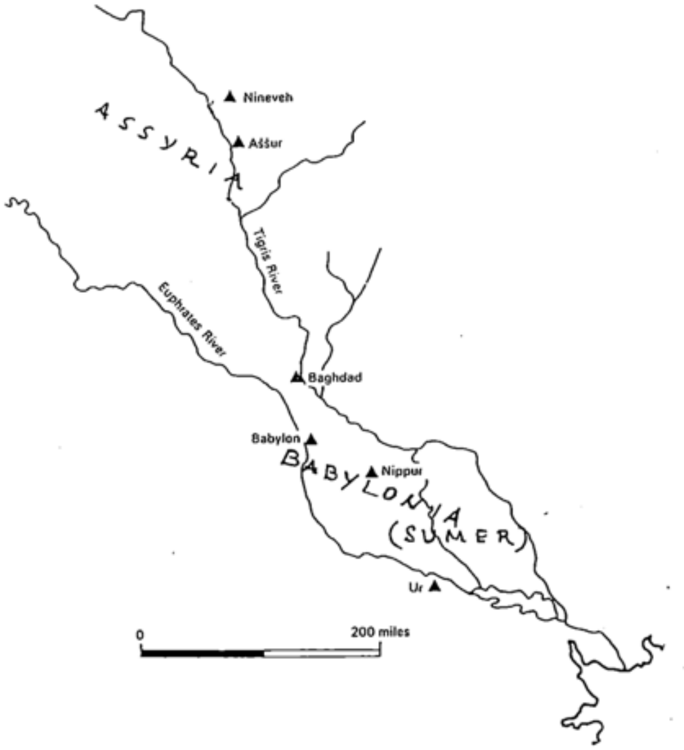
—John Hawley

Pretty similar, aren't they? Myths and scientific theories are both basically *stories*, with characters and actions and dramatic consequences following from those actions. For a creation myth, those consequences are the structure and content of the Universe. There's a "cause" and a "reason" for everything in the Universe. Just like in modern cosmology. The real difference seems to be that science, unlike most religion, has managed to forge a tool for its own continuous reshaping and improvement (and even refutation). That's sometimes called the "scientific method"... but I'd describe it as more of a general scientific mindset, which thrives on skepticism and debate, and is highly distrustful of authority. Found in people of all ages and persuasions, and at the root of many whodunit stories. Seemingly thriving more since ~1600, in the aftermath of the European Renaissance, but plenty evident in other eras (the Greeks and Babylonians).

The improvement will likely never end, and in a thousand years, our scientist-descendants will likely heap scorn on us for our crude 21st century beliefs. They, of course, will finally have gotten everything figured out.

2. From Sumer to Stonehenge

(a) Babylonia



Modern-day Iraq was the seat of several ancient and advanced civilizations. I use the term *Babylon* here to include essentially all the civilizations inhabiting, roughly, the Tigris and Euphrates valleys ("Mesopotamia") during this long interval. There probably were others comparably ancient and advanced, but because these early Iraqis wrote in cuneiform (deciphered) and on clay tablets (preserved – extant in today's museums), we're able to study these civilizations pretty well. As you might guess, the written records are primarily of commerce (trade in goats and barleycorn, etc.). But there is also literature and mathematics; we know their creation stories, much of their history, and their system for counting (base 60, with negative numbers and fractions – but no zero, and no irrationals).[3]

Let's estimate some dates to give perspective here:

Box 1: A Timeline of Babylon

-4000 to -3000	Sumer (a long-lasting early kingdom in the region)
-3100	Earliest known writing (cuneiform)
-2300	conquered by Akkad
-1870	city of Babylon (in the Akkadian Empire, on the Euphrates)
-1800	Code of Hammurabi (first written system of laws)
-> -600	Frequent strife with neighbors, esp. Assyria to the north
-604 to -561	Nebuchadnezzar, ziggurats, hanging gardens, etc.; also roughly the captivity of Israelites
-539	Persians (Cyrus the Great) conquer Babylon and free the Israelites
-331	Alexander conquers the Persians
-323	Alexander dies. His great empire dissolves into pieces, and the great flowering of astronomy and mathematics fragments too – though by no means dies.

Babylonian religion was essentially pantheistic; one scholar estimated they had 2000 gods. So many gods are likely to be forever warring unless they get organized... and so, apparently, they did. The *Enuma Elish* names two starter gods: Apsu and Tiamat. They have some kids... and some get quite powerful and ambitious. Various schemes and jealousies ensue (remember, this is polytheism). Eventually there is a huge struggle between Tiamat and Marduk (her grandson). Marduk gets control of the wind, which proves to be decisive (via dust storms, tornadoes, and drought). He decides to take over the Earth, and allocates some other regions to various allies and defeated rivals: two parts of the sky, and the subterranean world. Gods on the losing side are initially forced into slavery, but then get a pardon when Marduk decides to create humans to do all the work originally slated for gods. This works out well for most of the gods – if you don't count the actual casualties of the war. (Sound familiar?)

That's the creation of the Earth – from the strife of gods who pre-existed the Earth – and the creation of humans. Both gods and humans have to pay homage to Marduk.

Some scholars date this story to the time of Hammurapi (-1800), while others place it around -1150. The oldest extant copy dates from -700, so the date of actual origin can't be readily determined. With his ascendancy, Marduk wastes no time structuring the cosmos. He lays the constellations, sets the Sun and Moon ticking along and dividing the year (a luni-solar calendar), and sending the planets on their

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[3] The standard source for this subject is *The Exact Sciences in Antiquity,* by Otto Neugebauer. Another well-known scholar, specializing more in the astronomy of this era, is the Danish historian Asger Aaboe.

routes.

His zest was quickly emulated by his human subjects. Very omen-conscious and viewing astrology as a way for the heavens to communicate their intentions for Earth, the Babylonians became meticulous and incredibly skilled observers. Over centuries they kept careful records of planetary positions, which were mined much later by Hipparcos (c. 150 BCE). They also kept records of solar and lunar eclipses, and discovered the famous recurrence period of similar eclipses – the *saros*, which is 18 years and 11.33 days. Most astonishing to me, they even knew about "the precession of the equinoxes" – the very slow westward migration of the vernal equinox among the stars, requiring 26000 years to complete a cycle.

Despite all this precision and a rather advanced mathematics, there is no known evidence that the Babylonians tried to "explain" the celestial motions, as many of the Greeks did. They were consummate observers, and also very interested in how the planets' motions related to events on Earth. Most of what we call *astrology* comes from the Babylonians.

(b) Ancient Egypt

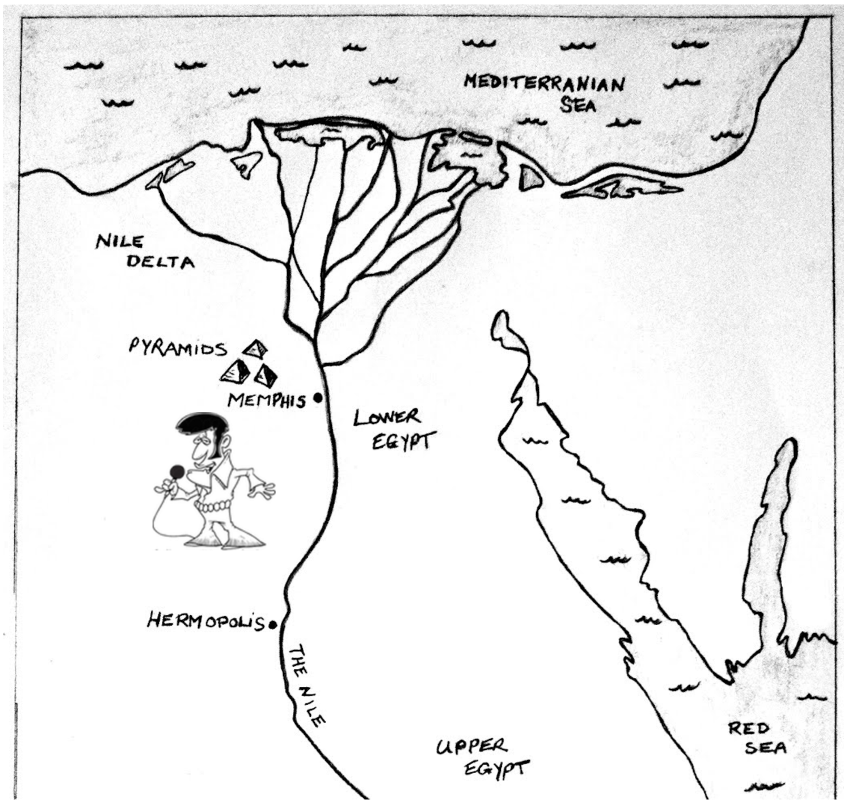
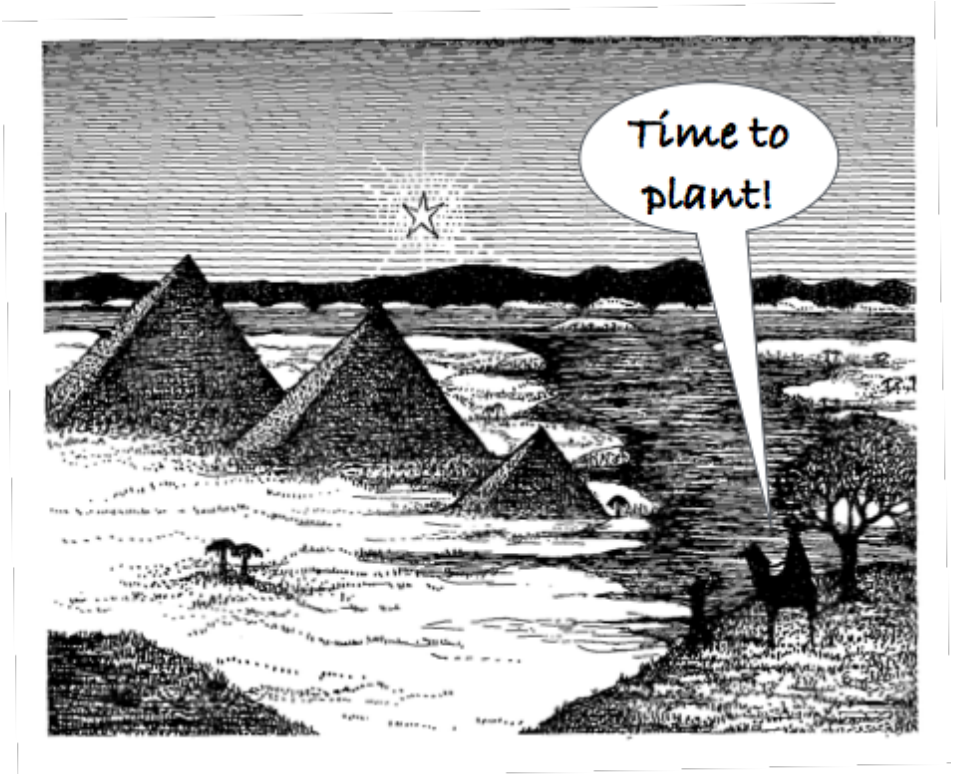


Figure 1: Geography of the lower Nile, breadbasket of lower Egypt. Practically all the farmland is in the Delta. Memphis was the capital, but scholars have not yet learned the exact location of Graceland.

Life along the Nile Valley probably wasn't a lot different from that of Mesopotamia. The ancient Egyptians are famous for their art, architecture, and shipbuilding – just for starters. And for more than 2000 years they seem to have had a stable society and culture. That's an amazing accomplishment. What about astronomy?

Egypt's lifeblood is the Nile, which drains the highlands of central Africa, 3000 miles away. Those highlands are equatorial, and hence have a climate with very rainy summers and dry winters. Thus the lower reaches of the Nile cycle regularly through drought and flood. Nearing its terminus at Alexandria, the Nile fans out into an enormous delta, which is one of the richest farmlands in the world. With help from irrigation, the upriver regions can be productive too. Despite its own very dry climate, Egypt has always been able to support agriculture on a vast scale.

The equatorial rains start to fall in May-June, causing downriver floods in July-August. (The river is 4000 miles long, so it takes a while!) So you want to plant your seeds in July; sooner than that, scavengers eat the seeds... and later, you're knee-deep in water. How do you know when it's July? The Farmer's Almanac won't be printed for another 4000 years. Well, that's where astronomy comes in. You could use the Sun, but that would require measuring instruments and mathematics. Or you could scan the eastern sky every morning before sunrise (you're up anyway, to milk the cows). One day you see Sirius, the brightest star in the sky, just emerging from the glare of morning twilight. Bingo, that's July 1 more or less, depending on exactly what century you live in (it changes on a 26000 year cycle, so the date will be essentially constant throughout your life). So you plant your seeds, congratulate yourself when the flood comes, take the crop to market, and count the cash rolling in. Courtesy of equatorial rains and Sirius. No wonder that star (Osiris) was a great god in Egypt's pantheon.



This is known as the *heliacal rising* of Sirius. The celestial sphere rotates rapidly around the Earth (once a day), but all the stars slip slowly forward relative to the Sun, due to the Sun's yearly motion. Thus the time of a star's rising relative to the Sun (*helios*) varies smoothly through the year – and that of Sirius has been in July-August during recent millennia. If you live at a mid-northern latitude and have a clear southeastern horizon, you can verify this yourself any August morning.

The importance of all this favored precision in timekeeping, and we'll discuss this in detail when discussing **the calendar**.

It's possible that future scholars will hold a different opinion (discovery and deciphering of ancient materials is a recent and ongoing phenomenon), but at present there is no compelling evidence that Egyptians went far beyond this in astronomy. At least not at the level of the Babylonians, or the Greeks soon to follow. They certainly incorporated astronomy into their architecture, though; many temples are oriented N-S or E-W, and there are many claims of the Sun's rays falling precisely into some inner chamber at exactly noon on some particular day (usually a solstice). In 1894 Norman Lockyer wrote a famous book "The Dawn of Astronomy", in which he argued for such things. Some of the claims are impressively precise, especially as regards the Great Pyramid of Giza – oriented N-S within 0.1%, and with a perimeter-to-height ratio equal to 2π within 0.05%. And here's a weird one:

$$\frac{H^2}{A} = 1.618... = \text{"}\textit{the golden mean}\text{"}$$

where H is the Great Pyramid's height, A is the area of each face, and the golden mean is that famous number in art and architecture, which is supposedly the most pleasing aspect ratio of a rectangle. For mystics and numerologists, it's also the limiting ratio of successive terms of the Fibonacci series (each number being the sum of the two previous numbers):

1, 1, 2, 3, 5, 8, 13, 21, 34, 55, 89,..., etc.

Try computing those ratios... but be warned, numerology can be addictive. A quite fascinating modern book about this number is *The Golden Ratio*, by Mario Livio.

(c) The Bible

Another account of cosmogenesis from (roughly) this era is the Bible – basically the Book of Genesis. I include this account in the appendix (up to Genesis 3:6). It's chock full of obvious myth and possible history, and it's often hard to tell them apart. But in general the Bible, plus all the exegesis which followed, is about how to live, not how we came to exist. Admittedly, along the way some books were lost, dropped, or disapproved. Maybe they treated astronomy more thoroughly; but not the modern Hebrew or Christian bible. The scant references seem to express hostility to astronomy. Zephaniah says that the Lord condemns all those "that worship the host of heaven upon the housetops". Oops, that would be me. Isaiah gets even more intense: "Let now the astrologers, the star-gazers, the monthly prognosticators, stand up and save you from these things that shall come upon you. They shall be as stubble; the fire shall burn them, and they shall not be delivered from the power of the flame."

It's possible that these are mainly condemnations of polytheism, or of what we would today call "astrology". Or just condemnations of contemporary rivals:

Chaldeans (Babylonians) or Canaanites ("Phoenicians"). There's plenty of that in the Bible. As far as present-day scholarship is concerned, there just doesn't seem to be very much astronomy content. In Genesis 3:6, however, Eve's bite of the apple presents a beautiful and succinct model for the style of **science.**[4] Curiosity – and disobedience.

(d) Stonehenge

Then there's Stonehenge. Here we have almost none of the tools of scholarship available: archeology, philology, religion, architecture. It's all a blank. Whoever built Stonehenge apparently left no written records – of this monument, or of anything else which might give a clue about its purpose. They left hardly any clues about what else they liked to do (besides build mysterious stone structures with no obvious purpose)...but fortunately also some pottery, a few stone tools, and especially **bones**. Through carbon-14 dating, the latter have established reliable dates for the construction of Stonehenge. Congrats to those littering workmen who tossed their chicken-salad sandwiches into those holes.

The results were flat-out amazing. It appears that there were 3 separate construction episodes at Stonehenge. Around the year -2800, the 56 Aubrey holes were dug, and presumably filled with wooden posts (or something which decayed). Around -2200, the large standing stones known as "bluestones" were brought in from ~150 miles away (based on the nearest suitable quarry). This would have given Stonehenge a look similar to what it has today. And around -2100, the smaller and rougher "sarsen stones" arrived. All these ages are slightly disputed among scholars... but carbon-14 doesn't lie: it's incredibly ancient. The oldest Mycenaean tombs date from -1600; so a thousand years before the oldest stone structures in Greece, someone was building Stonehenge.

"But it's just such a long *wait* till the Iron Age . . . I say we give it a go with the rocks."

Here's the date summary, along with archeologists' terms for the people/culture prevalent in southern England at the time:

Stonehenge I = -2800, Aubrey holes, Neolithic ("New Stone Age") people
II = -2200, bluestones, "Beaker people"
III = -2100, sarsen stones, "Wessex people".

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[4] Not to mention computing.

Stonehenge is a pretty small structure; the inner, iconic part is about the size of a large house. And the whole thing consists of just 70 stones, which are in such a fallen-apart state that its purpose remains unknown. What makes it remarkable is the claim that it is a sophisticated astronomical observatory, and in particular, is an analog computer for predicting lunar and solar eclipses. This was highly publicized in Gerald Hawkins' 1963 book *Stonehenge Decoded*, picked up by BBC, and the hype machine has been roaring ever since. Measuring hundreds of sightlines between stones and gaps between stones, Hawkins concluded that many of them – too many to be pure coincidence – were at azimuth angles which represented critical rising/setting phenomena for the Sun and Moon.

One astronomical orientation appears to be a sure thing. From the center of the stone circle, the heelstone – by far the oldest part of the monument – points to midsummer sunrise (June 22, which used to be called “Midsummer Day”). This is the basic axis of Stonehenge. Nothing remarkable there, however; modern solar homes are usually oriented exactly E-W, and midsummer day is a natural thing to celebrate in a cold climate.

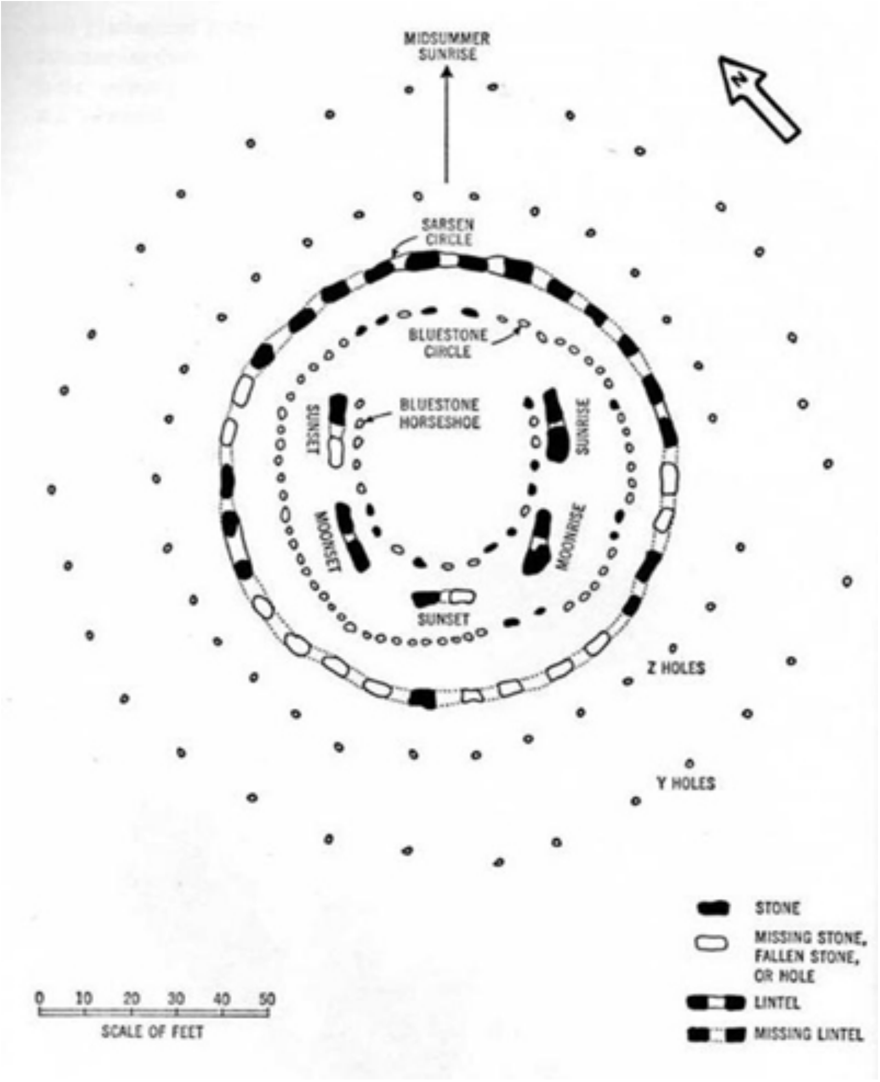


Figure 2: The geometry of Stonehenge. The heelstone is directly above, and the orientation of the "horseshoe" to the June 22 sunrise (midsummer) is evident.

The allegations concerning moonrise/moonset are more interesting, though complex (see Figure 5). The Moon's orbital plane is inclined about 5 degrees from the ecliptic; adding that to the 23.5 degrees tilt of the ecliptic plane, the Moon can rise and set with declinations between -29 and +29 degrees. The Sun rises and sets at a place exactly determined by the calendar date – the same every year – but the moonrise/ moonset position varies monthly over this wide range. For an eclipse to occur, the Moon must be aligned with the Sun (new moon, and solar eclipse if the alignment is sufficiently precise) or opposite (full moon, or lunar eclipse if the alignment is sufficiently precise).

If you're really fascinated by eclipses and don't quite have the math skills to figure all this out on paper (or don't even *have* paper), you could use these moonrise/ moonset observations to predict when an eclipse is going to occur. For example, on Midsummer Day, we know the Sun's declination is +23.5 degrees. The Moon needs to be also at 23.5+/-1 degrees for a solar eclipse to occur, or -23.5 degrees for a lunar eclipse. You can't necessarily measure declinations in the sky (zero stars visible in daylight, and poor visibility of stars near a brightly illuminated Moon). But with a clear horizon you can always measure the azimuth angles of sunrise/sunset and moonrise/moonst. In modern lingo, the Moon has to be exactly new or full, and has to be quite near a *NODE* in its orbit (place where the orbital planes intersect). Get the idea? **The azimuth observations are a proxy for the difficult-to-get observations of declination**.

Figure 3: The rising angle of the sun, viewed near the Earth's equator (latitude ~10°)

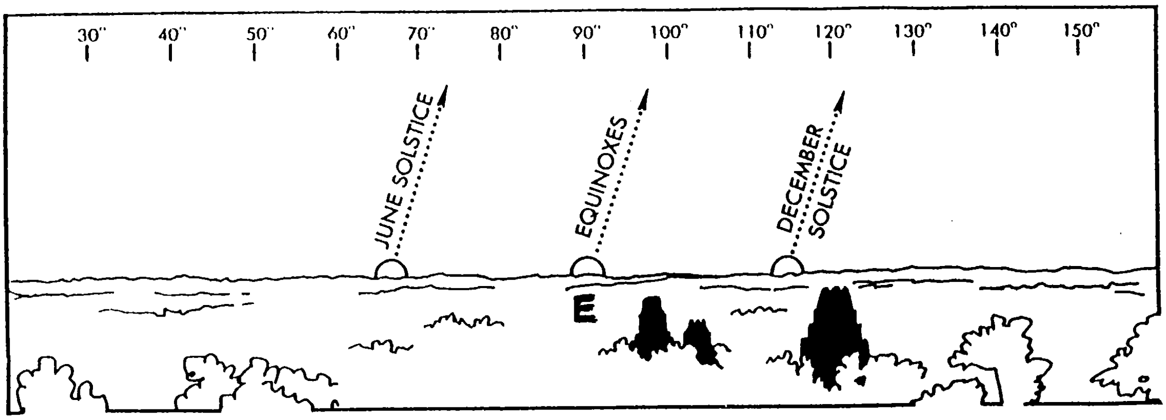
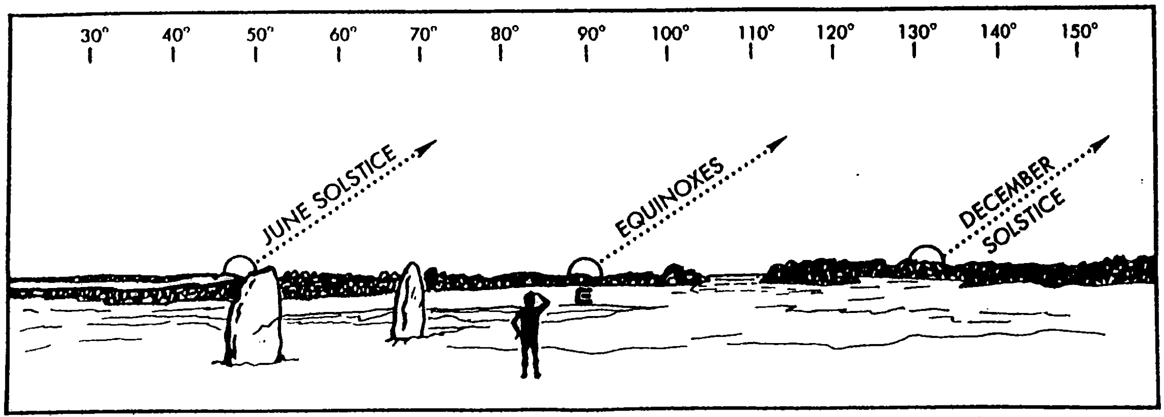


Figure 4: The rising angle of the sun, viewed at the latitude of Stonehenge



Was this the motivation and/or procedure of the Stonehengers? No one knows. But today, *we* are interested in eclipses, and we could use that procedure to predict eclipses. This is the basic argument of Hawkins and his yes-it's-an-observatory allies.

Since the bombshell of the carbon-14 tests, scholarship has moved the ball forward somewhat. Hawkins' original claim of "too many coincident angles" has been mostly discredited as regards the actual stones. Arguments about probability are famously tricky; there's just no clear way to know what large family of possible sightlines you should consider, from which to single out the "interesting" ones. The Aubrey postholes are another matter. One of the famous periodicities in eclipse prediction, certainly known to Greeks and probably the Babylonians (since the latter probably are the Greeks' source for empirical data), is the Metonic cycle of 18.61 years. 18.61 x 3 is sufficiently close to 56, the number of Aubrey holes, that – given the ±1° tolerance in the Moon's position – we could probably use the sightlines towards the original posts (long since decayed) to measure azimuths with sufficient accuracy to predict eclipses. Assuming we were so motivated.

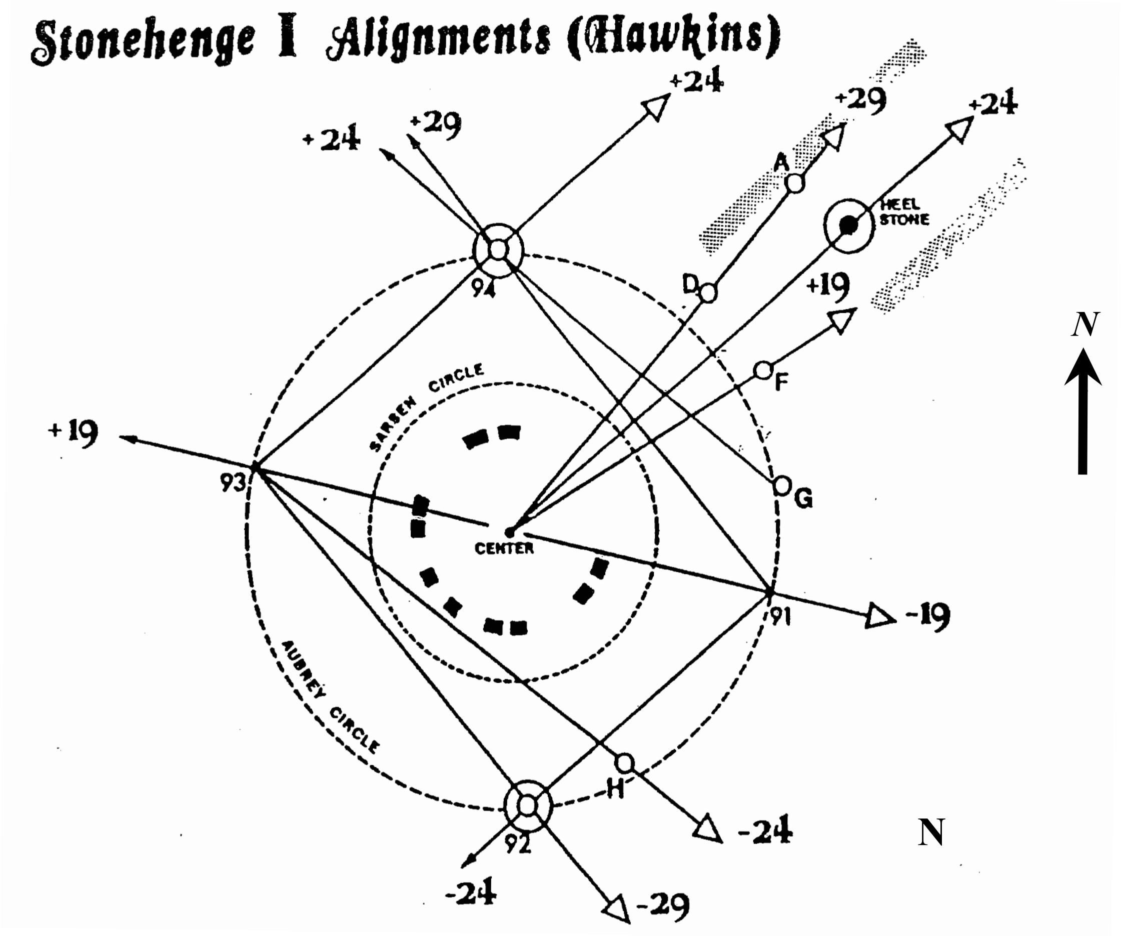


Figure 5: Hawkins' alignments at Stonehenge I. Gerald Hawkins identified numerous astronomical alignments between the features of the earliest phase, Stonehenge I. Some solstilial alignments (+24 and -24) and lunar standstill alignments (+19, -19, +29, and -29) appeared to fit the rectangular geometry of the stations, while others seemed to avoid any obvious geometric pattern.

That raises the possibility that only Stonehenge I, with the wooden Aubrey holes only, had true astronomical significance – and the other two construction episodes (with the stones) were basically unsuccessful efforts to recreate or improve on the original. Probably this should go back to archeologists for further progress. But so far, no great treasure trove of archeological evidence has been found; so the central question of who built it, and why, is still quite unanswered.

Just to tantalize a little more, there may actually have been references to Stonehenge in ancient literature. Diodorus Siculus was a 1st century Greek geographer, who wrote of a spherical temple of the sun god Apollo in Hyperborea ("beyond the north wind"). "Spherical" was also commonly used to mean "astronomical", and Hyperborea was a general term for regions far to the north of the Mediterranean. I also recall some possible references by Plutarch or Herodotus, but haven't been able to track them down.

“Now that we can tell time, I’d like to suggest that we begin imposing deadlines.”

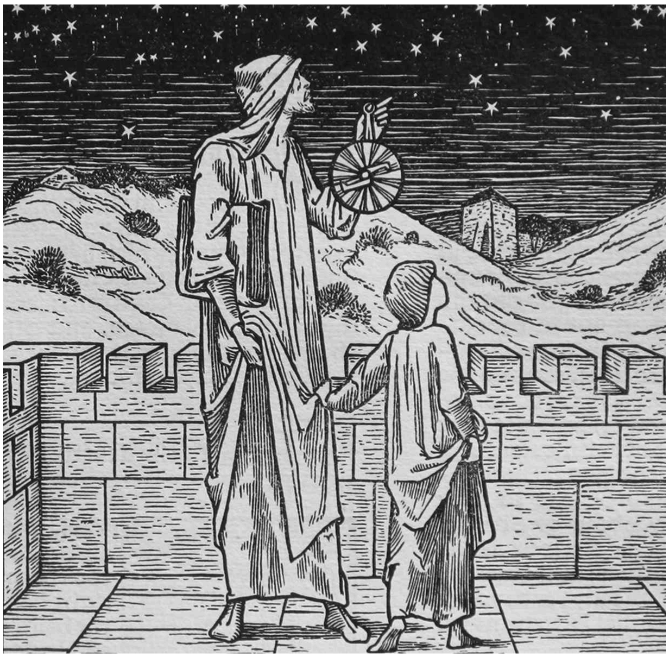
Chapter II
Celestial Motions and Coordinates

Lord, I have loved your sky,
Be it said against or for me,
Have loved it clear and high,
Or low and stormy.

Till I have reeled and stumbled
From looking up too much
And falled and been humbled
To wear a crutch.

My love for every Heaven
O'er which you, Lord, have lorded
From number One to Seven
Should be rewarded.

But if that seems to tend
To my undue renown,
At least you ought to send
Me up, not down.
–Robert Frost, Astrometaphysical



Except for farmers and sailors, very few people now know, even roughly, how the stars move. But before the age of books and clocks and the mass indoctrination oddly labeled as "education", everyone must have known this. It's the key to knowing what time it is – likely a critical skill in practically every culture. You can learn it in just a few hours looking up at the nighttime sky. Not just them, but you too. In this class, I hope and expect you'll become a passably good ancient astronomer.

A great start is to cast off the idea that "it's really the Earth that is moving". Whenever you allegedly learned this, you almost certainly didn't hear the evidence, and it's contrary to common sense. Ask yourself: do you know any evidence supporting this outrageous proposition? Understanding the motion of stars and planets is much, MUCH more difficult if you suppose that your observing platform is moving. For at least a few weeks, cast off your heliocentric baggage!

Stars rise in the east, more or less, and set in the west, more or less. The key to understanding this is to imagine the Universe as one big crystal sphere, spinning about the Earth every 24 hours (actually 23^h 56^m, but we'll get to that). Depending on where you are on Earth, the sunrise/sunset and star-rise/star-set motions look somewhat different:

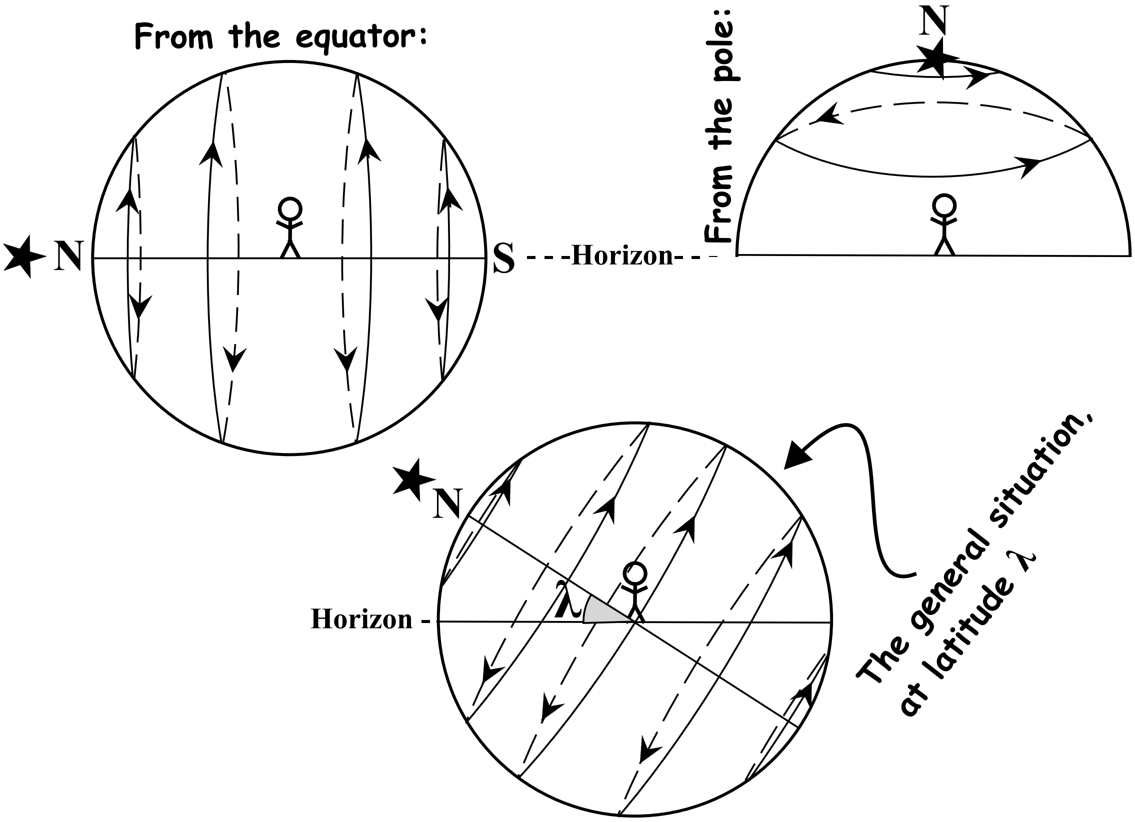
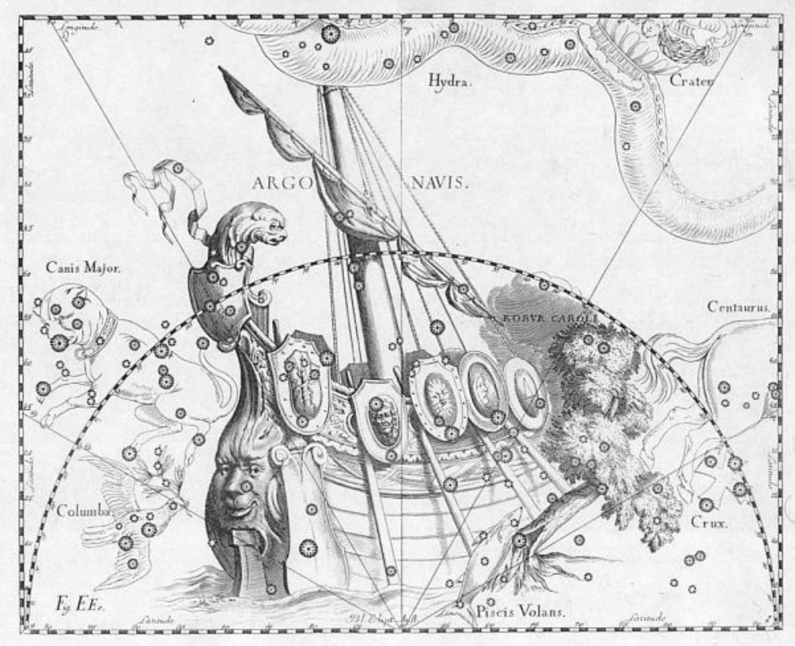


Figure 6: The rising angles of stars at various locations on Earth**.** From the equator, everything rises straight up; twilights are brief. From the poles, stars "rise" parallel to the horizon – so of course they don't rise at all, just roll along parallel to the horizon. From an intermediate latitude, stars rise at a slant, and that angle of slant λ, relative to vertical, is your latitude on Earth.

When you behold the entire night sky, it looks like a large bowl of stars, slowly rotating around the Earth. Except for observers near the poles, every star rises in the east, takes about 6 hours to "cross the meridian", or *culminate* . . . then takes 6 more hours to set in the west. If the star happens to be the Sun, then we call this phenomenon "day".

If you look at stars directly in the north, things change a bit; look at the bottom image in Figure 6. Stars still execute big circular arcs with a 24 hour period; but the arcs are smaller, somewhat confined to the north, and the stars are above the horizon much longer than a mere 12 hours. The Big Dipper, for example, is a *circumpolar* asterism – above the horizon 24 hours a day for any observer north of Georgia. Polaris itself never rises or sets either, indeed hardly budges at all. It's 1 degree from the true north celestial pole (NCP), so it just executes little 1-degree circles around the true NCP. Some stars, those in the far south, are never seen at all. These motions are decently illustrated (maybe) by the last of the drawings in Figure 6. But they're much better visualized by looking at some star trails, and some time-lapse movies of the sky at night. I'll show some in class; here's a potpourri of others, though some are specialized to the topic of precession (not exactly a nightly affair – takes 26000 years).

Alone, in thy cold skies,
Thou keep'st thy old unmoving station yet,
Nor join'st the dances of that glittering train
Nor dipp'st thy virgin orb in the blue western main.
– William Cullen Bryant, "Ode to the North Star"



Star trails
http://petapixel.com/2015/04/14/a-six-hour-long-exposure-of-the-celestial-north-pole/

star-trail movies from California:
http://www.danheller.com/kings-canyon-star-trails-1.html

Visualizing the motions in various directions (mid-northern):
http://www.kadamsphoto.com/nightphotography/analyzing-star-trails-part-one-shape-of-the-lines/

Great star trails as seen from Ecuador: NCP and SCP both on the horizon!
http://sguisard.astrosurf.com/Pagim/From_pole_to_pole.html#Picture3

lotta fascinating and detailed stuff about precession here:
http://www.crystalinks.com/precession.html

and here's a slightly crazy one:
http://www.ancient-wisdom.com/precession.htm

many motions of the earth and Sun are ably reviewed here::
https://www.youtube.com/watch?v=82p-DYgGFjI

The best of these is the one from Ecuador.

All these motions are naturally explained by supposing that stars are all located on a celestial sphere, spinning around the Earth. Like any spinning sphere, it has an axis, a pole, and an equator (the ***celestial equator***). Stars are little lights rigidly attached to this sphere. We specify the positions of stars with spherical coordinates – latitude and longitude. Latitude is degrees up from the celestial equator, and we call it ***declination***: + means towards the NCP, and - means towards the SCP. Longitude is degrees east of an arbitrary point on the celestial sphere, namely the vernal equinox. But by convention it's described not as degrees longitude but as hours-minutes-seconds of ***right ascension…*** where I hour of RA = 60 minutes, and 1 minute = 60 seconds. Since these minutes and seconds are measures of angle, they are often called called “arc-minutes” and “arc-seconds”, to prevent confusion. You can see, however, that the RA coordinate is analogous to time. In fact, that's why it exists – to specify easily and exactly when in the diurnal rotation cycle (known to mortals as "day") a given star or constellation appears in the sky.

Figure 7: NEXT PAGE

Figure 7: The Celestial Sphere, or at least most of it. This is entirely analogous to the "map of the world" you probably had in your 5th-grade classroom. The Earth is a sphere, and can be represented by longitude and latitude... **and the celestial sphere can be represented by its version of longitude and latitude, which we call right-ascension and declination.**

People often ask "where is the Earth on this map (Figure 7)?" NOWHERE! It's a map of the sphere known as "the sky", not a map of our planet. The question makes exactly as much sense as asking "where is the sky?" on a map of the Earth.

Figure 7 excludes the north-polar region of the sky (declinations above +60°), for the same reason that most world maps exclude the polar regions – because areas get distorted in this type of projection. Figure 8 shows a map of the far-northern part of the sky. Note that Polaris is very close to (about 1° away from) the north celestial pole (NCP). And the true celestial pole moves, ever so slowly. It traces out a big circle 23° in radius, ever so slowly – taking 26000 years to complete the circle. Polaris has only been a good pole star for a few hundred years; and in another thousand, we won't have a pole star at all. About 4000 years ago, the medium-bright star Thuban was a decent but not great pole star; that would have been the pole star for the ancient Eqyptians.

Because the NCP moves around, so does the celestial equator (the locus of all points 90° from the pole). So the coordinates of stars change slowly – and the vernal equinox moves slowly westward at a rate of 1 degree per 70 years. That's the **precession of the equinoxes.**

Try to visualize this starry sky – the celestial sphere – around us. Just go out and spend 3 minutes looking up on a clear night; doesn't it look like a big sphere? Come back an hour or two later, and notice that it has moved – *rotated* – slightly westward. If it's winter, look south to Orion, or look north to Ursa Major; these will show the rotation prominently.[5] If you're really patient and/or take a time-exposure of the far-northern sky, you'll see that the rotation is basically around the medium-bright star Polaris. So now you have an *axis* for the sphere, and also an *equator* (the locus of points 90 degrees from the pole). Over the rest of your life, the stars will maintain fixed positions on that sphere – which you should call ***celestial***, since life is full of spheres (hydro-, bio-, litho-, influence, Dyson, etc.). The celestial sphere will just continue to grind around you, completing a revolution every 23 hours and 56 minutes.

You're well on your way to becoming a certified ancient astronomer. But as the final credential, you also need to be familiar with what happens in the daytime sky... and with the seven stars which wander, the famous *planetes* of the Greeks. All seven grind around the Earth east-to-west just like the fixed stars. But they change their position on the celestial sphere very slightly from one night to the next. You could

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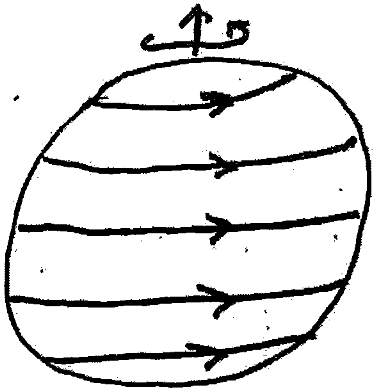
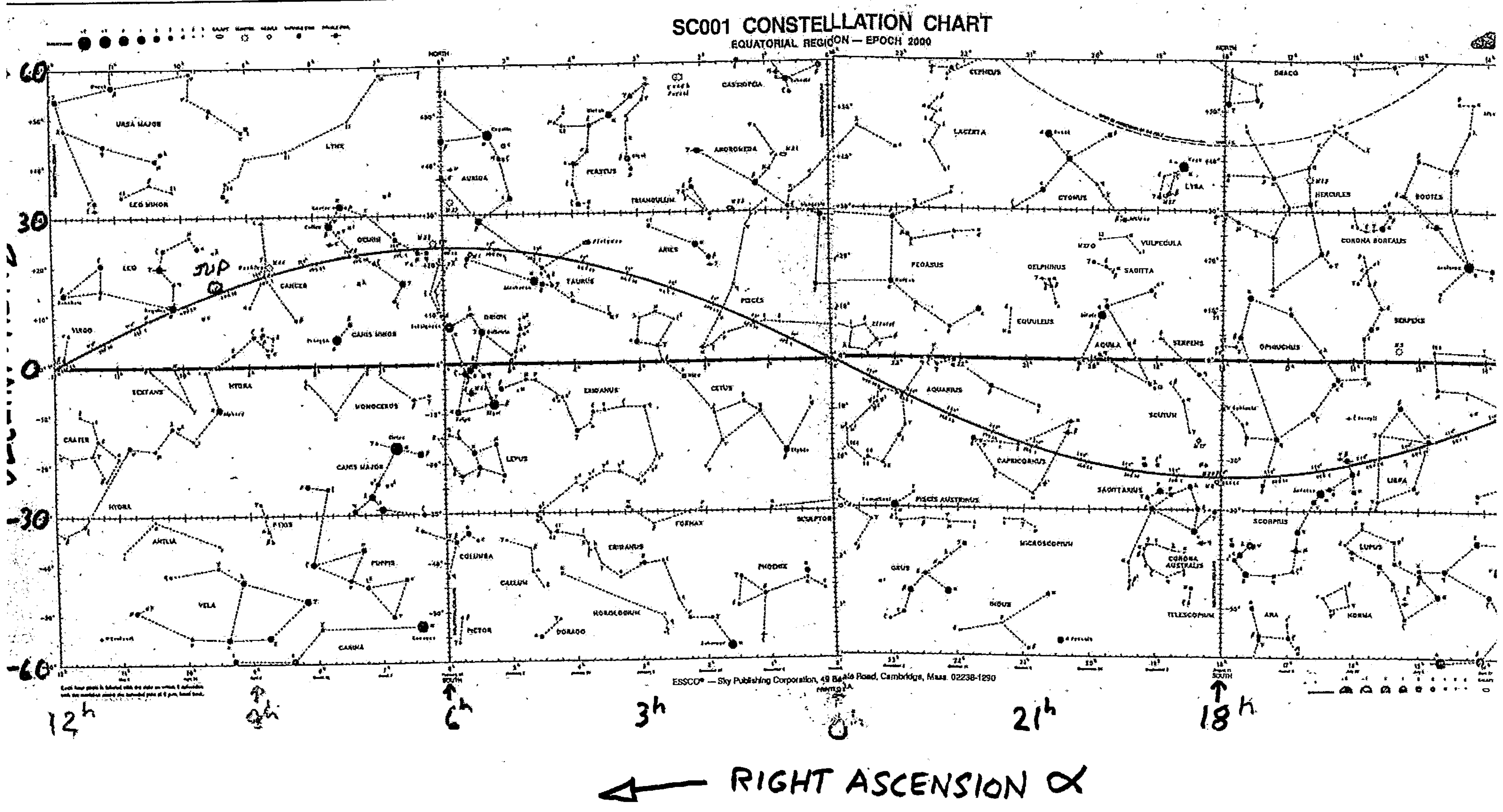
[5] Don't try to visualize the precession, though. If you can visualize that, join the circus, become an NFL quarterback, or make an appointment at Health Services.



can be projected onto a flat map ("Mercator projection):

⇒ every star has coords (α, δ) - which are fixed on the celestial sphere



describe this by saying that they have rotation periods slightly different from $23^h\ 56^m$, and also slightly different from each other. Or you could say that that they share in the daily rotation of the celestial sphere, but have their own quite slow west-to-east rotation superimposed. Most of the Greeks favored the latter.

Actually, the truth is that you only greatly care about one of these planets. Since your daily life is ruled by the Sun, you decide that its motion – not that of the zillion stars, or the other six planets – should be the basis of your time-keeping. Good idea! You define the "day" as the interval between meridian passages of the Sun, create 24 smaller intervals called "hours" which can be easily marked on a sundial, and establish yet smaller intervals (minutes, seconds) – because of your Babylonian fondness for "60".

Oh, and the ***meridian*** is the great bisector of the sky, separating the eastern half from the western half. Think of it as a giant clothes-line passing from the northern point on your horizon, through the point overhead (the ***zenith***), to the southern point on your horizon. Essential terms. The Sun, of course, crosses the meridian every day at roughly noon, for any latitude. But for our latitude, it never reaches the zenith (it only does so within the tropics).

Having wisely decided to adopt the Sun as your 24-hour standard, the other planets come out to:

Moon – variable but averages $24^h 40^m$
Venus, Mercury, Mars – variable but averages close to $24^h 4^m$
Jupiter, Saturn – variable but averages $23^h 57^m$
The fixed stars – precisely $23^h 56^m 4^s$.

These numbers are of little consequence to normal life, although some of your highbrow friends might choose to call this last one the "sidereal day".

So much for the day, and the hour (you construct an hourglass, using the sand all around you, to mark out the hours). But since the Sun moves annually among the stars, occupying each of the 12 zodiacal constellations in turn, you need also to have a ***year***. You'll need this for farming (growth seasons, flooding seasons, etc.), and commerce (when to hit the market with the latest spring fashions). The Sun's duration and changing angle in the sky dominates your life, and over thousands of years you and your predecessors have measured that long period to be 365.2422 days.

But whether you like geocentrism or heliocentrism, 24 hours and 365.2422 days are not the actual periods of rotation and revolution. One day, amazingly, a time-traveller appears and shows you Box 2 of this book. His credentials seem good (lists of all future Kentucky Derby winners, etc.; your descendants might even make some money from all this). You see that there are many, many "periods" up there in the sky – many wheels spinning away up at different rates. And 24 hours and 365.2422 days have no true physical significance; they're just convenient mathematical couplings of the "true" periods of rotation and revolution.

Figure 8: Next Page

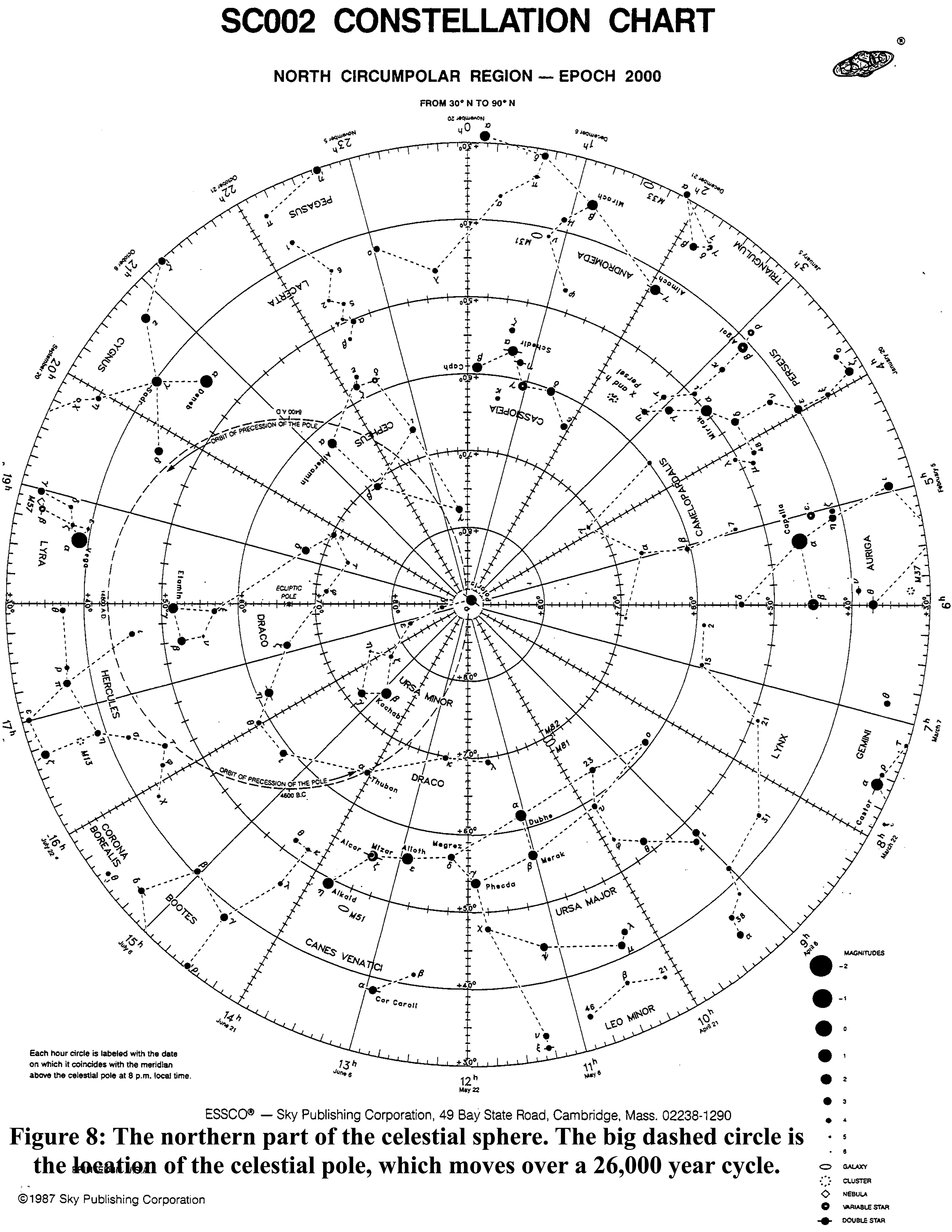


Figure 8: The northern part of the celestial sphere. The big dashed circle is the location of the celestial pole, which moves over a 26,000 year cycle.

No need to get excited, though, or even tell the neighbors. Mostly not needed for your ancient-astronomer certification.

Read whatever portions seem interesting. Ask questions in class. Visit a planetarium. Spin a celestial sphere. Watch how the Moon, or any star, moves in the course of a night.

Planets are quite a different story. They require adding complications to the Greek geocentric universe, and we'll be studying those complications soon, when we reach Ptolemy.

Box 2: Arcana on Coordinates, Time, the Calendar, and Eclipses

The Basics

Rotation of the Celestial Sphere – every 23h 56m

Description of events/objects in the sky: *altitude*, *azimuth* (degrees E of N)

Annual motion of the Sun: *the ecliptic*

The great bisector of the sky, separating E from W: *the meridian*

Positions of stars on celestial sphere:
declination: degrees, minutes, seconds
right ascension: hours, minutes, seconds (1 hour = 15 degrees)

You should be able to read the coordinates from the SC1 and SC2 constellation charts. If you could use that to figure out what's in the sky at a given time, that would be great. (Hint: compare the star's RA with that of the Sun on that date.)

Motions of the Sky

You should definitely know the motions of the sky as seen from the Earth's equator and poles – because they're simple. The motions from intermediate latitudes are harder to visualize; but you're probably going to spend your life at one – so try!

Time

Whew. What a subject. Because practically everything you've been told is not quite correct.

The Earth doesn't spin around every 24 hours...

Because during that day, the Sun moves approximately 1° eastward (since it moves 360° in 365 days). So the Earth has to spin 360+1° around to get the Sun back on the meridian. Takes an extra 4 minutes. In inertial space ("absolute space" in philosopher's language), the Earth spins around every 23h 56m – **the sidereal day.**

The Earth doesn't orbit the Sun every 365.2422 days...

Because during a year, the Earth's axis wobbles slightly, like a spinning top (precession). As the axis wobbles around on its 26000 years cycle, the timing of summer/ winter changes a lot – 6 months in 13000 years. Very confusing if you're an Egyptian farmer. To eliminate this, we slightly nudge the definition of the year so it always snows in January and bakes in July. Earth's true orbital period, with respect to the stars, is 365.2536 d. Astronomers would never have voted for this awkward coupling of periods, but we get paid to be finicky about these numerical things (and to take our orders from farmers, emperors, etc).

And the earliest sunset isn't December 21 (it's December 5)...

Because of the Sun's elliptical orbit, changing its speed slightly around the year (from its nominal 1 degree per day). The shortest entire day is December 21, but the time of true noon (when the Sun is exactly on the meridian) moves around during the year from ~11:35 a.m. to 12:25 p.m. The deviation from true noon is called “the equation of time”, and is the wiggly curve on most sundials. (Except the Columbia “sundial”, which is not a sundial at all. For the real thing, check the little guy between Pupin and CEPSR.)

Some Exact Numbers in Case You are Hugely Interested in Such Things

1 sidereal year	365.25636 d	Physical (true)
1 tropical year	365.24219 d	Calendar (for humans)
1 anomalistic year	365.25964 d	Elliptical orbit (apsidal)
1 "eclipse" year	346.6203 d	Interval between successive returns of the sun to the same node on the moon's orbit
1 sidereal month	27.32166 d	Physical (true)
1 synodic month	29.53059 d	Lunar phases
1 anomalistic month	27.55455 d	Elliptical orbit (apsidal)

Calendar Machinations

In order to keep the seasons under control, we need a calendar which has exactly 365.2422 days. Anything else, and it eventually snows in July. The ***Julian calendar*** does pretty well: (7x30 d) + (5x31 d) = 365 d, then add a leap day every four years. This yields 365.25 d. The error is 0.0078 d = 11m14s.

This makes an error of 1 day per 128 years. By the 16th century, the error was 10 days. By subtracting 3 leap days every 400 years, the error is reduced to 0.0003 d = 26 s per year. So it was announced in 1564 that October 4 would be followed by October 15, and subsequently the ***Gregorian calendar*** (the modern civil calendar) would prevail. This discontinuity in time-keeping means that historical dates are often designated O.S. (Old Style) and N.S. (New Style) to eliminate the ambiguity. An example is the 1917 "October Revolution" in Russia. Czarist Russia never went on the Gregorian calendar, so the Bolsheviks had to skip 12 days – and the revolution actually occurred in November (N.S.). Same for all dates in the British Empire. Those Brits didn't want to accept anything "Papist."

We could improve on the Gregorian calendar, but why bother? Actual time-keeping is possible to millisecond or even microsecond accuracy, and you can always learn the exact time here:

http://www.physlink.com/Reference/ExactTime.cfm

This site also has some fascinating links to the history of time-keeping.

Eclipses

These would occur every month if the Moon's orbit weren't tilted with respect to the ecliptic. As it is, the eclipse condition can be stated thus:

(1) When the Moon is near new or full, is it near the ecliptic (within 1°)?

OR

(2) When the Moon crosses the ecliptic, is it near new or full phase?

These are equivalent conditions.

Roughly, since the Moon's orbit is inclined to the ecliptic by 5°, there's a 1 in 5 chance of an eclipse each month. So you'd might expect 2 solar and 2 lunar eclipses per year. But most are partial – no big deal. Total eclipses occur at a rate closer to 1 every 2-3 years.

The Moon's line of nodes “regresses” (moves backward relative to the Moon's orbital motion), so the Sun encounters a line of nodes in less than a year – namely, in 346.6 days (the so-called “eclipse year”). So if an eclipse occurred today, would one occur 346.6 days from now. No, *because the Moon has to also be full or new, and 346.6 is not an integer multiple of 29.53*. If you pound your calculator keys for a few hours, you'll discover that these numbers become “commensurate” every 6585.3 days, because

223 lunar months = 6585.3 days

19 eclipse years = 6585.3 days

Thus an eclipse virtually identical to today's eclipse will occur in 18 years 11 ⅓ days – the famous *saros* cycle, known to the Babylonians.

Some Terms You Should Know

equinoxes
ecliptic
partial, total eclipses
meridian
waning gibbous

zodiac
apogee, perigee
Age of Aquarius
waxing crescent
zenith

line of nodes
precession
equation of time
aphelion, perihelion
umbra, penumbra

solstices
tropics
annular eclipse
meridian transit

Chapter III
Greek Astronomy and its Aftermath

To Archimedes came a youth eager for knowledge.
Teach me, O Master, he said, of that art divine
Which noble service has rendered the lore of the heavens,
And back of Uranus yet another planet revealed.
Truly, the sage replied, this art is divine as thou sayest,
But divine it was ere it ever the cosmos explored,
Ere noble service it rendered the lore of the heavens,
And back of Uranus yet another planet revealed.
What in the cosmos thou seest is but the reflection of God;
The God that reigns in Olympus is Number Eternal.

– Tobias Dantzig, *Number: The Language of Science*

Around 600 BC, something new seems to have emerged in the eastern Mediterranean. According to today's conventional historical accounts, it was the birth of philosophy... and in astronomy, the consideration of the **causes** of celestial motions. A seeming departure from explanations in terms of myths and/or whims of gods – and also from a mere description of those motions. The great astronomers of that era (say 600 to 300 BC) began to make *models* of the Universe (basically the starry sphere), and began to explain phenomena in terms of the *nature* of things: earth, air, fire, water, celestial matter (sometimes called “quintessence” or "ether"). Pretty close to what physicists have done ever since.

This era saw extensive developments in mathematics (Euclid), physics/ engineering (Archimedes), and essentially the birth of universities (Plato's Academy).

Like-minded philosophers gathered in schools to investigate and promote their type of thinking and research (associated with Pythagoras, and Thales, and Socrates/Plato). Much of their teaching was probably oral-only (Pythagoras, Socrates), but there were plenty of writers... and although most of the Greek writings have not survived, it was common for contemporary and later writers to comment extensively on the teachings of their predecessors. So with effort we can piece together some evidence of what these guys probably taught. Many of the later commentaries are basically refutations, suggesting that they – like their modern counterparts – found conflict and argument to be a productive way of moving the ball forward. If you've read anything of Plato, particularly the Socratic dialogues, you're well aware of this.

I use the word "philosopher" here on purpose. No one in our story would have thought of himself as a "physicist" (that would have meant *physician*) or "scientist" (that word didn't exist until about 1800). "Natural philosophy" would have been the contemporary word, or perhaps just *philosopher* if the subjects discussed included bigger issues (truth, beauty, reality, ethics, the one and the many, etc.)

1. Pythagoras

Pythagoras is a good place to start. He's way back there (600 BC), and they don't come any bigger. Here's what Arthur Koestler said about him:

> "The sixth century scene evokes the image of an orchestra expectantly tuning up, each player absorbed in his own instrument, deaf to the caterwauling of the others. Then there is a silence, the conductor enters the stage, raps three times, and harmony emerges from the chaos. The maestro is Pythagoras of Samos, whose influence on the ideas... of the human race was probably greater than that of any single man before or after him."

And this about a guy from whom we have no surviving work, and who indeed may never have written anything down! He gathered his own "cult" about him in southern Italy... and what we know comes from the many remarks, mostly critical and often derisive, which later Greeks made about him. Aristotle was particularly sneering. When the big shots are still savaging you 300 years later, you know you're onto something.

The summary of Pythagoreanism is: ***number rules the Universe***. He discovered that the pitch of a note depends on the length of the string, and that the harmonies occur for integer ratios of the length. He discovered mysterious relations between integers, the theorem that bears his name, and the existence of "numbers" which could not be expressed as ratios of integers. In fact, he discovered a *proof* that such things exist – as, for example, the length of the hypotenuse of right triangles. Twenty-six centuries later, geometry students were still memorizing his proof! (It's my only pleasant memory of high-school geometry.) He was horrified at such things – he called them *arrhetos* or "unspeakable" – because they seemed to violate his dictum. He allegedly forbade his followers to mention them to anyone (hence unspeakable). Someone spilled the beans a little later, and the study of irrational numbers was born.

"CELESTIAL MUSIC, MY EYE. WE WERE JUST PICKING UP SOME FM STATION IN VIENNA."

Speaking of beans, Pythagoras prohibited eating meat and beans, and thought that all true scientists should be vegetarians. He preached self-denial, shared property, and equal status for women. Even the rights of animals. (Didn't get a lot of traction on any of these subjects, did he?). Above all he taught that harmonies and numbers are the world's basic ingredients. The most famous consequence was the actual music played by celestial bodies in their daily motions. We just don't hear it... maybe because it's omnipresent, or because we're too distracted by the world's and our own troubles. As Lorenzo tells Jessica in *The Merchant of Venice*:

> There's not the smallest orb which thou behold'st,
> But in his motion like an angel sings...
> Such harmony is in immortal souls;
> But, whilst this muddy vesture of decay
> Doth grossly close it in, we cannot hear it.

Why does Koestler accord him – deservedly – such a lofty status? Because of the exalted role of number. We know of no one earlier, and practically no one later, who gave such primacy to numbers. *The God That Reigns in Olympus is Number Eternal.* We lost that awe for numbers for about 2000 years... but it came back in spades with Kepler, and now runs as strong as ever. Even the vegetarianism and animal rights are coming back. Pythagoras's credentials as prophet could hardly be shinier.

2. Thales

Thales was a near-contemporary of Pythagoras, from Miletus, on the west coast of modern Turkey. This region of Greece was called Ionia (a term still used in modern geography), and Thales is said to be the founder of the Ionian school of philosophy.

Also sometimes even "The Father of Science", since his methods of reasoning appear to resemble that of modern scientists (at our best; at our worst, we're a bunch of sheep).

Full disclosure: we have none of his writings, so we can't be really sure of what he believed or taught. But we do have books from many Greeks from the next few generations of philosophers and historians, and many of them mention Thales and specifically cite his books. So we have some idea of his teachings, and the frequent mentions and respectful tones of later writers suggest that Thales was considered the dominant "pre-Socratic" philosopher. (I omit Pythagoras, who was often considered more of a mystic/visionary/eccentric... and who may not have actually written anything). Even today, many histories of astronomy start with Thales, based on the fragmentary evidence of commentators.

Thales taught that explanations should be sought not in myths or gods, but in physical laws, especially geometry. (All the Greeks were aces in geometry, even as far back as 600 BC). He said that the world started from water, that land merely floated on water, and that the Earth was a sphere. He was widely known as a stargazer, and a popular legend says that he once fell into a well while stargazing. According to Herodotus, he once correctly predicted a total solar eclipse.

Most of the medium-famous Greek philosophers of the next 200 years were, to a considerable extent, followers or critics of Thales: Anaxagoras, Anaximander, Zeno, Parmenides, Democritus, Diogenes. You've probably heard of some of them. Of course, they fanned out over a much wider landscape of issues, that we would today describe as physics, mathematics, philosophy, or ethics.

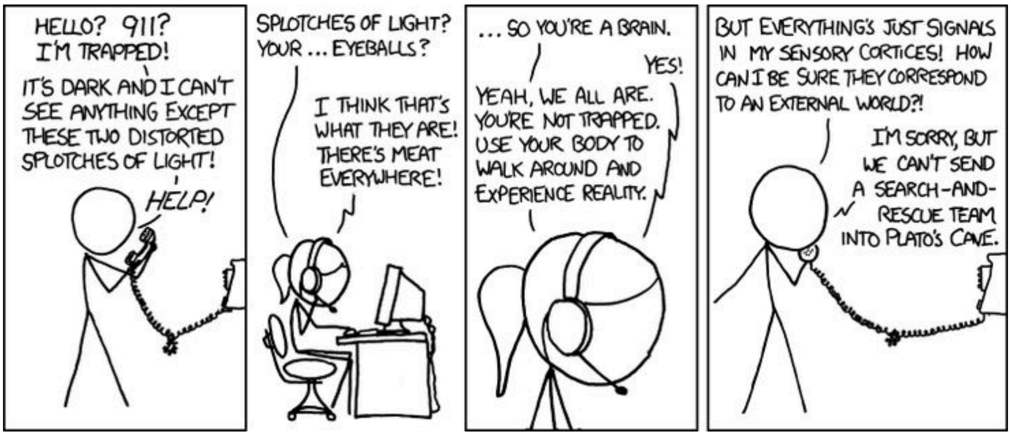
"Excuse me, Officer. I'm an academic. Where am I?"

3. Plato and Eudoxus

Alfred North Whitehead once famously said that all Western philosophy consists of a series of footnotes to Plato (423-347 BC). If you read Plato, you might get a sense of this. His writing is brilliant, even electrifying. And the subject range is vast – but unfortunately, not vast enough to include much on astronomy. During his time, it became common for philosophers to explain phenomena in terms of the "nature" of things... and in a few passages he tells us his understanding of celestial matter. It's perfect, therefore moves in the most perfect geometrical path – a circle. His student Eudoxus seems to have been the astronomy (and mathematics) specialist at the Academy, and Eudoxus went further with this. He taught that the round Earth was surrounded by a series of concentric spheres with stars fixed to them. The outer sphere moved around every 23h 56m, in a perfect circle about a stationary Earth at the center. So far, so good. Within that huge outer sphere are seven smaller spheres which move at slightly different rates. Each has just one star on it – namely, the "planetos", or "wandering stars". The spheres are all transparent, since you have to be able to see through 'em. They execute perfect, uniform circular motion; they have to – that's their nature.

Eudoxus and Plato were both aware that this hypothesis was somewhat flawed as an explanation of the planets (i.e. the seven wandering stars: Moon, Sun, Mercury, Venus, Mars, Jupiter, Saturn). Why? Because they don't move at an exact uniform rate, like the fixed stars do. Both Plato and Eudoxus hypothesize that these apparently chaotic motions can be represented as *combinations* of uniform circular motion. This was the predecessor of the detailed epicycle/eccentric/equant theories of Hipparcos and Ptolemy, which would soon become standard equipment for astronomers for 15 centuries.

Plato is perhaps best known for his cave allegory. He likened humans to prisoners in a cave, chained so they can only look at a wall in front of them. Behind them, unseen, are objects which are truly real, and jailers who project their shadows on the wall. Our "reality" is just the shadows. And if one of us breaks the chains, turns around, and then tells the rest of us excitedly about the real objects behind us, we will surely consider him crazy. Or, possibly, a 21st century theoretical physicist. We'll have more to say about that at the end of the semester.



4. Aristotle

Aristotle, surely one of the greatest of philosophers, wrote on practically every subject, and extensively on astronomy – mainly in his *Physics*, and in *De Caelo*. He argued that the Universe is spherical and finite, centered on a spherical Earth. The arguments for a spherical Earth were similar to those given in later centuries, and probably earlier by the pre-Socratics:

(1) the fact that new stars come into view as you walk north to south;
(2) in lunar eclipses, the shadow of the Earth is always round; and
(3) when ships disappear over the horizon, the mast disappears last.

Aristotle wrote extensively about physics, and incorporated his views on astronomy into a coherent whole. He advocated 5 fundamental elements: earth, air, fire, water, and celestial ether (the stars). The stars are perfect – therefore by nature unchangeable, and moving in a circle since that is the most perfect figure. Earthly matter is by nature corrupt, impure, subject to decay, by nature at rest unless acted on by a force.

His ideas would have a profound effect on the progress of science for many centuries. But oddly, not for the several centuries following Aristotle. Over the next 400 years, Greek science advanced brilliantly on several fronts: mathematics (Euclid), engineering (Archimedes), and astronomy (Hipparchus and Ptolemy). None of this progress built on Aristotle's teachings to any great extent. His later prominence in European thought probably owed more to the Catholic Church's – and especially Thomas Aquinas's – adoption of Aristotle as their favorite pagan author.

"He's not seeing anyone right now, due to the curvature of the earth."

5. Plato versus Aristotle

In terms of physics, Plato and Aristotle represent two opposite extremes. Plato considered events in the world, and patterns among them, to be just shadows cast by the "Forms" or "Ideas" behind them. This is close to the view of modern theoretical physics: the fundamental realities are the equations, and events are merely very complex manifestations of those basic truths. So complex, in fact, that we can't even understand in detail the physics of a man walking across a room (quantum mechanics has mastered the hydrogen atom, the hydrogen molecule, and the helium atom; nothing more complicated can be precisely solved).

Plato is thus considered the father of Idealism – although Pythagoras could equally be called that. Aristotle could be considered the father of Empiricism. But not quite in the modern sense. He seldom, or perhaps never, appeals to what we would call *experiment,* but rather to "observation" in its simplest form. That doesn't prevent him from being occasionally wrong even in some simple empirical matters ("women have fewer teeth than men").

Both views attracted many followers over the next 18 centuries (and for Plato, even to the present). But shortly after that Golden Age of Greece, science and mathematics would progress quickly in ways far beyond Plato and Aristotle. It's somewhat true that all subsequent Western philosophy is a footnote to Plato... but philosophy spawned some precocious offspring, who carried the ball rapidly forward in ways not really anticipated in the fourth century BC.

6. Euclid and Archimedes

Two of the great mathematicians of history. You mostly know the story on Euclid (300 BC). Greatest geometer in history... and the Greeks were all about geometry. His *Elements* was still a "standard textbook" 22 centuries later. What a record! Not any more – and if you look at it, you won't wonder why. To any modern math student, it's utterly impenetrable. The Greeks, as well as about 60 later generations, must have been awfully skilled in geometry to actually read it, and to willfully inflict it on students. Hardly an equation anywhere – just extremely complex figures, plus thousands of assertions, and proofs, of *congruence*. Save your brain: ours is an age of algebra, not geometry.

Archimedes (c. 250 BC) is usually regarded as the greatest inventor of all time, and might deserve that label also in mathematics. He was especially fascinated by large numbers, and posed many mathematical problems which were (and are) famous in number theory – sometimes in the form of poems. But as for many Greek authors, few of his writings have survived. Fortunately, Plutarch did write about him in his *Lives*, many contemporaries referred to him, always with awe... and a few of his works managed to endure, mainly through 9th-century translations into Arabic.

Archimedes cavorting in his multi-purpose physics lab

His one surviving work on astronomy is ***The Sand Reckoner***, perhaps the most information-packed 12 pages in the history of astronomy. For two reasons:

(1) He poses a problem we're still fascinated by: how big is the Universe, and how much matter ("grains of sand") is in it?
(2) To solve this problem, he adopted a *heliocentric* model, that of Aristarchus. His two-sentence summary[6] of that model is often considered the most reliable source for it (because Aristarchus's own work is lost).

This is historically significant because it's the only direct mention of Aristarchus's heliocentrism in classical works (apart from a very brief mention by Plutarch). But oddly, in the only extant work by Aristarchus himself (*On the Sizes of the Sun and Moon*), he adopts a specifically *geocentric* viewpoint. Exactly how and when Aristarchus's work became lost, it's awfully hard to say. Copernicus, Kepler, and Galileo all cite Aristarchus and lavish praise on him. They must have read his book on heliocentrism. These were all famous people, who lived not so long ago, and have been much studied by historians. Yet the book is considered lost. Mysterious.

Anyway, back to Archimedes. He interprets Aristarchus to mean

$$\frac{R_{universe}}{R_{Earth\,orbit}} = \frac{R_{sphere}}{R_{center}}$$

Note that this is dimensionally inconsistent, and invokes a meaningless concept (the radius of a sphere's center). I hope you are shocked by this... but maybe the greatest mathematician in history should be given a little leeway. (As should Barry Bonds, in a different sphere of human activity.) Archimedes added a few auxiliary assumptions, which removed the dimensional inconsistency, and deduced that there is room in the

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[6] "Aristarchus has written a book consisting of certain hypotheses, wherein it appears, as a consequence of the assumptions made, that the Universe is many times greater [than generally assumed]... His hypotheses are that the fixed stars and the Sun remain unmoved, and that the Earth revolves about the Sun on the circumference of a circle, the Sun lying in the middle of the floor, and that the sphere of the fixed stars is so great that the circle in which he supposes the Earth to revolve bears such a proportion to the distance of the fixed stars as the center of a sphere bears to its surface."

Universe for 8 x 10^{63} grains of sand.

Pretty good for the third century BC. Archimedes had to invent new mathematics (his particular brand of exponential notation) to express this result. Not infinity, he said – as Aristarchus and "King Gelon," whoever he was, had supposedly speculated – just 8 x 10^{63}.

In 212 BC, the Romans invaded Syracuse (the Sicilian city where Archimedes lived, not the basketball team which may or may not have a university attached to it). A soldier burst into Archimedes' house and demanded surrender. According to both Plutarch and Livy – usually considered excellent sources – Archimedes said “sure, as soon as I finish this proof I'm working out” (and sketching in the sand). The annoyed soldier then ran him through, despite his commander's explicit order not to harm Archimedes.

A fascinating and mysterious figure in this era is Seleucus, who flourished ~200 BCE. None of his writings have survived,[7] but we know of his work from the commentaries of Strabo and Plutarch – the great geographer and biographer of the next century, respectively. These are very reliable sources! Supposedly Seleucus believed that the Earth rotated on an axis and orbited the Sun – full-fledged heliocentrism. We don't know why he believed that... but then again, we don't really know why Aristarchus and Copernicus believed it, either.

That brings us up to about 200 BC. Let's dial back the clock a bit. Considered as history, these – and practically all – stories of the history of scientific ideas ignore a crucial ingredient: the canvas of culture and society where all these people live. One of the great clashes of civilizations and armies is about to occur, with great repercussions in society and in astronomy.

7. The Egyptian Greeks

The word “Egypt” means different things in different millennia. When Alexander invaded Persia in 333 BC, his astronomers (OK, maybe they waited a while till things cooled off) were amazed to find all the Babylonian records and books in the Persian libraries.This was the age of Aristotle and Euclid, so there resulted a perfect storm for astronomy... Babylonian records, Greek geometry, Greek culture. Along with, *mirabile dictu*, leisure time and no military threats! Plus the clearest skies available anywhere. This was the true heyday of so-called "Greek astronomy", though most of it happened in the distant parts of Alexander's Empire – especially in Egypt, where Hipparchus (c. 150 BC) and Ptolemy (c. 150 AD) lived.[8]

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7. Survival of books is a recurring challenge in this story. Remember, all books were written by hand. They had to survive many centuries of hazard by fire, flood, political upheaval, religious zealotry, and plain old human error or indifference (“lost”).

8. This can get confusing: too many Ptolemies, and too many Greeks. The

The great Greek astronomer of this era was Hipparchus (c. 150 BC). Little survives of his work, but Ptolemy, whose *Almagest* entirely survives, mentions Hipparchus's work in great detail – and there are other reliable sources, including Pliny the Elder. So we "know a lot" about his work, though without the ability to really study it. Hipparchus was certainly one of the greatest observers in history. He measured – presumably using Babylonian records – the precession rate, and got an accurate result. He prepared the first known detailed star catalog, invented the magnitude system for describing brightness, and undertook to find the distances of Sun, Moon, and stars by trigonometric parallax. Wow. We're still working on parallax, so obviously that enterprise proved to be a keeper.

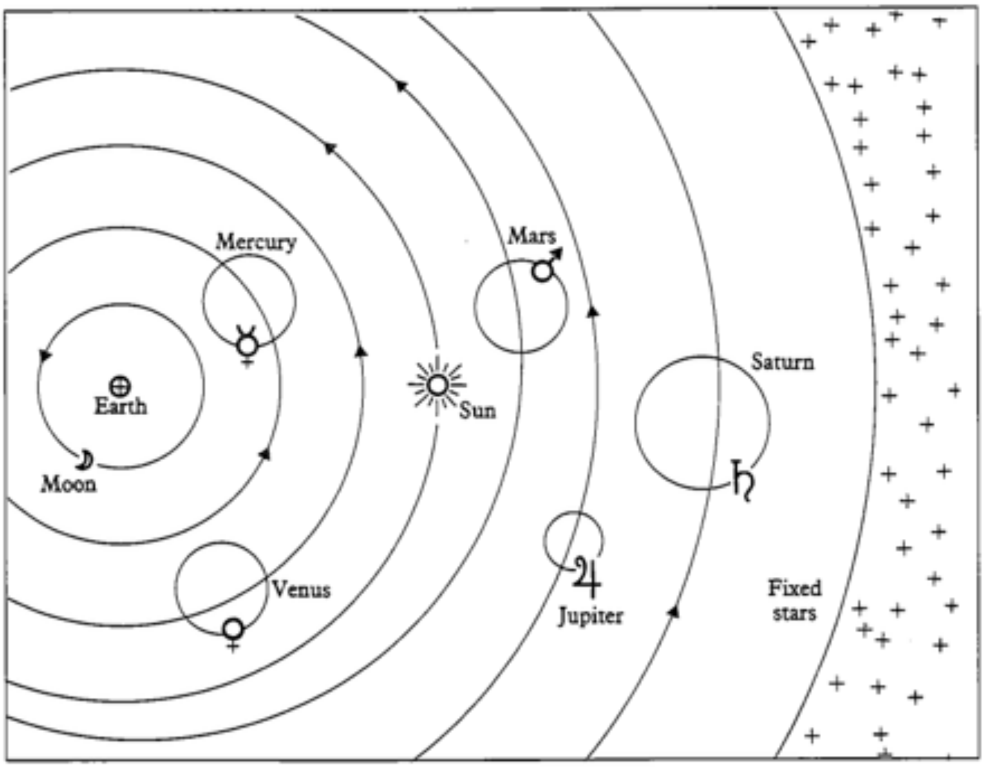

Figure 9: Geocentric cosmology, simplified version. The full version is too scary to show here. Each planet, including the sun and moon, orbits on a small circle (epicycle), whose center orbits the Earth on a bigger circle (deferent). Sometimes there are additional gadgets (minor epicycles, equants). All the circular motions occur at a uniform rate, and the astronomer's goal is to find those rates in order to "save the phenomena" (match the observed planetary positions.)

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historical setting was basically this. Alexander's conquest of Egypt was bloodless (the Egyptians were none too thrilled by their Persian occupiers), benign (arguable perhaps), and northern (most of it near the Mediterranean port, soon to be called Alexandria). He took the title of Pharaoh, but then promptly left on his eastern adventures. After his death, one of his generals was installed as King (and Pharaoh) Ptolemy I--and started a dynasty which ruled Egypt for 300 years. I think all the later kings were also Ptolemies. But Claudius Ptolemy, the astronomer and geographer, was a different guy altogether. I imagine that's as close as any astronomer ever got to being king.

History buffs might enjoy reading about a 2005 attempt to "rediscover" Hipparchus' original star catalog, which is lost along with practically all his other works.Basically, Schaefer's argument is: the famous and mysterious Farnese globe shows *precessed* constellations, and their positions indicate a source appropriate to the time of Hipparchus. Historians have not accepted this, but it's fun to think about. See www.phys.lsu.edu/farnese.

Hipparchus is also credited with the invention of epicycles as a scheme for explaining planetary motions – although other scholars attribute this to Apollonius (ironically, the incontestable source for the mathematics of ellipses, which would dethrone epicycles 18 centuries later). But there is little doubt about who developed epicycles in great detail... and that's Ptolemy. He was a tremendously skilled Greek (i.e. Egyptian) geometer who appeared to have full access to Hipparchus's books and observations. His famous book is the *Almagest*; and like many Greek books of antiquity, it has been preserved through its translations into Arabic (hence the Arabic name). In fact, it's now fully translated into English (if you consider 2nd-century Greek geometry to be "English"). Ptolemy is also a source of information about many other earlier Greek astronomers.

Ptolemy obtained few if any observations of his own. He doesn't consistently specify the source of his data; but when he does, it's usually Hipparchus. In today's language, Ptolemy was definitely a *theorist* (as was Copernicus).

The *Almagest* is entirely preserved, and it's a work of great mathematical (meaning geometry; these Greeks weren't big on algebra) precision and empirical (observational) scope. In class and in textbooks, you'll find basic discussions of Ptolemy's model. Eccentrics, equants, epicycles... pretty messy stuff. It was the geocentric model adopted by European astronomers until c. 1600, and is the "Great World System" which Galileo critiqued in his famous 1632 Dialogue – although more generally, Galileo discusses *geocentrism*... and discusses the underlying physics somewhat more than the astronomical issues.

Ptolemy is often the first astronomer to get onto the radar screen of history, as reported by people who write astronomy textbooks. This is pretty myopic. It gets progressively legitimized, because astronomers primarily consult the "histories" written by other astronomers, who are similarly incurious about history and anxious to get to Newton (if not Hubble). Each such account degrades the accuracy a little further.

I'm anxious to get to Newton too, but wanted to pause briefly here and send a small "Bah, humbug" off into the ether. I feel better now.

8. The "Dark Ages" and the Arabs

This term now has a precise meaning in cosmology. In the aftermath of the big bang, there must have been an interval after the elementary constituents of today's Universe (protons and electrons) formed, and before they condensed into stars and galaxies. Since there were no stars, we can't see any light from that era, although it may well have been a time of quite important events (perhaps the first appearance of *structure*?). We call that era the Dark Ages.

But the meaning implied here, at Columbia in 2016, is the more conventional one: very roughly, the period 300-1500 AD. I'll zip through it pretty fast.

Plutarch (c. 100 AD) doesn't quite fit here; he's a Greek Greek (lived near Delphi) and not an astronomer at all.[9] So he's not in the previous category. But he was an immensely popular writer – especially his ***Lives***, which has perhaps never gone out of print, and might be the most frequently read non-religious book in history. He wrote another well-known tract (actually part of his *Morals*) entitled "On the Face in the Moon", in which he describes the Moon as terrestrial: with mountains, rivers, and valleys. He didn't prove it... but Plutarch's fame was so great that Galileo very likely knew about this speculation, when he wrote about his telescopic discoveries in 1610. It's worth bearing in mind; Galileo was not above shading the truth just a tad about the novelty of his discoveries.

Courtesy of Stevenson

"Something goes around something, but that's as far as I've got..."

Hypatia was an Egyptian Greek who lived in Alexandria, born ~360 AD. She's perhaps best known for her messy demise: in 415 or 416, a mob of Christian zealots dragged her into a church, where they beat her to death with roofing tiles (!), then tore apart and burned her body. Before becoming a victim of religious politics, Hypatia was a gifted mathematician, astronomer, and philosopher. She and her father, Theon, wrote a commentary to Ptolemy's *Almagest*, which remained the primary version of that text for several centuries. She ran her own philosophy school, where she also taught math and astronomy. But in the early 5th century, Alexandria was being torn apart by radical Jewish and Christian fundamentalists – a bad time to be a famous pagan astronomer. And so, thanks to this and some bad political choices, Hypatia had her disastrous meeting with construction materials. Her works and legacy, however, went on to survive the mob. She has become slightly trendy in recent years; there's even a not-bad movie about her (*Agora*, 2004).

HYPATIA

The Catholic Church was none too interested in scientific matters during this era — perhaps even hostile. Augustine, in particular, railed against pagan curiosity as sinful. Even Thomas Aquinas ran into big trouble for being too independent, getting

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[9] In fact, he's often considered "Roman," since he lived under the governance of the Roman Empire.

pronounced a heretic from many pulpits. So there wasn't much contribution to our story from Europe. But Jean Buridan, a 13th-century French priest, did experiments and wrote impressively about the science of motion, and came up with a theory of i*mpetus*, which closely resembles the modern concepts of inertia and momentum. And Buridan, along with many others, knew that falling bodies didn't obey the physics of Aristotle (from experiments similar to Gaileo's famous "Tower of Pisa" experiments). So the "darkness" was not quite as unrelieved as you might have learned in high school.[10]

Then there were the Arabs. The word “Arab” is kind of sloppy, though. The so-called Arab Empire extended far beyond Arabia into north Africa, Europe, and central Asia, and some notable astronomers who fall under this banner actually come from Persia or India. However, the alternative is to say “Islamic astronomers,” which isn’t quite right either.[11] So just note that a variety of origins and cultures are hereby lumped under the banner of “Arab astronomy.”

As Europe was descending into the Dark Ages, astronomy was flourishing in the Middle East as the empire entered its Golden Age. The Greek classics, increasingly abandoned in their land of origin, were snapped up by the Arabs and preserved by a massive translation campaign. In fact, the name by which Ptolemy’s seminal work is popularly known — *Almagest* — comes from the Arabic title, *al Megiste* (which is itself a corruption of the Greek for “the greatest”).[12] We see similar influences in English words such as algebra and algorithm, which are derived from the names of their Arab inventors.

The catalyst that Greek philosophers provided for scientific investigation dovetailed nicely with a series of interested Arab rulers with deep pockets and existing religious imperatives. In Islam, daily prayer times (determined by the position of the sun), the lunar calendar, the beginning of holidays and the commencement and breaking of fasts, all demanded a rigidly precise understanding of celestial motions. Furthermore, *al qibla,* or the direction of prayer towards Mecca, called for exact knowledge of the size and shape of the Earth — as did rulers eager to know exactly what proportion of the planet fell under their rule.

Taking on this task was al-Biruni (973-1052 A.D.), famed mathematician,

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[10] Two excellent histories on these matters, including the "Scientific Revolution" which followed, are Herbert Butterfield's *The Origins of Modern Science* and Alexander Koyre's *From the Closed World to the Infinite Universe.*

[11] Any more than saying that Galileo was a "Catholic astronomer."

[12] The genesis of the title *Almagest* is a microcosm of the history of Western astronomy. As James Evans writes, "The original title was something like *The 13 books of the Mathematical Composition of Claudius Ptolemy.* Later the work may simply have been known as *Megale Syntaxis*, the Great Composition. The superlative form of the Greek *megale* (great) is *megiste.* Arabic astronomers of the early Middle Ages joined to this the Arabic article *al-,* giving *al-megiste*, which was later corrupted by medieval Latin writers to Almagest. A thousand years of history, embracing Greek, Arabic, and Latin traditions, are thus contained in one word. No better example could be wished of the continuity of the Western astronomical tradition."

astronomer, and ethnographer, among other careers. Of course, the circumference of the Earth had been measured before — remember Eratosthenes — and two centuries earlier, the Caliph al-Mamun had sent a team into the desert to perform a similar calculation. Al-Biruni, however, was the first to determine the circumference mathematically, using a fairly simple equation that was nonetheless a novel synthesis of algebra and geometry. He got a result within 1% of the modern value (~25000 miles). As he dryly wrote in his *Book of Determining Location*, "Here is another method for the determination of the circumference of the Earth. It does not require walking in deserts."

That al-Biruni was refining an experiment done by a team dispatched by al-Mamun was telling. Al-Mamun was a half-Persian 9th century caliph who enthusiastically supported science and philosophy. He founded an academy which did many translations, built what were arguably the world's first observatories, and compiled star catalogues which gave stars their modern names (Betelgeuse, Rigel, Altair, Aldebaran, etc.) and recorded the ever-changing positions of planets with great precision – not matched until Tycho Brahe's great feats 700 years later. These catalogues were used by Copernicus, and must have been (he doesn't tell us, so we can only speculate) a critical influence driving him to suspect that Ptolemy's geocentric model could not account for the observed motions.

The Arabs should also be noted for their construction of observatories. The Greek philosophers were cerebral, relying more on mathematics and thought experiments than actual observation. The Arabs were the observers to the Greeks' theorists. They were aided greatly by the breadth of their empire, and by robust trade networks — this was the time of the famous Silk Road — that made knowledge a cosmopolitan product. In fact, the so-called Arabic numerals that we use today were actually developed by Indian Hindus, taken up by Persian mathematicians in India, and then made their way to the West via the Arabs. Here's an imagined response of one Arab mathematician (al-Khwarizmi) upon learning of the Indian invention of zero:

> "Steeped in a tradition of faith and magic, he yearns to find the secrets of the universe in numbers. He writes mathematical problems; he dreams numbers . . . In numbers and equations spinning out their series, he senses the hidden codes of the universe, the numerical representation of the complexity of God's creation. . . . Al-Khwarizmi is at first dumbfounded, then awed, and then gratified to the depths of his soul. Each evening he awaits the new day's revelation of mathematics. He lies awake at night up on the roof of his quarters at the House of Wisdom . . . watching the half sphere of the heavens orbit Polaris, the middle sky shifting off to the south. At the center of the base of the hemisphere of heaven, he ponders what he has learned the previous day, unable to sleep because of the anticipation of what he will find. . . . Weak and drunk with the world that is now exploding in his head, al-Khwarizmi

> knows that mathematics has to be the code work of the divine."
>
> — *Lost History*, Michael Morgan

The greatest name of all in this story is Omar Khayyam (1048-1131), best known for his stunningly beautiful Persian *Rubaiyat.* Have you read this amazing poem? It's as famous world-wide as the Odyssey, and more accessible.[13] More than a poet, however, Khayyam also wore the hats of astronomer and mathematician, and made many great contributions in those areas (solution of cubic equations; creation of the Persian Jalali calendar, which is technically more accurate than our present Gregorian).

"From core of Earth to Saturn's apogee,
I loosed the knots of heaven's mystery;
The barriers of fake and fraud I crossed,
Yea, all the bars save that of Destiny."

"For in and out, above, about, below,
'Tis nothing but a Magic Shadow-show,
Play'd in a Box whose Candle is the Sun,
Round which we Phantom Figures come and go."

Khayyam was a swashbuckling character, and there are several movies about him – including one 1922 silent which is classified as a "lost film" (I didn't know such things existed).

But the circle turns on, and from the thirteenth century, the religious orthodoxy began to move from seeing empirical reasoning as a form of worship to worry that it might instead encourage apostasy, or even wrath from God that His secrets were being pried into. By the fifteenth century many of the great observatories had been destroyed, just in time for Europe to re-emerge into the Renaissance. Many of the Arab and Greek à la Arab works had found their way into Europe through Muslim-occupied Spain, and so the cycle of rediscovery began anew.

Around 1500, world events primed the pump for scientific changes. The printing press. Discovery of the New World. Discovery of the Southern Hemisphere. The Reformation. The Thirty Years War. The wide recognition of calendar problems. Overall, a dreadful century for authority. Enter Copernicus (1473-1543). Copernicus was a mighty unlikely revolutionary... and his reasons for advocating a Sun-centered cosmos are still not really known. In fact, it's not even known whether he *did* advocate a heliocentric view – only that he published one.

So that brings us up to the "Scientific Revolution": Copernicus, Galileo, Brahe, Kepler, Newton... with other significant contributions from Descartes, Huygens, Leibniz. That's the next major item on the menu.

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13. There are many translations; I recommend that of Edward FitzGerald.

Chapter IV
Copernicus, Brahe, Kepler

1. Nicolas Copernicus, 1473-1543

In 1543, more or less on his deathbed, Nicolaus Copernicus saw the printed version of his now-famous book "***de Revolutionibus Orbium Coelestium***" (On the Revolutions of Heavenly Spheres). This is now commonly regarded as one of the milestones in the history of science, along with Newton's *Principia* and Darwin's *Origin of Species*. But the status of Copernicus' book in the pantheon of science was very heavily influenced by the path to *de Rev* (world events set the stage for a change in thinking)... and by the century which followed. Galileo, Kepler, and Newton – revolutionaries all –found in the timid Copernicus the seeds of a new idea, and ran with it. Copernicus himself would have been quite amazed by what followed.

He was born in Poland in 1473, and worked throughout his life as a Catholic priest ("canon" in church parlance, probably indicating mainly administrative duties). Priesthood meant something very different then; priests had children, made money, and were frequently the administrators and scholars of their community. This was slightly before the Protestant Reformation (Luther nailed up his famous 95 theses in 1517). Poland ("Prussia", as it was then called) was subsequently a battleground of the Reformation, but it appears that this conflict did not figure much in Copernicus's life and work.

De Rev famously advocated a heliocentric model of the solar system, and of course this requires setting the Earth in motion. More specifically, it requires hypothesizing *three* motions of the Earth: 24-hour rotation on its axis, 365-day revolution around the Sun, and 26000-year wobbling ("precession") of the rotation axis. They're all true, they're all startling, and they have justly earned Copernicus a place in the pantheon.

How did he arrive at these conclusions? This question still puzzles historians, and Copernicus himself doesn't quite tell us. Astronomers often say that the heliocentric system was “simpler” – but it required just as many epicycles, and had the huge demerit of being incompatible with common sense and all known physics. The "Copernican Revolution" still needed ellipses, inertia, gravity, and the telescope to make its impact; these were still 100-150 years away. Copernicus describes his new system in great detail, but never makes the point-for-point comparison with the

Ptolemaic system – which Galileo later did so eloquently and forcefully in his *Dialogue on the Two Great World-Systems*.

Yet he came to his views, for whatever reason, early on. Around 1514 he wrote his *Commentariolus* ("Brief Comments"), which contained the full outline of his heliocentric system. This 40-page book was apparently never published in his lifetime, but circulated privately and became fairly well known among astronomers. It even came to the attention of Martin Luther, who thought it was ridiculous, and Pope Clement VII, who expressed interest. And it became known to Joachim Rheticus, a young mathematician who studied with Copernicus and resolved to get the old man's work into print. In 1540 Rheticus published *Narratio Prima*, the first published account of Copernicus's work. One can imagine conversations between the two men: "All right Joachim, if you're so enthralled with heliocentrism, why don't *you* publish it?"... followed by "OK Nick, now that your theory has been "published" twice without details, and you've reached your biblically mandated three score and ten, what should happen to that thick manuscript you've guarded all these years?" The master's work followed in 1543.

The events surrounding the publication of *de Rev* have fascinated historians. In particular, how did Copernicus regard his own theory? The book itself is a highly detailed and mathematical (meaning *geometrical*; both physics and algebra are still a few generations in the future) treatment of celestial motion. It's no masterpiece of literature, but is consistent with the default assumption that the author actually believes what he's writing. However, it also contains an unsigned preface which basically says "this exercise in mathematics yields tools useful for computation, but is not necessarily true or even probable, because certain knowledge can only be obtained through divine revelation". Speaking of revelation, modern scholarship has now revealed the source of the preface to be Andreas Osiander, a Lutheran priest and theologian. This now-infamous preface has itself become the subject of historical debate: who wrote it (considered settled by now), when, for what purpose, and whether Copernicus even knew about it.

In 1992 Owen Gingerich published his book *The Great Copernicus Chase,* which detailed his personal history of trying to track down every extant copy of Copernicus's work (and many other adventurous in astronomical archeology). It's a great read. A short version is available in *The American Scholar* 49, 81 (1980).

2. Tycho Brahe, 1546-1601

On November 11, 1572, the Danish nobleman Tycho Brahe saw a new and very bright star in the constellation Cassiopeia. Nearly everyone alive would have seen it, since it was the brightest star in one of the most famous constellations. And in those days, everyone knew their constellations.

It appeared out of nowhere and stayed bright for months. Tycho went to the astronomers at the University of Copenhagen, where he had attended, and asked what was known about this star. How could there even *be* a new star, especially one so bright? He was shocked to find no one there who was particularly interested. He later wrote "O thick wits..., O blind watchers of the skies." As a 25-year-old who had not yet found his calling in life, he decided that a Danish nobleman would show them how a proper job is done.

And did he ever. There were some astronomical instruments at a nearby monastery (telescopes haven't been invented yet), and he made accurate measures of the star's position for the several months it stayed bright. The star stayed fixed in the exact spot where it appeared in Cassiopeia; thus it could not originate in the atmosphere, and could not be a planet. It was *change* in the firmament, contrary to Aristotle's teachings. He wrote a short book, *De Nova Stella*, coining the word "nova". (Although the object is now classified as a **super**nova, and the remnant of this exploded star continues to be studied even today.) Tycho then received a grant of land and money from the king of Denmark, and he established an observatory – Uraniborg – on the small island of Hveen.

"Astronomy" at that time meant studying positions of planets in the sky. There was no physics, there were no telescopes to show planetary detail, and there was no clue at all about the nature of stars. Astronomers studied tables of planetary motion, and Tycho studied the two tables of past and predicted motions, corresponding to the geocentric and heliocentric assumptions. He compared those predictions with his initial observations, and was chagrined to find that both disagreed sharply with his own observations. He decided that astronomy needed new tables, and new observations to furnish a proper test that would distinguish between the geocentric and heliocentric models.

Image 1: Tycho at Uraniborg

To improve the observations, he needed better instruments. So he used his royal grant to construct large instruments for measuring angles in the sky, and over the next 20 years accumulated a storehouse of planetary positions probably 5-10 times more accurate than the records of his time. He realized pretty soon that the Copernican and Ptolemaic models both made quite poor predictions.

In the modern euphemism, Tycho was a “colorful” character. At age 20, he had half his nose sliced off in a duel, and later paintings show him with a gold or brass nose. He accumulated great wealth from agriculture on his island, but was ill-tempered and tyrannical in dealings with his subjects. He was perhaps jealous of the younger astronomers, and restricted their access to his data. Complaints about Tycho reached the new king, who in 1597 told Tycho to take a hike.

To the south of Denmark lay the Holy Roman Empire, that peculiar quasi-religious, quasi-German, quasi-everything, neither-holy-nor-Roman entity which had been hanging around since the time of Charlemagne. Emperor Rudolf II invited Tycho Brahe to work in Prague, build a new observatory, and bring some of his assistants. Which he did. But in 1601 Tycho died, under circumstances considered mysterious – so much so that his remains were exhumed and analyzed in 1901, and then again in 2010. Large but not quite fatal concentrations of mercury were found in his hair, and that led to suspicions about foul play. (By 1601, mercury in food was a well-known method of dispatching foes, and there were some of the usual provocations for murder... you know, marital indiscretions, denial of access to scientific data, etc.)

Late in life, Tycho came up with his own model for the planetary system. Earth was at the center, with the Moon and Sun revolving around it. But then the other 5 planets revolved around the Sun. On his deathbed, Tycho reportedly asked his talented young assistant, Johannes Kepler, to strive to make this hybrid model fit the observational data. Kepler probably said “sure, boss”... but with his love of mathematical elegance, had no intention of actually doing so.

3. Johannes Kepler, 1571-1630

Johannes Kepler was the one to finally figure out the shapes of the planetary orbits. His mother exposed him to the major astronomical events of his first decade:

the 1580 lunar eclipse, and especially the Great Comet of 1577, which was seen throughout the world and found its way into much literature and art. College degree in hand, he obtained his first job in 1595, teaching mathematics and astronomy at the university in Graz. That same year, he was struck with a vision that was to change his life. He wrote a book about it, the *Mysterium Cosmographicum,* and logged the date of his vision (July 19).

Kepler had studied both Ptolemaic and Copernican systems in college, and under the tutelage of his famous professor (Michael Maestlin) had come to favor the Copernican. There are six planets in the Copernican system, and Kepler's epiphany was that he had hit upon the deep reason for the number *six* – the five "perfect solids" which all those Greek-geometry-savvy guys must have been familiar with.[14] For each of these solids, you can inscribe a sphere within it, and circumscribe it by another sphere, with each sphere touching every face in the middle. The radii of these pairs of spheres have a definite ratio, and Kepler computed them. (Actually, Euclid probably computed them 1800 years earlier.) He found that if you arrange them in a particular order, the radii come out very close to: 0.4, 0.7, 1.0, 1.6, 5, and 12 units. Very close to the actual radii of the planetary orbits in astronomical units (which were known in the Copernican system, although the numerical value of the astronomical unit in meters was completely unknown).

This blew Kepler's mind. Always a card-carrying Pythagorean, he must have felt like he was actually hearing the music of the spheres. In 1596 he published the *Mysterium*, which gave the world a first look at what would become his trademark: mathematical excellence, astronomical data, religious fervor, humility, and breadth of vision – all intertwined so thoroughly that the book was really hard to read. All the more so today.

Fortunately for everyone, the young Kepler did not go on to start a new religion based on Euclid. And even better, he got a nice job offer in 1600 from Europe's most famous astronomer, Tycho Brahe. Brahe was established as the "imperial mathematician" in Prague, and had the world's best data for planetary motions; the job was potentially permanent; and Prague was more tolerant of Kepler's Lutheran faith. Kepler took the job.

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[14] For anyone reading this who is less than 400 years old and/or has never won a Nobel Prize in solid geometry, they are: tetrahedron (pyramid), hexahedron (cube), octahedron (8 sides), dodecahedron (12 sides), and icosahedron (20 sides). These are solids in which each face is a regular polygon, with the same number of faces meeting at each vertex. They were well-known to the Greeks and much discussed by Euclid, who proved mathematically that there are only five. Plato had speculated that each of the five elements (earth, air, fire, water, ether) consisted of one of these.

Before Tycho's untimely death in 1601, he discussed with his assistants – Kepler and Christen Longomontanus – how the work would be carried forward. Each planet presented its own challenge. Mercury was flat-out impossible; it was hardly ever possible to see it (due to the solar glare), so observations were fragmentary. But the Sun, Venus, Jupiter, and Saturn were pretty tractable. Both the Ptolemaic and the Copernican systems could adequately "explain" (find suitable combinations of deferents and epicycles) these four planets. By far the biggest problems were Mars and the Moon. They just never did what either system predicted.

Tycho assigned Mars to Kepler, and the Moon to Longomontanus. This was fateful; it gave Kepler the opportunity to discover the famous laws which bear his name, and relegated Longomontanus to a task so difficult that we are still working on it today.[15]

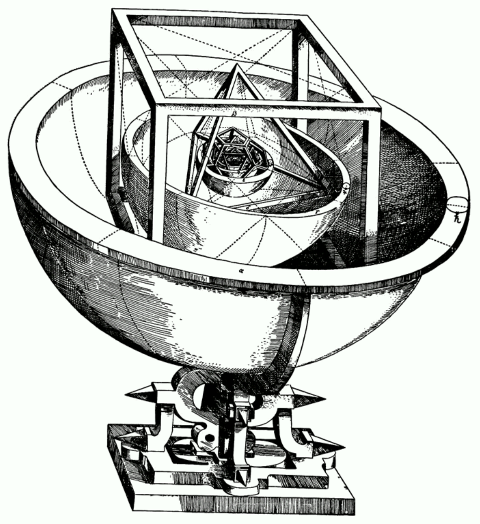

Figure 10: Kepler's Five Perfect Solids

Meanwhile, another great spectacle occurred in the night sky: the supernova of 1604, the last recorded supernova in our Galaxy. Kepler began nightly observation of this star, and showed – as Tycho did for the 1572 star – that it never changed its position, thus belonging to the sphere of the fixed stars. It also guaranteed him a great deal of work in... gulp... *astrology*. Astrologers had fixed on 1600 as a year of great portent, since Jesus was born near the year 0 and Charlemagne was crowned in the year 800. Here was a brilliant light, brighter than any star, which must signify the beginning of a new era. A new era in what? For a high-quality answer, go to the best astronomer around, and that was apparently Kepler, the new imperial mathematician (he succeeded Tycho). And he knew plenty about astrology, having cast horoscopes for friends in college. But he managed to wade through the horoscope work and keep focus on his real prey, the motion of Mars.

This was to culminate in the 1609 publication of *Astronomia Nova*, a landmark book in the history of astronomy. It gets that label basically from the discovery of the true shape of planetary orbits: an ***ellipse***. But unlike virtually any other scientific book, Kepler wants you to know about every agonizing step in the reasoning – including all the trips down blind alleys. He wants you to share in his exultation, too. In the preface he states his theological and philosophical views:

> "Why waste words? Geometry existed before the Creation, is co-eternal with the mind of God, is God himself (what exists in God that is not himself?); geometry provided God with a model for the Creation and was implanted into man, together with God's own likeness – and not

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[15] The Moon-Earth-Sun system is an example of a *three-body problem* in gravitation theory. It has no solution "in closed form" (viz., an algebraic formula). In later centuries, "theories" of the Moon's motion were expressed in very long polynomials, with as many as 200 terms. Poor old Longomontanus never had a chance.

> merely conveyed to his mind through his eyes....
>
> … So much for the authority of Holy Scripture. Now as regards the opinions of the saints about these matters of nature... in theology the weight of Authority, but in Philosophy the weight of Reason alone, is valid. Therefore a saint was Lactantius, who denied the earth's roundness; a saint was Augustine, who admitted the roundness but denied that antipodes exist. Sacred is the Holy Office of our day, which admits the smallness of the earth but denies its motion; but to me more sacred than all these is Truth, when I, with all respect for the doctors of the Church, demonstrate from philosophy that the earth is round, circumhabited by antipodes, of a most insignificant smallness, and **a swift wanderer among the stars**."

This was a bold declaration. Astronomy was dangerous stuff for Copernicus, and got really dangerous in the early 17th century. In Rome, Giordano Bruno had been burned at the stake in 1600. Galileo's injunction and trial were not far off (1616 and 1632). And the Thirty Years' War was about to erupt (1618-1648). Kepler was Protestant, but Prague was mostly Catholic. It was a time to be "politically correct," not bold.

After showing his hand so audaciously, the hard work begins. He starts by comparing the predictions of the Ptolemaic and Tychonic systems with Tycho's very precise observations. No dice – a very bad fit. Then he sets the Earth in motion (the Copernican system). After optimizing all the adjustable parameters of the circles (the sizes and rotation speeds on the deferent and epicycles), he gets a much better fit – good to within 8 minutes of arc. Sounds excellent: one-seventh of one degree. Had Tycho never been born, it would have been cause for celebration. But Kepler is pretty sure that Tycho's data are accurate to ~2 arc-minutes. So...

> "...for us, who by divine goodness were given an accurate observer such as Tycho Brahe, for us it is fitting that we should acknowledge this divine gift and put it to use.... For if I had believed that we could ignore those eight minutes, I would have patched up my hypothesis accordingly. But since it was not permissible to ignore them, **those eight minutes point the road to a complete reformation of astronomy.**"

Kepler concludes that the path is not a circle, nor a combination of circles, but an oval. Many more pages of tortured geometry and lament (his, and yours too, if you read it) follow... until Kepler finally realizes that it's a particular kind of oval, namely an *ellipse*. Kepler, an ace at geometry, knew all about ellipses (as did Apollonius and Euclid many centuries earlier). He then quickly checked the other planets, including Earth, to see if they conformed. They did. In retrospect it's easy to see why this only could have been discovered by studying Mars. The Martian ellipse has an eccentricity $e = 0.09$, but the other planets have quite low eccentricities – so low that their orbits are practically indistinguishable from circles (a circle is a special case of an ellipse, with $e = 0$).[16]

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[16] Mercury is an exception at $e = 0.20$, but the observational data for Mercury

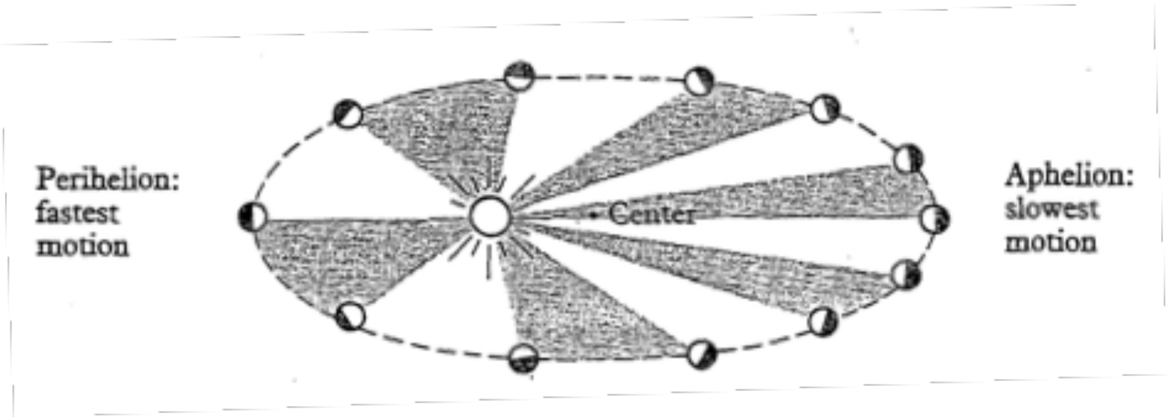

Figure 11: Kepler I. Planets move in ellipses, with the sun at one focus. Kepler II. Faster at perihelion. dA/dt=constant. "Law of Areas"

Kepler then states the first two of his famous laws of planetary motion:

1. The planets move in ellipses with the Sun at one focus.
2. The planets sweep out equal areas in equal times: dA/dt = constant.

Years later he arrives at his Third Law:

3. The squares of the orbital periods are proportional to the cubes of the semimajor axes: $P^2 = ka^3$, where k is a constant. In "astronomical" nomenclature, we can set $k = 1$ if P is measured in years, and a in astronomical units.

Actually, there's a fourth law, hardly ever discussed and yet possibly a major clue to heliocentrism in Kepler's mind. I call it Kepler's zeroeth law, since it was found before the other three:

0. The planes of all planetary orbits pass through the center of the Sun.

Kepler kept up a steady stream of writing for most of his life, including the *Harmonice Mundi*, where his Third Law was presented. He had plenty of daily stresses:

(1) Tolerating the constant presence of soldiers in his house; he lived in the city walls, so sentries were everywhere during the Thirty Years' War.
(2) Defending his mother in lengthy witchcraft trials.
(3) Dealing with the constant requests for horoscopes, his main source of income.

Kepler seems to have been the first astronomer to confront the question of ***why*** the planets move. The Greeks would have said "it's their nature". But once you adopt a heliocentric model, this is harder to say, because *one* of those moving planets is the big ol' sluggish Earth, made of rocks, dirt, etc. – stuff which seems naturally inclined to just sit there, not move.

So Kepler comes up with a novel suggestion. William Gilbert had published his great work *De Magnete* in 1600, suggesting that the Earth was a gigantic magnet – thus explaining why those mysterious *lodestones* always pointed north. Lodestones were

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were too fragmentary to use.

extensively used by mariners for navigation at the time, and were regarded practically as sorcery by many sailors. Kepler thought that if the Earth could reach out by this invisible force to align the lodestones, then maybe the Sun reaches out by the same invisible force to "sweep" the planets along. **The Sun is a magnetic broom, sweeping all the planets forward in their orbits.**

Galileo will improve on this very substantially in 1632, with a proper and complete understanding of inertia. But the full theory of planetary motion has to wait for Newton in 1687.

Chapter V
Galileo: Eppur Si Muove

Wandering between two worlds, one dead,
The other powerless to be born.
- Matthew Arnold

Galileo was born in Pisa in 1564, the son of Vincenzo Galilei, a famous musician and often credited with important discoveries in the physics of music. Vincenzo experimented with strings of different length and under different tensions, and discovered the mathematical rules governing the music produced. Like his son, Vincenzo was well endowed with creativity, independence, and arrogance... which eventually played out in tragedy for his son. Also like his son, he strongly and publicly advocated that *reason*, or better yet *experiment*, should be used to prove any assertion – not *authority*, as more commonly practiced at the time (or any time). He wanted his talented son to be a doctor.

But Galileo dropped out of medical school, preferring math and physics, and at age 25 began teaching these subjects at Pisa and Padua. He was known for applying mathematics and experiment to physical problems, an approach rare at the time. He wrote a famous treatise on motion (*De Motu*) in which he described new instruments for measuring length and time – especially the water clock, which would be critical in his measurements of the dynamics of falling bodies. By 1597, he had read Kepler's ***Mysterium Cosmographicum***, became interested in astronomy, and began a correspondence with the young German mathematician:

> "Like you, I accepted the Copernican position several years ago and discovered from thence the cause of many effects which are doubtless inexplicable by the current theories.... I have not dared until now to bring my reasons and refutations into the open, being warned by the fortunes of Copernicus himself, our master."

This correspondence continued for decades, and was important to both men, as well as to the history of science. It was especially important to Kepler, who was lonely, and really, *really* needed a friend with a telescope. He constantly and unsuccessfully begged Galileo to send him one of his reject telescopes. Instead, Galileo would send his discoveries, and even these were coded in the form of Latin anagrams. Here's the first he sent:

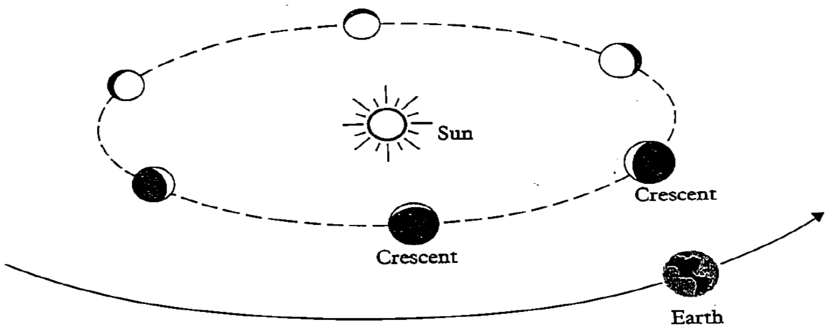
SMAISMRMILMEPOETALEUMIBUNENUGTTAURIAS,

which Kepler guessed was "Hail, burning twin, offspring of Mars". Months later, Galileo decoded it: "I have observed the highest planet in triplet form". This was his description of the odd appearance of Saturn (which he attributed to two moons).

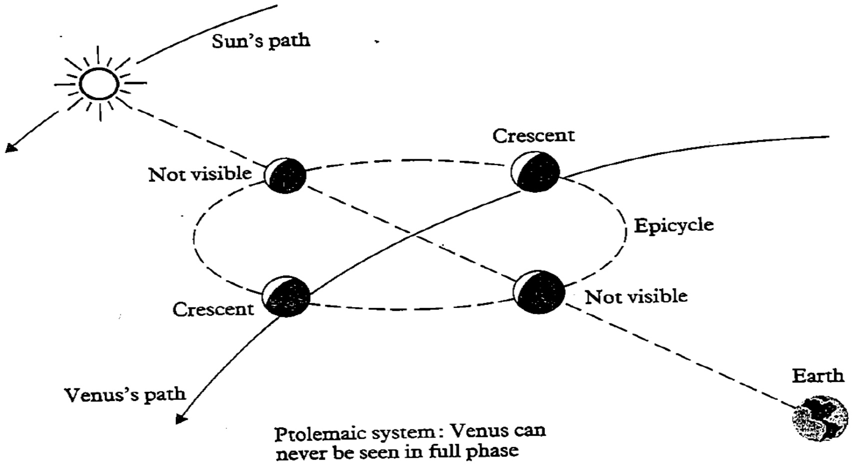
Later, Galileo sent another anagram:

HAEC IMMATURA A ME IAM FRUSTRA LEGUNTUROY.

“These immature things are being sought by me in vain.” Kepler again tried to decode it, trying, among other things, "there is a red spot on Jupiter which rotates mathematically". He pleaded with Galileo to reveal the secret, but no dice. After about a year, Galileo coughed it up: "The mother of love (Venus) emulates the shapes of Cynthia (the Moon)." In other words, that Venus shows phases. More important, it shows a *full* range of phases – from new to crescent to half to full, and back again. This is **only possible if Venus orbits the Sun**, not the Earth. To any astronomer familiar with the Ptolemaic/Copernican systems, it is (if you believe the evidence) a pretty convincing proof of heliocentrism.



Copernican system: Venus goes through all phases



Ptolemaic system: Venus can never be seen in full phase

Figure 12: The Phases of Venus, as viewed in geocentric and heliocentric conceptions. In a geocentric system, at the bottom, Venus would show only a series of crescents. In the top heliocentric conception, however, Venus exhibits a full range of phases – as Galileo saw, with the help of his handy dandy telescope.

➸ External Link: The Phases of Venus

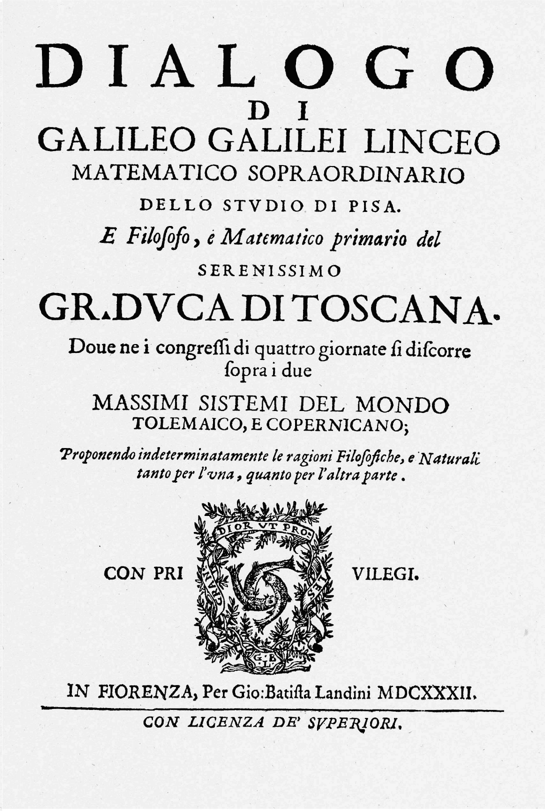
Here's a great animation of the phases of Venus in a heliocentric system:

http://astro.unl.edu/classaction/animations/renaissance/venusphases.html

In a geocentric system, Venus shows phases, but only up to a half-Venus at the most. The only way you can get a full Venus is to have it on the opposite side of the Sun, and that can never happen in a geocentric system.

Galileo's early telescopic discoveries astonished Europe: mountains on the Moon, resolution of the Milky Way into stars, Jupiter's moons, phases of Venus. He wrote about them brilliantly, and with considerable bombast. Some short excerpts from his 1610 *Starry Messenger* are given at the end of the chapter. He was certainly the most famous astronomer of his day, and maybe any day. Among all scientists, only Darwin and Einstein are in his class (scientific acumen plus high public profile).

His story is very much bound up with the stresses and politics of his time. So let's get some of the relevant chronology and politics of Italy, or what would become Italy, roughly sketched. Venice, Florence, and Rome are powerful city-states; Rome is very influential, and the Catholic Church is highly embattled in a lengthy ideological and shooting war with the Protestants. The Inquisition is going strong. Rome's great power is borderline enforceable in Florence, but not at all in Venice. Amid this background, Galileo sets out on his astronomical career:



DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
E Filoſofo, e Matematico primario del
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congreſſi di quattro giornate ſi diſcorre
ſopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
Proponendo indeterminatamente le ragioni Filoſofiche, e Naturali
tanto per l'vna, quanto per l'altra parte.

CON PRI VILEGI.

IN FIORENZA, Per Gio:Batiſta Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

The Rise and Fall of Galileo

1592	Galileo accepts a position at Padua, in the Venetian Republic.
1600	Giordano Bruno is burned at the stake in Rome for advocating the plurality of worlds, and a few other related theological heresies.

1604 A new star appears in the sky. Europeans everywhere marvel at this star, and Galileo gives a series of lectures on it, in which he shows that the absence of parallax requires the star to lie beyond the Moon – and therefore is evidence of change (lack of perfection) in the heavens.

1609 Kepler publishes the *Astronomia Nova*, containing the first two of Kepler's Three Laws (plus the zeroeth, hardly ever mentioned but probably the most important of all). In May, Galileo hears about the Dutch spyglass, and begins to build his own; his first 3x telescope is completed in June. The following month, Thomas Harriot makes a series of lunar observations through his own 6x telescope. In August, Galileo formally presents an 8x telescope to the Venetian Senate, and is rewarded by lifetime tenure and a doubling of his salary.

1610 On January 7-10, Galileo trains his telescope on Jupiter, and discovered its four large moons. Four nights that change the world... and would assign the number for this class. The scene from Bertolt Brecht's *Galileo* is given in the appendix. It begins with a chant:

"January ten, sixteen hundred and ten:
Galileo Galilei abolishes heaven."

The discovery of Jupiter's moons has great impact. It shows that Earth is not the only body with a moon, and makes the interpretation of Earth as “just another planet” more plausible. In addition, it removes one of the powerful *physical* arguments against a moving Earth. Many scholars had said “if the Earth moves, how can it hang onto its moon?” Well, there is Jupiter up there in the sky, moving around *something* (the Earth? the Sun?) and apparently having no difficulty hanging onto four moons.

1610 In March Galileo announces his discoveries in *The Starry Messenger* (*Sidereus Nuncius)*, a beautiful little book dedicated to the Cosimo de Medici. He is then appointed "Chief Mathematician of the University of Pisa and Philosopher and Mathematician to the Grand Duke" of Tuscany. He moves from Padua to Florence to begin this lifetime appointment. This is basically his reach for the big time. It brings peril, since Rome has great sway in Florence.

1611-2 Other telescopes pop up around Europe. The word "telescope" is first used. Sunspots are discovered. Galileo announces the phases of Venus, visits Rome, and publishes a few other short works. Cardinal Bellarmine asks the papal astronomers – Jesuits who were among the best astronomers in the world – if Galileo’s work has merit. They tell him: *yes*, absolutely.

1614-5 Tommaso Caccini, a Dominican friar, preaches a sermon in Florence against Galileo, and declares the Copernican view to be a heresy. He gives a deposition to the Roman Inquisition. Galileo, ever confident that he will prevail in any argument, travels to Rome.

1616 The Inquisition's consultants declare that heliocentrism is "absurd in philosophy and formally heretical", and that the Earth's annual motion is "absurd in philosophy and at least erroneous in theology". On orders of Pope Paul V, Cardinal Bellarmine informs Galileo that he is forbidden to "hold or defend" the Copernican theory. An unsigned transcript in the Inquisition file, discovered in 1633, states that Galileo is also forbidden to discuss the theory orally or in writing. At Galileo's request, Bellarmine gives him a letter stating that Galileo had not been on trial or condemned by the Inquisition. The latter is presumably true on technical grounds, but the bottom line is clear: Galileo is now on probation.

1618-9 Several bright comets appear. Various European rulers write to ask Galileo's opinion, but he gives none.

1621-3 Paul V dies, and then Gregory XV. Cardinal Barberini, a friend and patron of Galileo, becomes Pope Urban VIII. Galileo visits Rome, and the new Pope assures him that he can write about the Copernican hypothesis as long as he treats it as only a theory.

1625-9 Galileo writes a treatise on finding longitude at sea by using the eclipses of Jupiter's moons... and sells the idea to Spain. (Definitely not a smart idea.)

1630-2 Galileo finishes the *Dialogue on the Two Great World-Systems* (comparison of Ptolemaic and Copernican), clears the censors, and publishes in Florence (in Italian; also not a smart idea).

1632 Pope Urban VIII halts distribution and appoints a commission to examine the book. The Inquisition summons Galileo to Rome, which is considered a prelude to a trial. Galileo cites poor health and requests that the interviews be moved to Florence. The Inquisition says no dice... comply or we'll bring you here in chains.

1633 Galileo travels to Rome. His 3-week trial ends in a plea offer; Galileo concedes he might have favored the Copernican theory too strongly, and offers to write a second book to correct that unintended lean. The Inquisition says no, you still don't get it.... He is "shown the instruments" (of torture), and signs an oath of affirmation, in which he confesses to his disobedience and errors. Three of the ten inquisitors do not sign the oath. He is sentenced to house arrest in Florence, where he is closely guarded and forbidden to travel anywhere for any reason.

1638 Galileo, now nearly blind, spends his captivity – how else? – rolling balls down inclined planes, and learns the laws of motion. Not gravity, and not calculus... but otherwise the main machinery of Newton's Laws. He writes his other famous tome, the *Discorsi* (*Discourses on Two New Sciences;* what we now call kinematics and dynamics). His friends smuggle it to Holland, where it is published by Louis Elsevier. That firm is still publishing scientific books, and selling them for very big bucks. Most of us feel that the debt has been paid.

1642 7 days into the new year, Galileo dies. 7 days from the end of the old year, on Christmas Day, Isaac Newton is born.

Galileo's story, and especially his conflict with the Church, has been fascinating to historians. Why did the Inquisition come down so hard on him? He was a physicist-astronomer, not a preacher. He was held in very high esteem by the Jesuit astronomers, and was sponsored by the most powerful family in Italy (the Medicis). Pope Urban VIII was known as a reformer, a patron of the arts, and indeed was a personal friend of Galileo.

One theory is that he was a victim of a Church power struggle between the Jesuits and the Dominicans. The Jesuits were the scholars (and still are), while the Dominicans were more inclined to find and punish heretics, sometimes with a touch of paranoia. Another theory is that the Pope read the book and found some of the pro-Ptolemy arguments, somewhat ridiculed by the Galileo character in the book, to be eerily similar to things he (Urban VIII) had said to Galileo in private conversation. Given a chance, Galileo would certainly have cleaned that up; but of course he was not given that chance.

GALILEO DESCRIBES HIS DISCOVERIES TO THE CHURCH

Legend has it that at the announcement of the verdict, Galileo said to the inquisitors, *Eppur Si Muove* (And Yet It Moves). There's some evidence for this, but it's thin and ambiguous. But if he did say it, it's pretty likely that the inquisitors would have done their best not to hear.

Whatever the underlying reason was for this punishment of a brilliant scientist, the effect was that Italian science slunk into a backwater, not to emerge for three hundred years. Galileo's *Dialogue* remained on the *Index of Prohibited Books* until the 20th century.

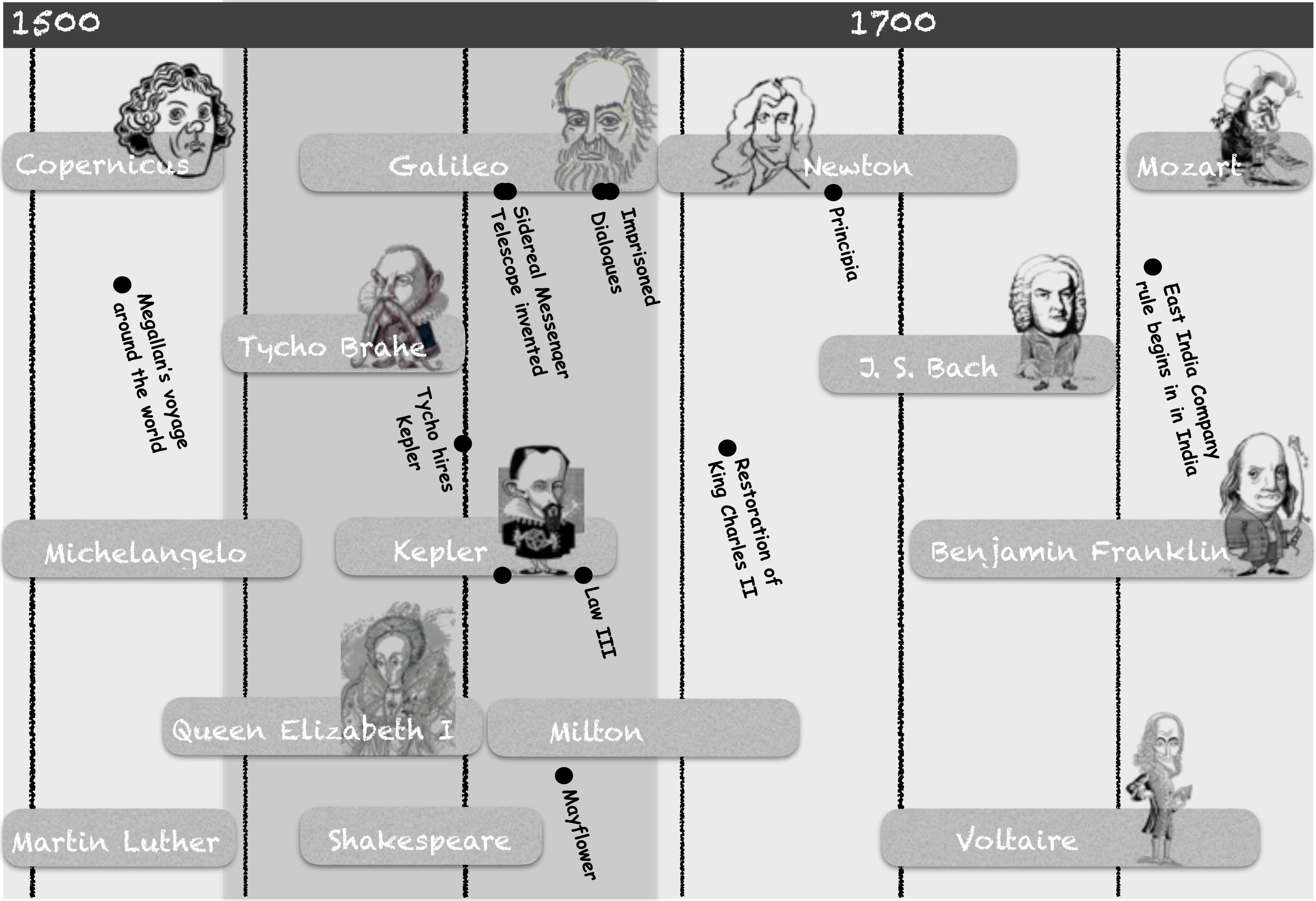
The standard history of the conflict is Giorgio de Santillana's *The Crime of Galileo*. There are many others; a popular and recent one is Dava Sobel's *Galileo's Daughter*. Bertolt Brecht wrote a great play about it (*Galileo*). We'll do a playreading; but in any event, sometime in your life, read that play. It's frequently produced in the USA. A short and outstanding film adaptation of it can be found here:

https://youtu.be/074YKv7Owzs

And the Indigo Girls had their say, too ("Galileo, King of Nightvision"):

https://www.youtube.com/watch?v=4RiU2T4Psyc

99 Years that Changed Astronomy



1500

1700

Copernicus

Galileo

Newton

Mozart

● Sidereal Messenger

● Telescope invented

● Dialoques

● Imprisoned

● Principia

● Megallan's voyage around the world

Tycho Brahe

J. S. Bach

● East India Company rule begins in in India

● Tycho hires Kepler

● Restoration of King Charles II

Michelangelo

Kepler

Benjamin Franklin

● Law III

Queen Elizabeth I

Milton

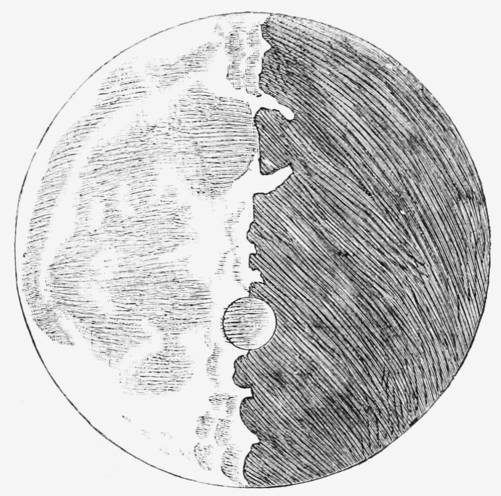
● Mayflower

Martin Luther

Shakespeare

Voltaire

1. Sidereus Nuncius (1610)



(a) Lunar Features

"The Moon is not smooth, uniform, and preceisely spherical as many philosphers believe it (and the other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the Earth, relieve by chains of mountains and deep valleys . . . This had never been seen by anyone before me."

(b) Thousands of New Stars

(c) The Nature of the Milky Way

"...scrutinized so directly and with such ocular certainty that all the disputes which have vexed philosophers though so many ages have been resolved. The galaxy is, in fact, nothing but a congeries of innumerable stars grouped together in clusters."

(d) Medicean Stars

"On the seventh day of January in this present year 1610, at the first hour of night, when I was viewing the heavenly bodies with a telescope, Jupiter presented itself to me, and because I had prepared a very excellent instrument for myself, I perceived (as I had not before on account of the weakness of my personal instrument) that beside the planet there were three starlets, small indeed, but very bright. Though I believed them to be among the host of fixed stars, they aroused my curiosity somewhat by appearing to lie in an exact straight line parallel to the eclipric, and by their being more splendid than others of their size . . . There were two stars on the eastern side and one on the west. The most easterly star and the western one appeared larger than the other. I paid no attention to the distances between them and Jupiter, for at the outset I thought them to be fixed stars, as I have said. But returning to the same investigation on January eight--led by what, I do not know--I found a very diffrent arrangement. The three starlets were now all to the west of Jupiter, closer together, and at equal intervals from one another.

On the tenth of Jaunary . . . there were but two of them, both easterly, the third (as I supposed) being hidden behind Jupiter. . . . There was no way in which such alterations could be attributed to Jupiter's motion, yet being certain that these were still the same stars I had observed . . . my perplexity was now transformed into amazement. I was sure that the apparent changes belonged not to Jupiter but to the observed stars, and I resolved to pursue this investgation with greater care and attention.

I had now decided beyond all question that there existed in the heavens three stars wandering about Jupiter as do Venus and Mercury about the sun, and thus became plainer than daylight from observations on similar occasions which followed. Nor were there just three such stars: four wanderers complete their revoltion about Jupiter."

(To curry favor with the ruler of Florence--Cosimo de Medici, a nine-year-old boy--Galileo named these "the Medicean Stars." They're now most commonly known as the Galilean satellites.)

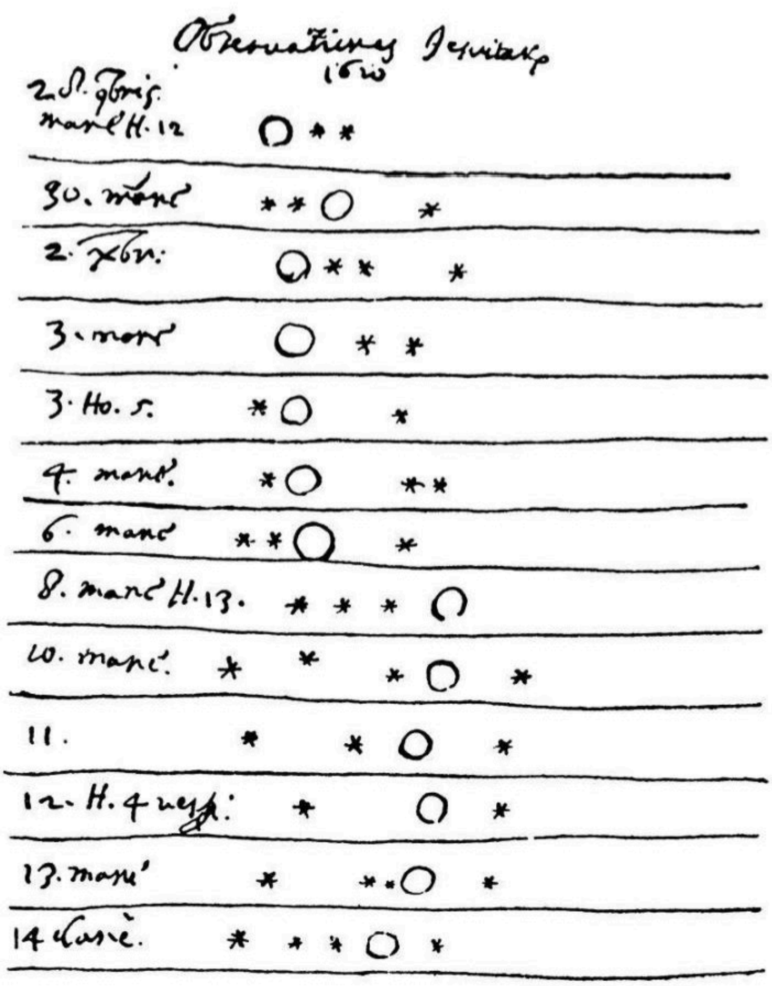


Image 2: Galileo's notebook for the Jupiter observations of January 1610

Chapter VI
Newton, 1642-1730

"I am as a child playing on the beach, while the great ocean of truth lies undiscovered all around me."

Isaac Newton was born in Woolsthorpe, England on Christmas Day in 1642. After his father's early death and his mother's remarriage, Isaac was raised by his maternal grandmother. He entered Trinity College (Cambridge University) and graduated in 1665. Due to an outbreak of Bubonic Plague in England, the university closed for two years, and Newton went home to his garden in Woolsthorpe, there to make three discoveries which changed the direction of theoretical physics:

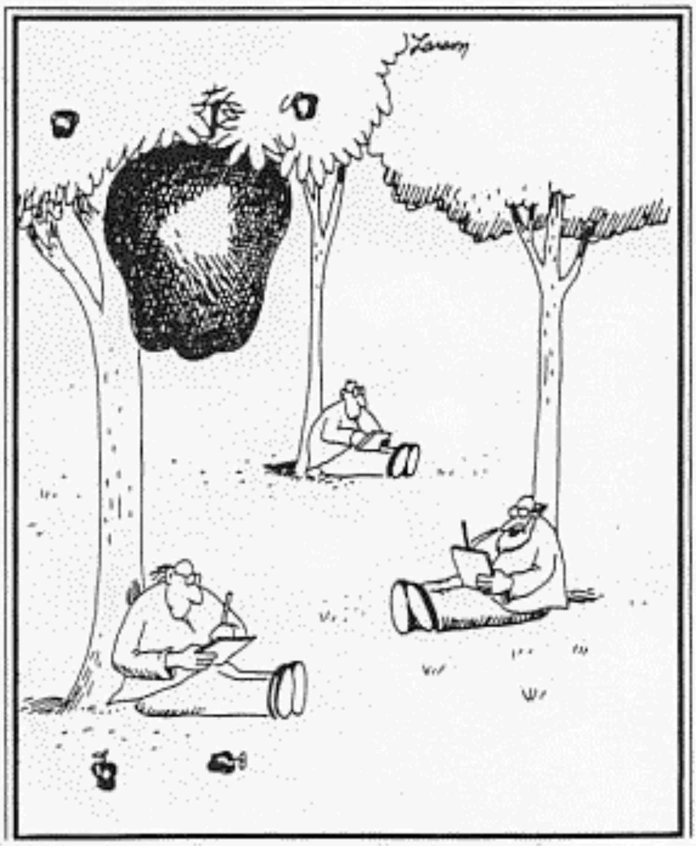
(1) the invention (discovery?) of calculus;
(2) the laws of motion; and
(3) the law of gravitation.

Like Copernicus, Newton did not publish his work for many years. He did give lectures at Cambridge, where he became the Lucasian professor of mathematics at a very early age, and at the Royal Society. Thus he acquired a reputation for brilliance, at least locally. It took the urging of his friends, especially Edmond Halley, before the larger world learned of Newton's discoveries.

Legend has it that Newton's discovery of the law of gravity was inspired by observing the fall of an apple in his garden. This may well be true, since there were indeed apple trees in his garden – in 1666 and, for that matter, today. York University even claims that they have an apple tree which is a direct descendant of the precise apple tree that Newton observed! The idea is that Newton sees the apple fall, looks up at the Moon, and wonders "hey, could the force which draws the apple to the ground also extend to the Moon?" This is a watershed moment in the history of science. Henry Pemberton, a friend of Newton and the writer of a contemporary textbook on physics, gave this account:

> "as the power of gravity is not found sensibly diminished at the tops of the loftiest buildings, nor even on the summits of the highest mountains... it appeared to him reasonable to conclude that this power must extend much farther than is usually thought; why not as high as the Moon, said he to himself; and if so, her motion must be influenced by it; **perhaps she is retained in her orbit thereby."**

And Newton himself left a memoir of those years:



"Nothing yet. ... How about you, Newton?"

> "In May 1665 I had the direct method of fluxions (differential calculus), and the next year in January had the theory of colours (white light being the sum of colours) and in May following I had entrance into the inverse method of fluxions (integral calculus). And the same year I began to think of gravity extending to the orb of the Moon; and having found out the force with which a globe revolving within a sphere presses the surface of the sphere, from Kepler's Rule of the periodical times of the Planets being in a sesquialterate proportion of their distances from the center of their Orbs ("Kepler's Third Law") I deducted that the force which keeps the Planets in their Orbs must be as the square of their distances from the centers about which they revolve: and thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at the surface of the Earth, and found them to answer pretty nearly. All this was in the two plague years of 1665 and 1666, for in those days I was in the prime of my age for invention, and minded Mathematicks and Philosophy more than at any time since."

"*Found them to answer pretty nearly*." In other words, that the acceleration of the apple, relative to that of the Moon, is equal to the ratio of distances, squared. The ORBITS pages explain this in more detail, showing the *validation* of universal gravity – for the Earth-Moon system, and for the solar system generally (Kepler's Third Law). Here is also a nice and well-illustrated primer on Newtonian gravity:

http://csep10.phys.utk.edu/astr161/lect/history/newtongrav.html

That's the story for gravity. But before you can really do this calculation, you need Newton's three laws of motion. Which, in case you have a momentary bout of amnesia, are:

1. The **law of inertia**: every object maintains a constant speed in a straight line, unless acted on by a **force**.

2. When a force acts on a body, the body accelerates at a rate proportional to the force, and inversely proportional to the mass: **F = ma**. Force and acceleration are

vector quantities.

3. The **action-reaction law**: when an object A exerts a force on object B, B automatically exerts a force back on A, of equal magnitude and in the opposite direction.

These three laws, plus gravity, are the famous "Newton's Laws". But to discover them, you definitely need calculus, which hadn't been invented yet. Why? Well, you have to know what the acceleration of the Moon is... and to know that, you have to know how acceleration is related to velocity:

$$a = \frac{v^2}{r} = \frac{\left(2\pi r/p\right)^2}{r} = \frac{4\pi^2 r}{p^2}$$

Since R and P are eminently measurable (400,000 km and 27.3 d), this is easy. But you need differential calculus to demonstrate that $a = \frac{v^2}{r}$. That's essentially why Newton had first to invent a new branch of mathematics.

And not only mathematics – also English (or Latin, the language of his *opus*). The concept of force was thoroughly muddled at the time, and Newton struggled mightily with it. Some of these struggles are documented in his notebooks from 1666:

> "...as the body (a) is to the body (b) so must the power or efficacy, vigor, strength or virtue of the cause which begets the same quantity of velocity..."

Power, efficacy, vigor, strength, virtue. The struggles of a young man trying to find words for a concept which had never been clearly articulated. Such were the laws of motion as they were first being thrashed out.

Newton published his great work in 1687: *Philosophiae Naturalis Principia Mathematica* (usually called "the Principia"), a three-volume work containing the three laws of motion plus the law of gravity, presented like a textbook of Euclidean geometry. He agonized plenty about gravity. Why is it an inverse-square law, rather than some other dependence? He thought it only reasonable that gravity would weaken with distance; but why not $1/r$, $1/r^3$, $1/r^4$, $1/r^{2.5}$, etc.? In "ORBITS" we reason, as did Newton eventually, that only a $1/r^2$ law would satisfy the hypothesis that the apple and the Moon are acted on by the same force. Pretty decent argument! But not quite good enough for Newton. He was able to show mathematically that these other force laws would not even result in **closed orbits**. We know, and so did Newton, that planetary orbits are stable and closed – after going around once, planets must return to the same place. Newton, being Newton, calculated which force laws produced closed orbits... and found that for integer exponents, only 2 and 5 (inverse-square and inverse fifth-power) produced closed orbits. Other weird exponents did: 11/4, 26/9, 47/16, etc... but these were philosophically repugnant, and of course failed the apple-versus-Moon test.

Actually, the apple-versus-Moon test didn't originally work out so well for any force law, because Newton was using an incorrect value for the radius of the Earth. Some old textbooks in his time gave the calibration 1 degree of latitude = 60 miles, whereas the true value is 69 miles. That played some role in making Newton hesitant about publishing. Sometime around 1684, in a fateful meeting with Halley, Newton learns about his error, and Halley learns what Newton has known for years: that an inverse-square force law leads to a closed elliptical orbit.

Newtonian gravity is “action at a distance”, unlike other forces which require some essentially tangible connection between bodies exerting forces on each other. How can bodies affect each other over vast distances? What *causes* gravity? This question mystified Newton. He expressed the opinion that gravity acting at a distance is “so great an absurdity, that I believe no man who has in philosophical matters a competent faculty of thinking, can ever fall into it.” But he had no solution to the riddle, either. “I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypothesis.” He stoutly maintained this last: ***Hypotheses non fingo.*** And yet the truth is that he did fingo a hypothesis, namely the one he deplored: action at a distance. This was eagerly pointed out and ridiculed by Newton's rivals, who were numerous and famous: Robert Hooke, Christian Huygens, and Gottfried Leibniz.

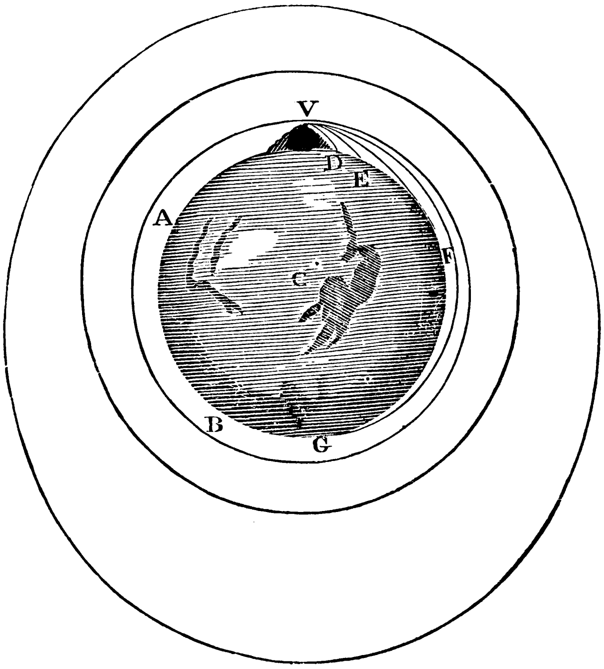


Figure 13: Newton's figure explaining how gravity acts on projectiles fired horizontally. Fire it weakly, and it follows a parabolic arc to the ground. More strongly, and it may go 1000 miles. Still more strongly, and it may go into orbit. Orbiting objects are "falling" around the Earth.

Before long, however, the amazing accuracy of Newton's Laws trumped such worries. These laws enabled extremely precise predictions of planetary motions hundreds of years into the future (and past, for that matter). The solar system now seemed like a giant machine humming along according to precisely known laws. Completely determined. It raised a number of deeper questions, which Newton did not shirk: the exactitude of predictions, the origin of the solar system, the role of God.

And whether there is such a thing as free will. Newtonian mechanics seemed completely deterministic. The Moon has no free will; why do we think *we* do? As Voltaire put it: “It would be very singular that all nature, all the planets, should obey eternal laws, and that there should be a little animal, five feet high, who, in contempt of these laws, could act as he pleased.” Planetary dynamics today, maybe social dynamics tomorrow. Are you really sure you had a choice when you decided to go, or not go, to the movies last Saturday night?

Such questions were much discussed in the 18th century. They still are.

Newton and Descartes were the two great philosopher-scientists of their century. They had much in common: both only children, raised by grandmothers, and seized in their 20s by grand visions: Newton, universal gravity; Descartes, a science of all human knowledge. Both wrote extensively in each other's field. Descartes wrote a lot about motion and inertia – and clarified, slightly before Newton, that inertia meant resistance to a *change* in motion, not just motion. He pronounced opinions on the solar system's origin (the vortex theory), motion ('impulsion" rather than gravity), and described motion with *algebra* (not then common). And Newton's sweep eventually went far beyond gravity, and far beyond physics: alchemy, biblical prophecy, the layout of Solomon's temple. By the time the amazing successes of Newton's theory leaked out thoroughly to the rest of the world (say around 1730), the stage was set for two great ideas which have resonated through Western society even to the present:

* Determinism ("Reductionism")

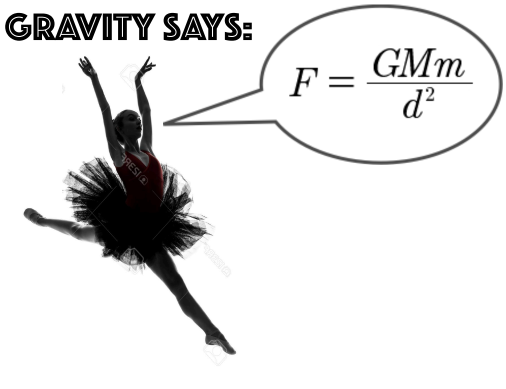
* The Infinite Perfectability of Humans

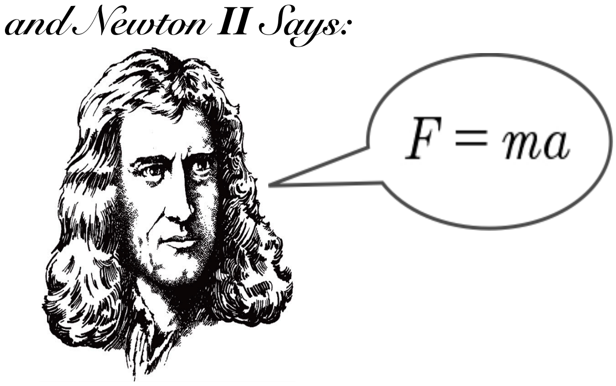
These ideas are not particularly compatible, but each flowed effortlessly out of the view that "A causes B".

The 17th century – that of Kepler, Galileo, and Newton – saw an immense change in how humans (certainly scholars, but extending to all educated people) viewed the world. The 18th... not so much. To many it seemed like Newton had figured everything out. Alexander Pope wrote in mid-century:

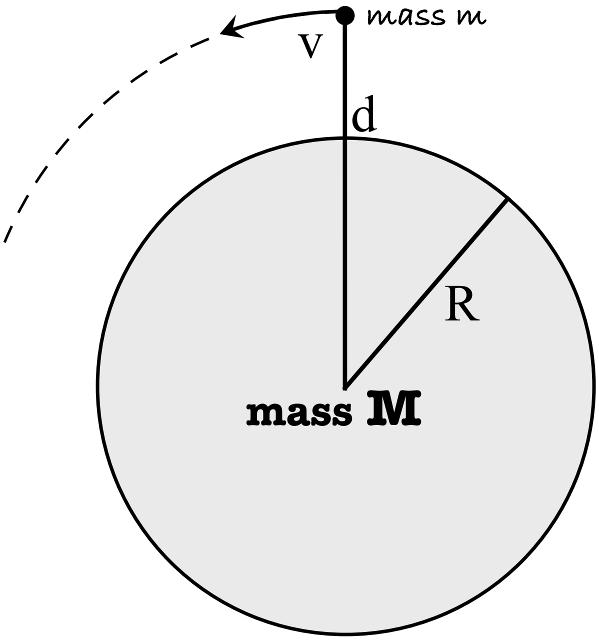
Nature and Nature's Laws lay hid in night
God said, Let Newton be! And all was light.
–Alexander Pope

1. Orbits





$$\text{This} \Rightarrow ma = \frac{GMm}{d^2} \Rightarrow a = \frac{GM}{d^2}$$



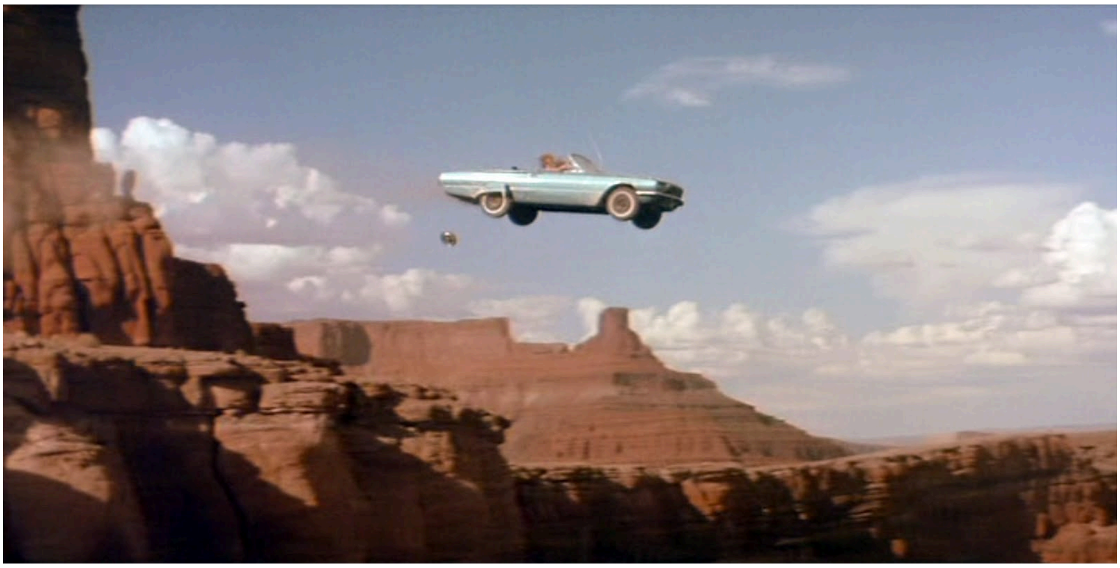
So if the little mass is just above the surface (d~R), and if the large mass is the Earth, then

$$a = \frac{GM_{\oplus}}{R_{\oplus}^2}$$

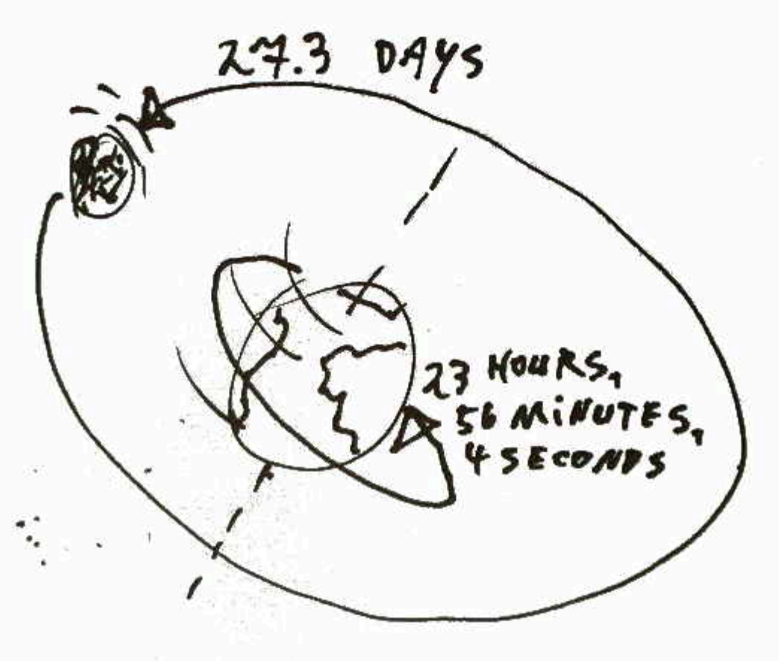
Evaluate!

$$= \frac{\left(6.7\text{x}10^{-11}\,\frac{m^3}{kg(s^2)}\right)\left(6\text{x}10^{24}kg\right)}{\left(6.4\text{x}10^{6}m\right)^2} \approx \frac{40\text{x}10^{13}m}{40\text{x}10^{12}s^2} \approx \boxed{10\,{}^{m}\!/_{s^2}}$$

of the famous 9.8m/s^2

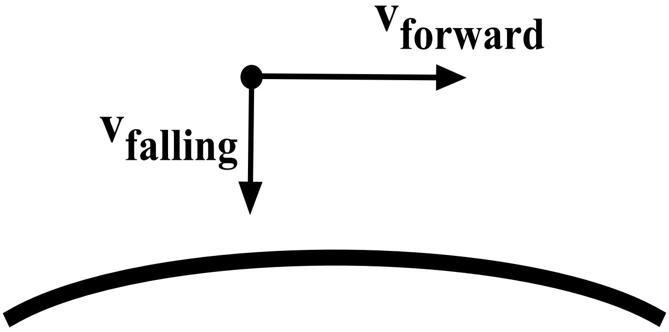


But this is for a falling body. What about an orbiting body, like the moon?



Galileo had recognized that a thrown ball (for example) has a horizontal component of motion, and a vertical component – and *only the latter is affected by gravity*. Furthermore, he recognized that the rate of falling – the famous 9.8m/s^2 – was independent of the horizontal component. Hence his famous galloping horse comparisons. Galileo suspected that, in princple, you could throw a ball so fast that it would go clear around the Earth – or "falling around the Earth," with the Earth's curved surface falling away at the same rate that the ball falls downward.

There he had to stop, because he could not calculate both quantities ($v_{forward}$, and the acceleration due to gravity) in comparable units – because he didn't know how to express $v_{forward}$ in terms of acceleration. How could he? Velocity and acceleration are fundamentally different quantities.



Enter Newton. To solve this problem, he needed to invent differential calculus. He managed to derive

$$a = \frac{v^2}{R}$$

as the acceleration of an object orbiting in a circle at uniform speed. This implied

$$a = \frac{GM_\oplus}{R_\oplus^2} = \frac{v^2}{R_\oplus}$$

$$=> v = \sqrt{\frac{GM_\oplus}{R_\oplus}} = \ldots = 7.8\text{x}10^3 \, {}^{m}\!/\!{}_{s}$$

~17,500 mph, the (now) famous v_{orb} for satellites in low Earth orbit.

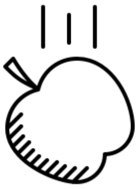
New let's compare **the acceleration of the moon with that of a falling apple.** For the moon,

$$v = \frac{2\pi R}{P} = \frac{(6.28)(4\text{x}10^8 m)}{(27.3)(86400 s)} = 1060 \, {}^{m}\!/_{s}$$

and therefore

$$a_{moon} = \frac{v^2}{R} = \frac{(1060 \, {}^{m}\!/_{s})^2}{(4\text{x}10^8 m)} = \boxed{0.0028 \, {}^{m}\!/_{s^2}}$$

The acceleration of the apple is, of course,



$$a_{apple} = \boxed{9.8 \, {}^{m}\!/_{s^2}}$$

These should be empirically measured accelerations. What should they be, acording to the hypothesis of universal gravitation?

$$a_{apple} = \frac{GM_\oplus}{R_\oplus^2}$$

$$a_{moon} = \frac{F_{Earth-moon}}{M_{moon}} = \frac{GM_\oplus M_{moon}}{d^2 m_{moon}}$$

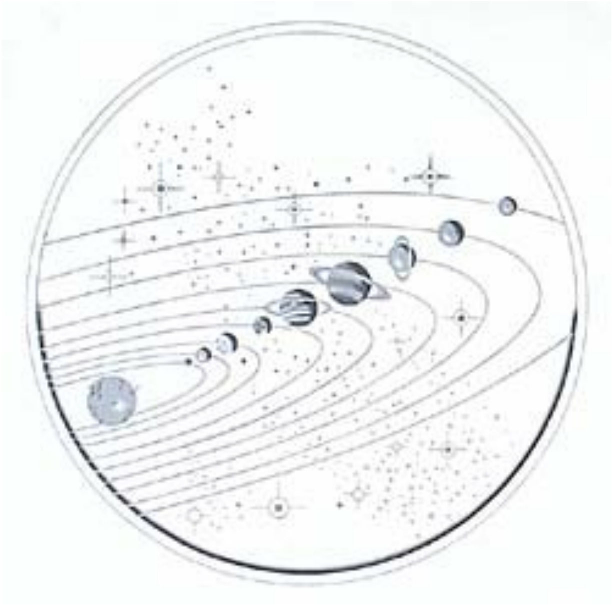
$$=> \frac{a_{apple}}{a_{moon}} \text{should be} \frac{GM_\oplus}{R_\oplus^2}\left(\frac{d^2}{GM_\oplus}\right) = \left(\frac{d}{R_\oplus}\right) \approx \left(\frac{4\text{x}10^8 m}{6.4\text{x}10^6 m}\right)^2$$

~3700

whereas empirically the ratio is ~3600

Good enough for astronomy!

So the force which draws the apple to the ground is the force which whirls the moon around in its orbit.

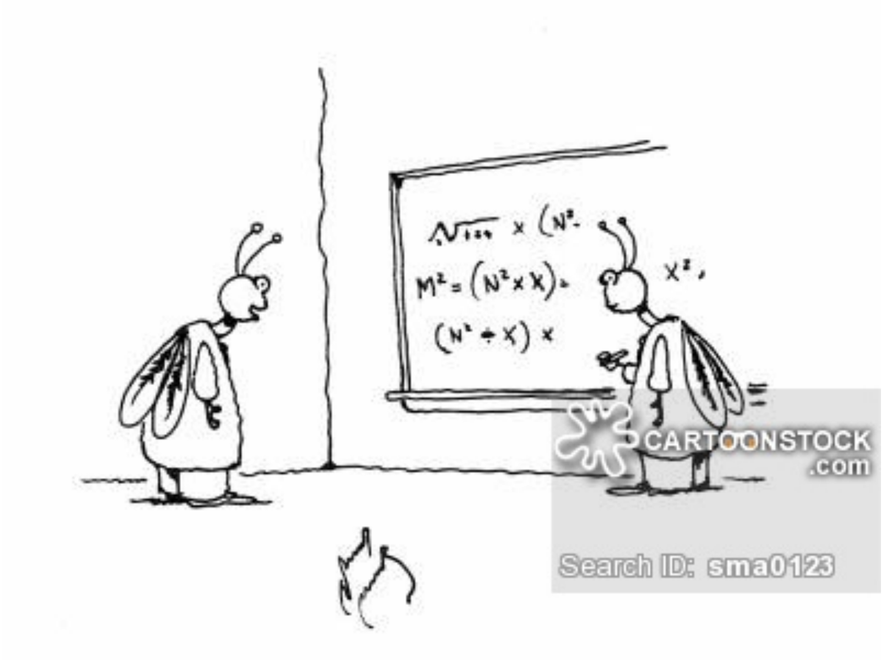


Now apply to **<u>the solar system,</u>** so the central object is now the sun, and each planet has a mass *m*:

$$\frac{mv^2}{R} = \frac{GMm}{R^2} = \frac{M}{R}\left(\frac{2\pi R}{P}\right)^2 = \frac{GMm}{R^2}$$

$$=> \frac{4\pi^2 R}{P^2} = \frac{GM}{R^2} => \boxed{P^2 = \frac{4\pi^2}{GM_\odot}R^3}$$

=K III!



"I think you're right, Bender. <u>We</u> revolve around the bulb."

Chapter VII
Energy and Entropy

Although the laws of mechanics were not formally articulated until Newton's *Principia* in 1687, earlier writers (especially Galileo) had many good insights into the subject. In 1644, analyzing collisions between objects, Descartes said that the "quantity of motion" – which he defined as mv – was conserved. In 1680 Leibniz argued that Descartes was wrong, but that something was conserved, namely what he called "living force", or *vis viva.* Leibniz defined this as mv^2. Shades of momentum and energy conservation! Leibniz recognized that there were many collisions in which mv^2 seemed to disappear – the "inelastic" collisions. His excuse for this was that "it is dissipated among the small parts of colliding objects". He offered no proof of this – but it's pretty close to the excuse we would make today.

In order to arrive at something like the modern concept of energy, we need to make allowance for at least two everyday circumstances, both exemplified by falling objects:

(1) the fact that falling objects accelerate (increasing v) as they fall; and
(2) the fact that falling objects quickly lose v when they impact.

Energy conservation fails unless you can account for these. The second is more or less taken care of by Leibniz's excuse – that energy (in the modern sense) is transformed into some other form... partly sound, but most commonly *heat.* Around 1840, James Joule did experiments to **prove** this; he heated water by swishing a paddle wheel with a known kinetic energy, and found that 1 calorie of heat was produced for every 4.18 J of kinetic energy that disappeared. Splendid! This became known as **the mechanical equivalent of heat**.

The first is more central to astronomy. Things fall after they are pushed up to some height h above the ground. A force is required to do this, and we say that this force does **work** on the object, where work = force x distance. The object has a weight mg, so the work = mgh. In modern terms, we say that the work gives the object a potential energy, namely

$$PE_{grav} = mgh \tag{1}$$

Now we drop the object, and it loses PE exactly as it gains KE. Just before it hits ground, the energy is all KE, so $(KE)_{final} = (PE)_{initial}$. Therefore

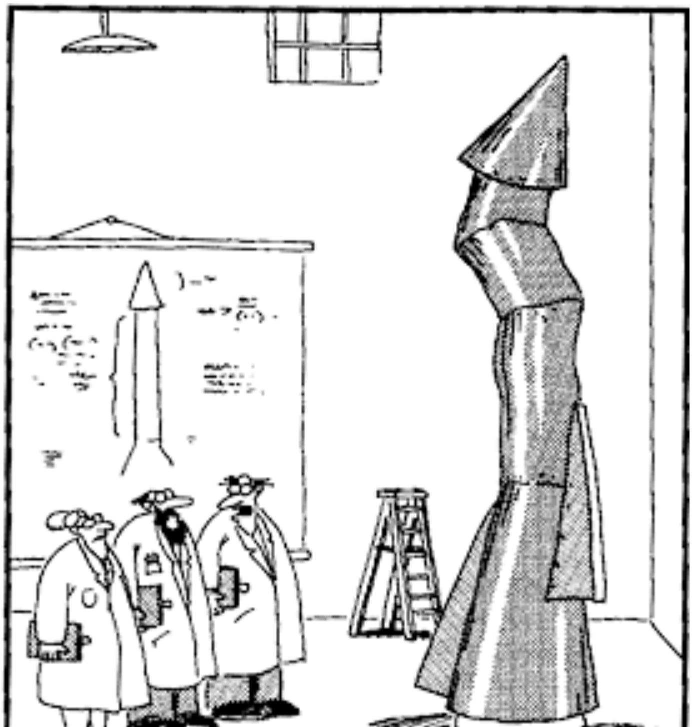
$$(\tfrac{1}{2})mv_{final}^2 = mgh, \text{ or } v_{final} = \sqrt{(2gh)} \qquad \textbf{(2)}$$

With this definition of PE, we can invoke energy conservation and fully explain falling objects. If we wished, we could extend the notion of “potential” energy to include springs (energy of compression) and explosions (chemical energy)... and successfully invoke conservation of energy (conversion to kinetic) all the way. If you like teleological explanations – many people, including many physicists, do – you can say that all these processes, while conserving total energy, involve movement towards a “lower” energy state. It's downright Aristotelian. Not **less** energy, but a more primitive form of energy. We'll discuss this soon when we discuss the “heat death of the Universe”.

Equation 2 works fine for dropping balls to the ground in the laboratory or from rooftops. But if you drop balls from a very great height (say the Moon), then Equation 2 tells a lie, because *g* is highly variable (9.8 m/s^2 near the ground, and really tiny near the Moon).

To correct for this, we need a definition of PE_{grav} that is more sophisticated than *mgh*. I'll derive it in class... but the result is that for a mass m separated by a distance R from another mass M, the PE is given by

$$PE_{grav} = \frac{-GMm}{R} \qquad \textbf{(3)}$$



"It's time we face reality, my friend. ... We're not exactly rocket scientists."

This has the very reasonable property that PE=0 when the objects are extremely far apart... and as the “test mass” m falls from large R to smaller R, PE becomes more negative (as KE becomes bigger).

This means that the total mechanical energy of a rocket ship, say, is

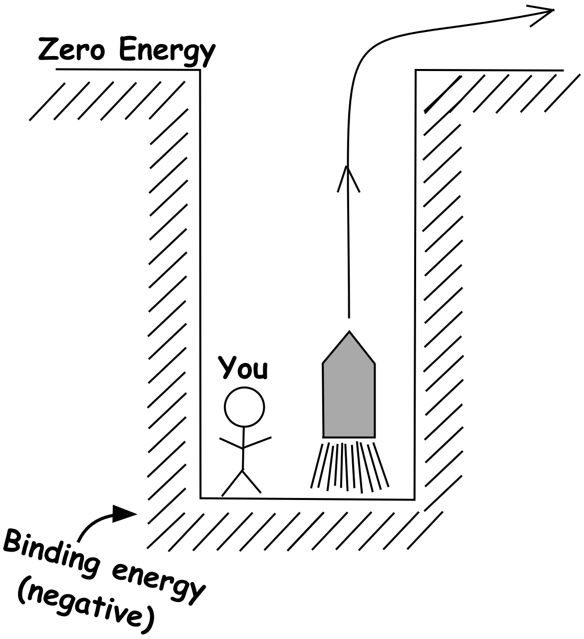
$$KE + PE = \tfrac{1}{2}mv^2 - \frac{GMm}{R} \qquad \textbf{(4)}$$

Now imagine that at launch, the rocket has <u>exactly</u> the escape velocity. This means it “uses up all its energy in escaping”... so, at escape, it has $v_{final} = 0$, $R_{final} = \infty$. Thus its total energy is zero. Therefore it must have started with zero energy, implying

$$\tfrac{1}{2}mv_{esc}^2 = \frac{GMm}{R_{Earth}} \qquad (5)$$

which implies $v_{esc} = \sqrt{\frac{2GM}{R_{Earth}}} \approx 11.2$ km/s. There it is – the escape velocity from the Earth's surface. A famous number (=25000 mph).

Think of yourself as living at the bottom of a deep well – because you most assuredly do. That well is $GM_{earth}m/R_{earth}$ deep, because if you want to leave the Earth and achieve a state of zero energy, you have to find that much (positive!) energy to reach that blissful state. Just to get back to zero. Google says that the average college debt is $29,000... so it's about 1 mph per dollar of debt. Good luck getting to zero.



Although this discussion is specific to gravitational potential energy, it applies to any situation where one object is bound to another (a human to the Earth, an electron to a proton, a proton to another proton or neutron in the nucleus, the quarks to each other in the proton). We frequently use the term **binding energy** to describe how tightly bound an object is. I'll use it about a million times in this class. Binding energy is always negative, because... well, take your pick:

- it takes input of energy to disrupt the binding, or
- the object falling in released energy as it fell in.

Both are true, and total energy is conserved.

Everyone knows that energy has many other forms – sound, heat, light, rest-mass, etc. - and perhaps the most familiar to us involve electrical potential energy: dynamite, gasoline, sugar, etc. (pretty much the same stuff). The conservation of energy is a truly grandiose law. Let's look at its sweep.

The mks unit of energy is the Joule, and 1 J = 1 N x m. Astronomers love orders of magnitude, so permit me to indulge in an innocent vice. Behold the power of exponents – in this guidebook to energies (in Joules):

Creation of Universe	10^{68}	100 mph fastball	10^{3}
$E = mc^2$ of Sun	10^{47}	1 kg of gasoline	10^{7}
Supernova explosion	10^{44}	1 kg of coal	10^{7}
Sun in 1 year	10^{34}	Small candy bar	10^{6}
Earth's KE	10^{33}	1 kg of TNT	10^{7}

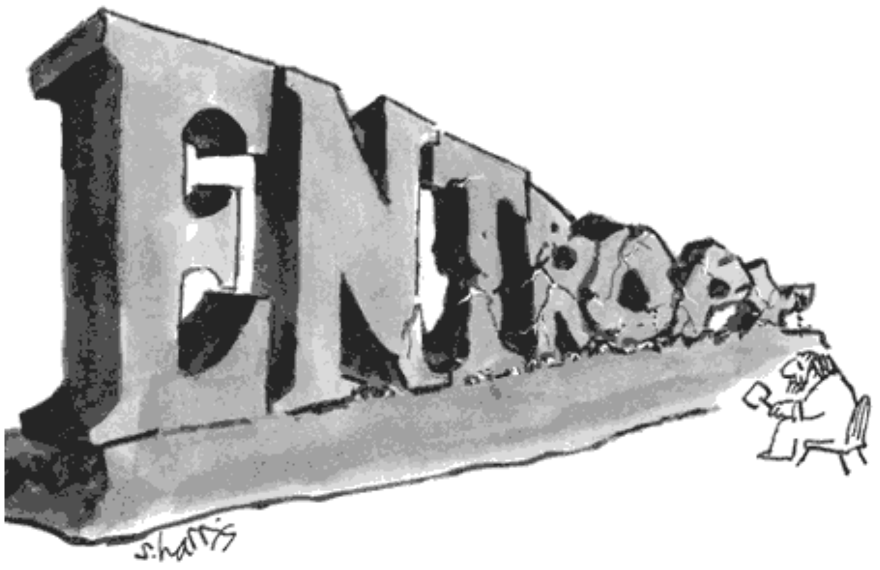
Earth's annual sunshine	10^{23}	Heartbeat	1
Krakatoa	10^{19}	Flea hop	10^{-7}
100 megaton H-bomb	10^{17}	Chemical reaction/atom	10^{-18}
Hurricane	10^{15}	Photon of light	10^{-19}
Lightning bolt	10^{10}	KE of air molecule	10^{-21}
1 hour running	10^{6}		

Not bad: a flea hop and the Big Bang, on the same scale. By the way, notice that gasoline, coal, candy, and TNT all provide about the same energy – about 10^7 J/kg. The reason is that they're all basically chemical reactions, in which outer electrons jump from higher to slightly lower energy states. The main difference is that in some (TNT), the electrons jump fast, while in others (candy) they take their own sweet time about it.

These energies from chemical reactions result from the fact that electrical *charges* obey a force law virtually identical to that of gravity... and thus charges which fall to lower energy states release energy, just as masses do.

You probably knew that. More esoteric is *mass-energy*, essentially discovered by Einstein in 1905. We'll discuss that extensively when we get into nuclear physics.

1. Increasing Entropy: The Second Law of Thermodynamics



By the mid-19th century, the great power of energy conservation – the first law of thermodynamics – became apparent. Two great discoveries in that era, the kinetic theory of gases and the nature of light, underlined further what was learned from the study of mechanical systems: that total energy – if you define it broadly enough to include these other types – was always conserved.

And indeed, both Newton's Laws and the newly discovered laws of electricity were completely time-reversible – run movies of planets or electrons forwards and then backwards, and you couldn't tell the difference. The energy just shuffles back and forth.

Now one important form of energy is *heat*, and the kinetic theory of gases teaches us that heat is simply microscopic kinetic energy. That being so, you'd expect that heat could smoothly shuffle back and forth to other forms of energy, like kinetic and potential do in a pendulum. It doesn't happen. Energy always flows from hot to cold, and never the reverse. We all pretty much know this, but when you look into why it's so, and in particular at the microscopic physics of collisions (which is what heat is), you can find no reason for it to be true.

19th-century physicists spent a lot of time thinking about this. It was the Industrial Revolution, and they all had great familiarity with furnaces, steam engines, etc. Some of them also tinkered with the idea of a "perpetual motion" machine; *that* would be a useful device, and it didn't seem so far-fetched: planets manage it very nicely. But all the perpetual-motion schemes failed, heat kept flowing from hot to cold, and every engine ever built required constant inputs of energy to keep operating properly. Eventually these failures became elevated to the status of a principle: *the second law of thermodynamics.*

In contrast to the planets, we see processes around us which seem to erode energy – or transform into a "less useful" form. Heated homes lose their heat to the outside, ice in warm water always melts, refrigerators need constant energy to operate, eggs scramble but never un-scramble, water tumbles over a waterfall but never re-ascends. The microscopic physics underlying these phenomena are time-reversible – but the observed processes always occur in one direction only, never the reverse. Thus we might hypothesize the existence of a *preferred arrow of time*, even though we can't really find it in the basic underlying equations of physics.

This principle was frequently discussed in the mid-19th century, in the context of understanding the flow of heat. In 1865 Rudolf Clausius coined the term *entropy* to describe a physical quantity, measured in J/K deg, which always increased when heat flow occurred. But in those days the nature of heat was still being debated; a popular theory supposed that heat was a fluid – called *caloric* – which flowed around like water. Around 1800, practically everyone believed this; that's how the term "heat flow" got into our language.

Meanwhile, back at the physics ranch, Ludwig Boltzmann and J. Willard Gibbs were developing the theory of statistical mechanics. This started with the kinetic theory of gases and, considering how many zillions of atoms/molecules make up any laboratory sample of gas, applied the laws of probability to it. Certain configurations of atoms are much more probable than others. For example, consider in Figure 14 the sudden spontaneous mixing of one chamber filled with pure oxygen, and another filled with pure nitrogen. Let 'em mix... and we all pretty much know what happens: they mix so that every part of the new chamber contains very close to a 50-50 mixture. Why? For the same reason that a million coin flips will produce nearly 50% heads:

because there are millions of sequences leading to that result, versus only one that produces all heads.

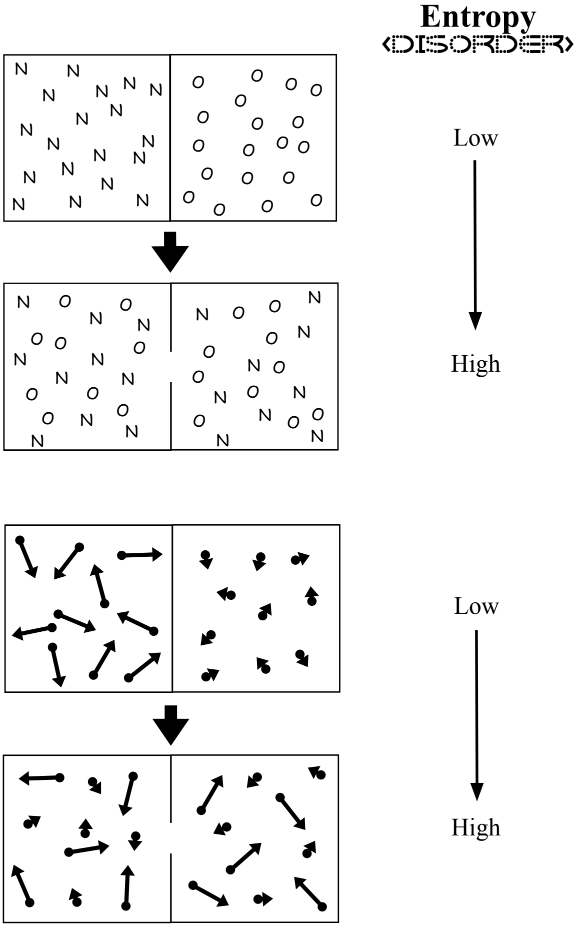


Figure 14: Upper Frames: cut the membrane between the two boxes, and the atoms mix.
Lower Frames: cut the membrane between the two boxes, and the fast and slow atoms (high and low temperatures) mix, and order evolves to disorder.

Now consider chambers with gases of different temperature. The kinetic theory says this means different KE...and even if every "hot" atom stays hot and every cold atom stays cold, every little sub-chamber will contain about equal proportions – implying uniform temperature. Before, there was a temperature difference, which can be used to do work; but not now. Nature has evolved towards a state of uniform temperature. This is even more true if, as seems likely, the hot atoms deliver some of their kick to the cold atoms.

Staying within the kitchen, solid objects offer other examples. Dishes and glasses break, if you give them half a chance, but never re-assemble. Eggs never unscramble. The list goes on, with no counterexamples.

So the thermodynamic guys (like Clausius), the probability guys (like Boltzmann and Gibbs), and everyone who dropped dishes in the kitchen were all lurching their way to a common principle: that *Nature evolves towards a state of increasing disorder*. Heat engines, refrigerators, separated gases, separated temperatures, eggs, dishes... they all represent a high degree of order in their constituent parts. And Nature always tends to destroy that order.

This is not derivable from any other law of physics, so it gets its own name – variously rendered as:

(I) the second law of thermodynamics;
(II) the law of increasing entropy; and
(III) the heat death of the Universe.

The reason that (III) is a viable name is that the second law guarantees the flow of heat from hot to cold... therefore rendering the distribution of heat inexorably more uniform. Once the Universe reaches a uniform temperature, nothing more can happen.

Although we call this a "law of physics", it has a status less exalted than the laws of mathematics and dynamics, and even quantum theory. It might get seriously demoted in the future – not because someone's broken dish spontaneously reassembles, but because of challenges from other areas of science. The behavior of living systems is a mild challenge (nobody paints the Mona Lisa, or climbs Mount Everest, by chance occurrence). The behavior of the Universe on the largest scales could also be a challenge. What if the Universe is actually finite in space? With a finite number of particles, doesn't that imply that given sufficient time, it will eventually return to its exact present configuration? That would spectacularly violate the Second Law. This has given rise to a small revival of a theme familiar in religion, philosophy, and literature: "the myth of the eternal return".

The World's great age begins anew,
The golden years return.
The earth doth like a snake renew
His winter weeds outworn...
Another Athens shall arise
And to remoter time
Bequeath, like sunset to the skies,
The splendor of its prime...
- Percy Shelley

The smart money is betting against any such future violation of the Second Law. But then again, the smart money was betting on the Red Sox.

Now the law of increasing entropy refers to a *closed system*. That's why it's frequently discussed with respect to the Universe as a whole, which we can be mildly confident is a closed system. But you can reduce entropy in little corners of the Universe. You do that every time you clean your room, and perhaps every time you make a friend. But have you noticed? – those things require energy. In thermodynamics, that energy is called **enthalpy**... and the *third law* of thermodynamics tells you how much enthalpy you have to supply to reduce the entropy. It always takes work. In the 1970s there was a bumper sticker:

REDUCE ENTROPY
WITH ENTHALPY
and love

Chapter VIII
Light: She Comes in Colors Everywhere

1. Particles versus Waves

Humans have always wondered what light is. It's such a prominent feature of the world, yet is so insubstantial. I remember at age 5 or thereabouts, I thought of light as rays which extended out from my eyes and latched onto the objects I saw. No mere spectator, I was an essential part of the process. In retrospect, I think this might have come from reading Superman comics (because his "X-ray vision" seemed to operate that way). Much later in my life, I was delighted to learn that Empedocles thought the same thing 25 centuries earlier, though perhaps for better reasons.

Four centuries after Empedocles, the Roman philosopher Lucretius wrote *De Rerum Natura*, a work which is now usually cited as the first published articulation of the particle theory of light. He did not credit me, or Empedocles, or anyone's eyeballs as playing an important role in the process.

In his *Opticks* (1704), Newton also strongly advocated a particle ("corpuscular") theory of light. By this time, there was already a published wave theory of light (by Descartes) – setting the stage for 200 years of struggle between the two views. Newton argued strenuously that Descartes could not be correct, because light travels strictly in a straight line, whereas waves always bend around obstacles, as anyone can observe for themselves at the beach. Pretty good argument! Newton also reported, and analyzed, *experiments*. The most famous was the one with prisms. Everyone in his day knew that prisms "break up" sunlight into the colors of the rainbow (ROYGBIV). But people wouldn't have said "break up"... but something more like "changes" – in other words, that prisms *change* white light into something different. By sending the ROYGBIV light through a second prism oriented opposite, Newton showed that the original light was recovered. He correctly interpreted that to mean that white light was basically just the sum of all colors.

Here's the first half, the easy part, of Newton's experiment:

https://www.youtube.com/watch?v=zphAHMPtu4g

But no crucial experiment was done, by the Rolling Stones or anyone else, to distinguish wave and particle theories. If light consists of waves, why doesn't it bend around corners? Also, what exactly is waving, and in what medium does it propagate? It travels in air, glass, water, and even the vacuum of space! If light consists of particles, then how can you explain interference phenomena (which were known at the time)? And where are the “spaces” between the particles?

Enter Thomas Young, an English physician who also made notable contributions in linguistics, vision, medicine, Egyptology, and materials science. He's sometimes described as "The Last Man Who Knew Everything".

Young described two experiments which are now commonly done in high-school physics labs. With a ripple tank he demonstrated that water waves interfere constructively and destructively, and that you could measure the wavelength by the interference pattern. This was well known at the time (1803). He did the same experiment with light, scratching two parallel slits on a glass painted black, and then looking back at the light source. If light consists of particles, you'll see two centers of light – one from light going through the top slit, and one through the bottom. But if light is a wave, then the wave goes through both slits, and there's potential for the light through the top slit to interfere with light through the bottom slit. Constructively, if the path difference is an integer number of wavelengths; and destructively, if it's a half-integer. Thus you'd get a pattern of alternating light and dark images. The latter is what you actually see:

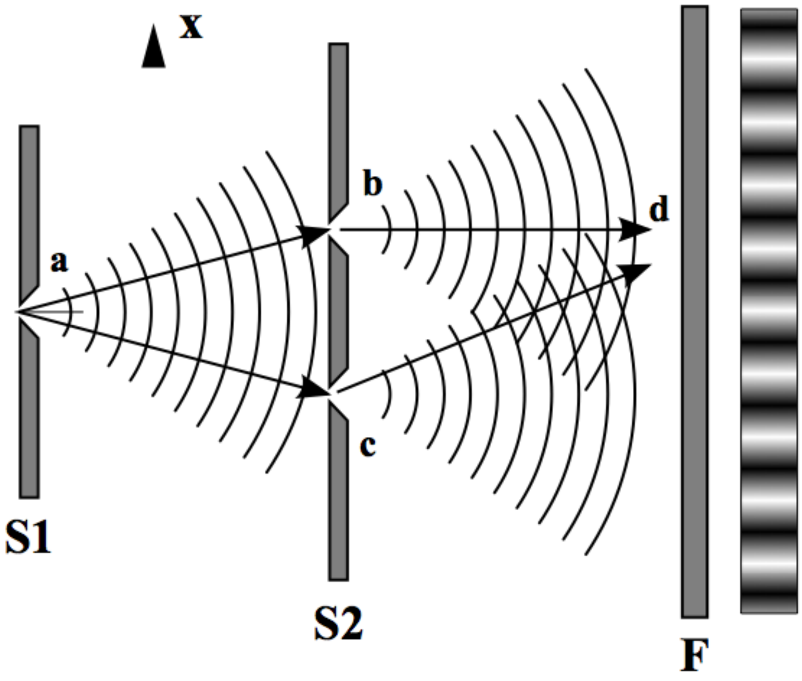


Figure 15: The Double-Slit Experiment. Light enters from the left. The wave arrives at the slits b and c. Since the same wave enters these slits, they leave (exiting b and c) in phase. Then they will arrive at the screen F in phase, if the path lengths b-d and c-d are equal, and also if they differ by λ, 2λ, 3λ, etc. Thus you get a pattern of alternating light and dark bands. https://upload.wikimedia.org/wikipedia/commons/8/86/Ebohr1_IP.svg

The many regularly alternating light and dark bands – resulting from interference – constitute a huge argument in favor of the wave theory. And it was an experiment that virtually anyone could do for themselves.

Despite the great reverence for all things Newtonian, Young's proposed theory of the wave nature of light gained rapid acceptance in England. Much less so across the Channel. In 1818, the French Royal Academy of Sciences held a competition for whoever could best explain the properties of light. These competitions were held annually on some announced topic in mathematics and/or physics, and became quite famous as the prize money was enough to attract entries from the most talented scientists in Europe. Over the years, some winning entries became classic papers in the history of mathematics.

The young civil engineer Augustin-Jean Fresnel submitted a paper, primarily mathematical, on the Wave Nature of Light. The math was very sound, but one of the judges, Simeon Poisson, found an apparently fatal flaw in it. Poisson said: if light is a wave, then if you have a point light source and an opaque round object casting a shadow, there should be a bright spot exactly at the middle of the shadow (since the path length from all points around the periphery of the round object was the same, all the waves should arrive in phase, and constructively interfere). That seemed ridiculous – who has ever seen such a thing? Shadows don't have bright spots at their centers.

There the matter might have rested, but one of the other judges, Dominique Arago, decided to actually do the experiment. He quickly set up an apparatus with a point light source in a darkened room... et sacre bleu! A bright spot, right in the center of the circular shadow. You can see this amazing effect yourself with a laser, which is bright enough and sufficiently point-like. Or you can consult a video:

http://physicsed.buffalostate.edu/pubs/StudentIndepStudy/EURP09/Spot/spot.html

http://www.princeton.edu/~rvdb/images/Questar/PoissonSpot.html

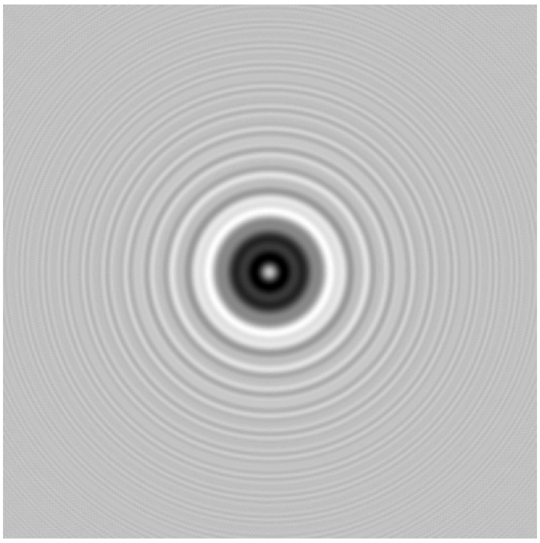


Figure 16: Poisson's Spot, idealized version. But demand the real thing! . . . or at least check out the videos.

Fortunately for science and for Fresnel's bank account, Arago reported this to the committee and Fresnel won the prize. But in an ironic twist of history, the phenomenon became known as “Poisson's spot” – named after the skeptical professor who thought the theory ridiculous, and not even worth the time to test.

Young's and Fresnel's work became very well known, and the wave theory of light had no serious competition for the rest of the 19th century. By century's end, the theory seemed unassailable: we knew the precise speed of light, and could measure wavelengths very accurately using “diffraction gratings” – devices similar to Young's double-slit, but with thousands of slits. Because the wavelength of light is tiny (0.0005 mm), it doesn't bend appreciably around macroscopic objects, just as a ripple in a pond doesn't bend around an aircraft carrier. This removes Newton's main argument against the wave theory. Late in the century, we even came to understand what's waving. James Clerk Maxwell showed that the behavior of charged particles in an electric or magnetic field should generate electric and magnetic waves travelling at a characteristic speed, which was $3x10^8$ m/s in empty space. That was the known speed of light. Therefore light is a travelling electromagnetic wave – a pattern of oscillating electric and magnetic fields.

Heinrich Hertz then clinched the matter. He raced electrons up and down wires by applying electric fields to them, and noticed that the electric fields propagated elsewhere in his laboratory. Thus he produced what we would now call *radio waves*. He measured the propagation speed to be $3\text{x}10^8$ m/s, suggesting that light and radio were merely two manifestations of the same thing. Both strictly obey the **wave equation**

$$v = f\lambda,$$

where v is the wave speed, λ is the wavelength, and f is the frequency ("cycles per second"). From that time forward, light was seen as just one aspect of **electromagnetic radiation**, which runs the gamut in frequency, from very low (radio) to very high (gamma-ray).

https://en.wikipedia.org/wiki/Electromagnetic_spectrum#/media/File:EM_Spectrum_Properties_edit.svg

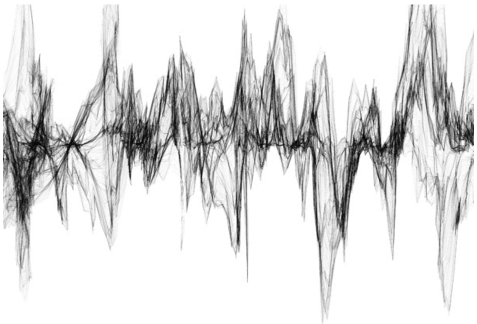
http://imagine.gsfc.nasa.gov/science/toolbox/emspectrum1.html

All this soon led to the development of radio, and subsequently television and radar. But Hertz died at age 37, never realizing the importance of his work. Asked about its importance, he replied "It's of no use whatsoever.... this is just an experiment that proves Maestro Maxwell was right." All he personally got out of it, decades later, was a few statues, and the naming of the SI unit of frequency (1 cycle/second = 1 hertz).

Waves and particles are completely different concepts. Everyone knows what particles are. They're by nature *localized* – in a definite small pocket of space, like a bullet. Thus they are the only physics concept protected by the U.S. Constitution (or at least one-half of one amendment to the Constitution). Waves are fundamentally non-localized, spread over at least one wavelength of space. Like waves in the ocean. Let's consider several types of wave, and especially emphasize the implications of wavelength.

1. **Ocean waves**. These waves travel towards the shore, but their main effect is to move floating objects simply up and down. So we say they are *transverse* – because the disturbance in the medium is perpendicular to the direction of travel, Waves breaking on the shore arrive about every 8 seconds, so $f = 0.12$ c/s. Their wavelength λ (distance between successive crests) is about 20 m, and then the wave equation tells us that their speed of travel should be $f\lambda = 2.4$ m/s, or about 6 mph. Healthy people walk at 3 mph, and run at about 15 mph. That's about right, isn't it? Waves travel at speeds somewhere between human walking and running speeds. Because the wave is spread over 20 m, it sweeps over everything much smaller, like a human or a piece of

driftwood... but is blocked by anything much bigger, like an island or a big ship.

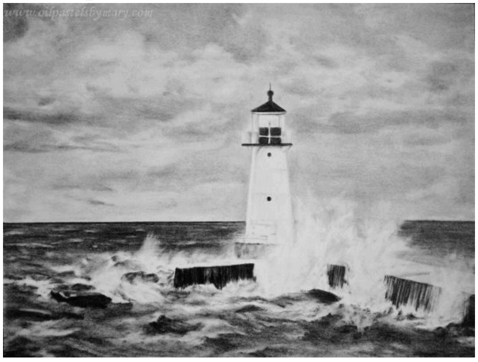


2. **Sound waves**. When your vocal cords vibrate, they create alternating pockets of dense and rarefied air, and this pattern then spreads through the room at "the speed of sound". It's a *longitudinal* wave – the alternation of density or pressure is along the direction of travel. The speed of sound in air is 300 m/s, and the frequency of human speech is around 200 c/s, so according to the wave equation, $\lambda = c/f$ = 1.5 m.

Since no one's head is that big, sound travels behind you almost as well as it travels in front of you – so you can hear people speak, even when their back is turned. On the other hand, an object as big as a house blocks sound. If you stand at your front door and speak in conversational tones, you won't be heard at the back door – unless someone cheats by opening both doors.

3. **Light waves on clear days**. On a clear day, you can easily see the Sun, and the Moon for that matter. You're at the bottom of an ocean of air, so why is it so easy? Because the air particles are molecules, only ~0.2 nm across... while the wavelength of light is 0.0005 mm = 500 nm. Thus light is 2500x bigger than the air particles, and sweeps over mere molecules with the greatest of ease. Like ocean waves over driftwood.

4. **Light waves on cloudy days**. A cloud is a really tiny perturbation on clear air, yet is enormously opaque to visible light. Flying through a cloud, sometimes you lose sight of your own aircraft's wings. And in a fog, which is simply a ground-based cloud, you can sometimes see only a few yards. Why? Because water droplets are enormous, ~1000x bigger than the wavelength of light. Thus they look like "the broad side of a barn" to an approaching light beam, and they scatter or absorb light very easily. All in the name of wavelength.

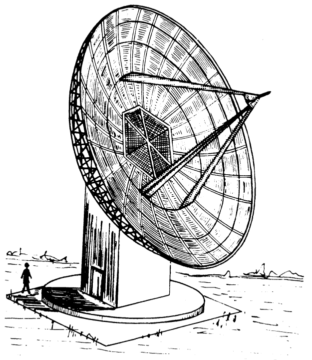


5. **Radio waves**. We're told that radio waves are just like light, yet we can certainly hear radio waves on the foggiest of days. Why? Again it's wavelength. Take the radio station 1010 WINS, broadcasting at 1010 khz ~ 1 MHz. The radio waves then have a wavelength given by $\lambda = c/f$, or

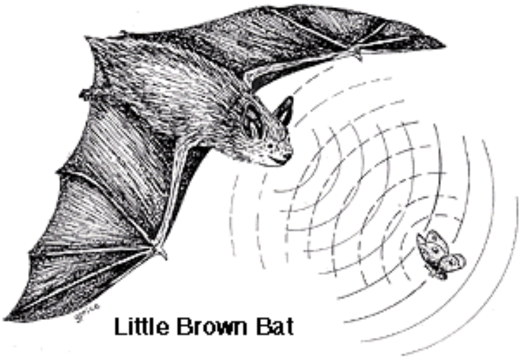
$$\lambda = \frac{(3\text{x}10^8 \, {}^{m}\!/\!{}_{s})}{10^6 s^{-1}} = 300m$$

So these waves will bend around anything less than ~300 m in size. Nothing in the atmosphere is that big – not even the cyclone-borne house in The Wizard of Oz. So radio waves go pretty much everywhere. I've even heard a rumor that there's such a thing as “radio astronomy”, and that it can be done easily in all weather, even rain, and during the daytime. If only someone had told me years ago....

6. **Radar** (RAdio Detection And Ranging). Here the humans generate the radio waves and await the reflection, learning something about the distance and size of the target (often an aircraft). Since you want the radar beam to reach the target and bounce back, you choose a frequency yielding a wavelength bigger than a raindrop and smaller than an airplane. You then get an echo which tells you the direction, distance, and possibly shape of the airplane.



7. **Bats**. Like baseball umpires, bats are famously blind. As nocturnal feeders, they usually don't have much ROYGBIV around to help them navigate. Instead they operate on *sound*; they emit very loud high-frequency sound pulses, which reflect off their insect prey and thereby tell the bats exactly where to swoop. These sound waves also reflect off trees, other bats, houses, clotheslines, etc.... so a bat needs some fancy software to disentangle these reflections from the ones which are going to provide dinner. Most importantly, the frequency must be very, very high. Because these are sounds, the wave equation tells us that reflection off a 1 mm insect corresponds to a frequency



Little Brown Bat

$$f = \frac{c}{\lambda} = \frac{(300\,{}^{m}\!/\!{}_{s})}{(10^{-3}m)} = 3\text{x}10^{5}Hz$$

300 khz! Most humans cannot hear much above 3 kHz. And a good thing too; an individual bat call is extremely loud, about 130 decibels.

Despite learning in school that “light is a wave” and sometimes vast experience with water waves, most people are basically unfamiliar with – or perhaps distrustful of – the concept of a wave. It's worth repeating: **a wave is spread out over one wavelength (at least).** I always ask students “when I turn around, why can you still hear my words, even though you can't see my face?” By far the most common class answer is “because the sound bounces off the blackboard”. Of course we could repeat the experiment in open air (no blackboard), and the result would be the same. So the answer must lie elsewhere. A human face is about 0.1 m across, so it presents an enormous barrier to light – about 20 million wavelengths of light... and no significant barrier to sound, because humans make sounds with $\lambda \approx 1.5$ m, much larger than anyone's head. ***Wavelength rules***.

2. Luminosity, Intensity, and the Inverse Square Law

This thorny issue of waves versus particles is about to get even thornier, but there are some other properties of light worth knowing and much less mysterious. Light carries energy, and objects (like the Sun for example) radiate that energy away at a rate L, the *luminosity*. Many experiments in the 18th and 19th centuries showed that the intensity of a light source (say a lamp) declines as the square of the distance. Just like Newton's famous law of gravity, and perhaps both for the same simple reason: geometry. Space is 3-dimensional, and the area of a sphere (in 3-dimensional space) is $4\pi R^2$. So if you construct imaginary spheres around a point light source like the Sun, the same luminosity – the entire luminosity – falls on each sphere, independent of radius. So the light that falls per unit area is just $L/4\pi R^2$. Let's write this as

$$Intensity = \frac{L}{4\pi d^2} \tag{6}$$

because we'll want to use R to describe the radius of the star.

http://hyperphysics.phy-astr.gsu.edu/hbase/forces/isq.html

Luminosity is measured in watts (joules per second), so intensity is measured in watts per square meter (W/m^2). Slightly above the Earth's surface, if you hold up a 1 square meter surface which is sensitive to all electromagnetic radiation (basically ROYGBIV + near UV + near IR) and is directly facing the Sun, it would be receiving 1400 W. So we say that the "solar constant" is 1400 W/m^2. Since we know the distance to the Sun is 1 AU = $1.5\text{x}10^{11}$ m, we can then use these numbers to compute the luminosity of the Sun (= $4\ \text{x}10^{26}$ W). More details on the solar constant can be found here:

http://www.azimuthproject.org/azimuth/show/Solar%20radiation

Fortunately for students, luminosity is always called luminosity. (At least in astronomy; in physics, it's more commonly called *power*.) The only wrinkle is that sometimes a luminosity is described relative to that of the Sun: "Sirius is 40 solar luminosities". No problem... but it would be useful to inscribe the number "$4\text{x}10^{26}$ W" somewhere in your brain.

Not so for intensity, where astronomers have sadly gone wild. We use brightness, intensity, and flux all to mean the identical thing (W/m^2). And perhaps more commonly than any of these, we use intensity on a logarithmic scale – the famous magnitude system, invented by Ptolemy. Ptolemy would probably advise us to settle on one sensible way to describe brightness, even if it wasn't his. But a tad later in this course, when we revisit stars, we'll get down and dirty with magnitudes.

3. Photons: Return of the Particles

In the last decade of the 19th century, many companies were trying to get rich by developing the perfect light bulb, which would radiate all the electrical energy in the form of visible light. The young German physicist Max Planck received a grant to work on this problem.

It called for advances in engineering and materials science – and turned out to be much more difficult than anyone then guessed, since the best incandescent bulbs of today still only radiate ~2% of the electrical energy consumed. But even worse, there was not even an established *theory* of a glowing filament, heated from electric current. (Edison made his advances mainly by experiment – as he put it, "1% inspiration, 99% perspiration".) So Planck hoped to develop a proper theory.

Experimental physicists worked on this problem by building a large oven, drilling a small hole in it ("holraum", or cavity) and studying the spectrum of the radiation coming out at various temperatures. In a dark room, so you don't get confused by ambient light. This was a good laboratory approximation to a perfect radiator, or, to use the now-popular term, a **blackbody**. A perfectly black object absorbs all the energy incident upon it, reflecting nothing, and then re-radiates it with a spectrum determined solely by its temperature: blue-ish if very hot, red if moderate, and far-infrared if very cool. A piece of charcoal, after the actual flames subside but while still glowing red-hot (about 800 K), is a good blackbody. The Sun, at 6000 K, is another one; the outer regions of the Sun absorb all the energy from the inside, and re-radiate it at a slightly lower temperature. (To be a good blackbody, there's no requirement that the object "look black" – only that it shines by its own heat. This is what ***thermal radiation*** means.)

The experimentalists had *empirically* learned the blackbody laws, but the prevailing theory was the "Rayleigh-Jeans" theory, which made a spectacularly bad prediction. It interpreted the radiation from glowing solids as the result of vibration of the constituent atoms. This is qualitatively correct; but quantitatively leads to a ridiculous result. All the overtones of the fundamental frequencies of vibration should also be present, which means that all blackbodies should emit enormous amounts of radiation at very high frequency. This was known as the ***ultraviolet catastrophe*** – in which all matter basically collapses in one gigantic burst of ultraviolet radiation. That's not the peaceful world we live in. The difference between prediction and experiment is shown here:

http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html#c4

Pretty bad prediction, hey? Now along comes Herr Planck and his revolutionary hypothesis. He showed that if you change one theoretical assumption about this radiating solid – that energy is radiated continuously – then everything changes. Atoms are actually moving in the electric fields of all their neighbor atoms, and the binding energies are quite modest; so there's no reason to expect very high energies to be present. Specifically, he assumed that the radiation is emitted in individual packets of energy called *quanta* or ***photons***, with each photon carrying an energy

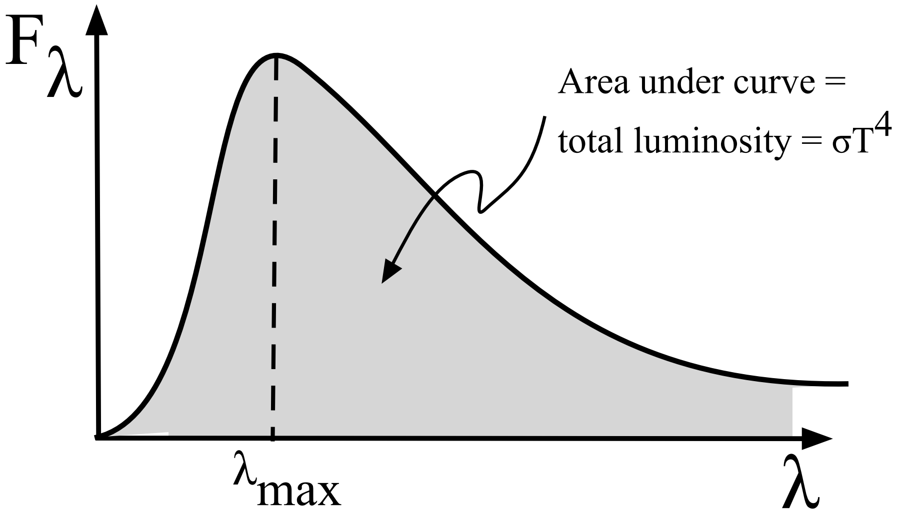
$$E = hf = \frac{hc}{\lambda}$$

where *h* is “Planck's constant” = 6.6 x 10^{-34} J · s. The number of photons at each wavelength then depends on temperature in a mathematically predictable way, and he derived a theoretical formula for blackbodies, which eliminated the ultraviolet catastrophe (whew!) and fit the experimental data excellently.

Unfortunately for us, the formula is a tad messy:

$$F_\lambda = \frac{2hc^2}{\lambda^2}\left(\frac{1}{e^{hc/\lambda kT} - 1}\right) \quad \textbf{(7)}$$

But if you calculate this messy thing out, you get something fairly simple, sort of like a Gaussian distribution:



And this yields very simple results explaining two laws which were known earlier from experiment. Wien's law, which tells you the peak of the blackbody distribution:

$$\boxed{\lambda_{\max} = \frac{(0.003m)}{T}} \quad \textbf{(8)}$$

where T is the temperature in Kelvin degrees (always Kelvin, folks!).

And the Stefan-Boltzmann law, which tells you the total area under the curve, which is the total light emitted:

$$\boxed{\text{Luminosity per square meter} = \sigma T^4} \quad \textbf{(9)}$$

where σ is the Stefan-Boltzmann constant = 5.7 x 10^{-8} W / [m^2 x (K deg$)^4$].

Let 's check these formulas for the Sun, which has T = 6000 K and R = 7 x 10^8

m. The Sun's area is $4\pi R^2$, so its total luminosity comes out to

$$L = 12.56\ (7 \times 10^{8})^{2}\ (5.7 \times 10^{-8})\ (6000)^{4} = 3.8 \times 10^{26}\ \mathrm{W}. \qquad \mathbf{(10)}$$

Close enough for astronomy. An extensive discussion of blackbody radiation is given here:

http://hyperphysics.phy-astr.gsu.edu/hbase/bbrc.html#c1

So particles were back, re-introduced to the world by Max Planck. But light is also a wave, as zillions of experiments like those of Young and Fresnel had shown. It's both, even though the concepts appear to be mutually exclusive. Which experiment you do determines which aspect of light will be manifest. We call this the *wave-particle duality*. In 1925, Louis de Broglie went one step further: he suggested that this duality applies to all matter, not just light. Protons, electrons, even baseballs. For an object's wavelength, he proposed the simple formula

$$\boxed{\text{de Broglie } \lambda \equiv \lambda_{deB} = h/p}$$

where $p = mv$, the object's momentum. (He didn't call it the de Broglie wavelength, but everyone else does.) For light, he used Einstein's formula $E = mc^2$, so light's de Broglie wavelength comes out to

$$\frac{h}{mv} = \frac{h}{(E/c^2)(c)} = \frac{h}{\left[(hc/\lambda)/c\right]} = \frac{h\lambda}{h} = \lambda$$

just the regular ol' wavelength of light. That's nice. Let's see what this implies for other things. Electrons whirling in a hydrogen atom have $v \sim 0.01\ c$, so if you work out λ_{deB}, you get (in mks units of course):

$$\frac{(6.6\text{x}10^{-34})}{(9\text{x}10^{-31})(0.01)(3\text{x}10^{8})} = 2.5\text{x}10^{-10}m$$

just about the size of an atom. An interesting result: an electron confined to an atom has about the size of the atom. And it's true. Electrons are not quite the little planets whirling around the nucleus that Rutherford and Bohr envisioned in 1912, and that you may have learned ("miniature solar system"). They're fuzzy things that occupy a lot of space – about all the space there is in the atom. And they're *waves* – in addition to being particles.

A few years later, the American physicists Davisson and Germer, working at Bell Labs (forerunner of today's AT&T; we'll be hearing more about that remarkable outfit), performed experiments in which electrons actually displayed interference effects ("diffraction"). That clinched the matter. Champagne (French) and Nobel prizes all around.

Later experiments showed that protons diffract too, so they manifest wave properties under certain conditions. No experimental results yet for baseballs, though it's suspicious that the San Francisco Giants have won the World Series in 2010, 2012, and 2014. Definite whiff of wave-like behavior.

Planck was 42 when he came up with his revolutionary $E = hf$ formula. Many young physicists recognized its great importance – certainly including Niels Bohr, the one who counted, since he took the next step in the quantum revolution. Planck went on to a Nobel Prize for this work, and eventually acclaim as the greatest physicist in Germany. But he was always vexed by the reluctance of older physicists to accept his hypothesis. Maybe they were too seduced by the previous century's love of waves. Late in life, he reflected:

> “A scientific truth does not triumph by convincing its opponents and making them see the light, but rather because its opponents eventually die, and a new generation grows up that is familiar with it.”

Chapter IX
Appendix

1. Ancient Astronomy

(a) Enuma Elish (Babylonian creation story)

This poem was written in the 12th century BC, but the myths on which it was based date back to ancient Sumer. The most complete text was found on seven clay tablets. Below is a translation from Tablet IV which tells of the great battle between the sky god Marduk and the earth goddess Tiamat.

Translator: N. K. Sandars

Tablet IV

They set up a throne for Marduk and he sat down facing his forefathers to receive the government. 'One god is greater than all great gods, a fairer fame, the word of command, the word from heaven, O Marduk, greater than all great gods, the honor and the fame, the will of Anu, great command, unaltering and eternal word! Where there is action the first to act, where there is government the first to govern; to glorify some, to humiliate some, that is the gift of the god, Truth absolute, unbounded will; which god dares question it? In their beautiful places a place is kept for you, Marduk, our avenger. 'We have called you here to receive the scepter, to make you king of the whole universe. When you sit down in the Synod you are the arbiter; in the battle your weapon crushes the enemy. 'Lord, save the life of any god who turns to you; but as for the one who grasped evil, from that one let his life drain out.' They conjured then a kind of apparition and made it appear in front of him, and they said to Marduk, the first-born son, 'Lord, your word among the gods arbitrates, destroys, creates: then speak and this apparition will disappear. Speak again, again it will appear.' He spoke and the apparition disappeared. Again he spoke and it appeared again. When the gods had proved his word they blessed him and cried, 'MARDUK IS KING!'

They robed him in robes of a king, the scepter and the throne they gave him, and matchless war-weapons as a shield against the adversary. 'Be off. Slit life from Tiamat, and may the winds carry her blood to the world's secret ends.'

The old gods had assigned to Bel what he would be and what he should do, always conquering, always succeeding; Then Marduk made a bow and strung it to be his own weapon, he set the arrow against the bow-string, in his right hand he grasped the mace and lifted it up, bow and quiver hung at his side, lightnings played in front of him, he was altogether an incandescence. He netted a net, a snare for Tiamat; the winds from their quarters held it, south wind, north, east wind, west, and no part of Tiamat could escape.

With the net, the gift of Anu, held close to his side, he himself raised up IMHULLU the atrocious wind, the tempest, the whirlwind, the hurricane, the wind of four and the wind of seven, the tumid wind worst of all. All seven winds were created and released to savage the guts of Tiamat, they towered behind him. Then the tornado ABUBA his last great ally, the signal for assault, he lifted up. He mounted the storm, his terrible chariot, reins hitched to the side, yoked four in hand the appalling team, sharp poisoned teeth, the Killer, the Pitiless, Trampler, Haste, they knew arts of plunder, skills of murder. He posted on his right the Batterer, best in the mêlée; on his left the Battle-fury that blasts the bravest, lapped in this armor, a leaping terror, a ghastly aureole; with a magic word clenched between his lips, a healing plant pressed in his palm, this lord struck out.

He took his route towards the rising sound of Tiamat's rage, and all the gods besides, the fathers of the gods pressed in around him, and the lord approached Tiamat. He surveyed her scanning the Deep, he sounded the plan of Kingu her consort; but so soon as Kingu sees him he falters, flusters, and the friendly gods who filled the ranks beside him- when they saw the brave hero, their eyes suddenly blurred.

But Tiamat without turning her neck roared, spitting defiance from bitter lips, 'Upstart, do you think yourself too great? Are they scurrying now from their holes to yours?' Then the lord raised the hurricane, the great weapon he flung his words at the termagant fury, 'Why are you rising, your pride vaulting, your heart set on faction, so that sons reject fathers? Mother of all, why did you have to mother war? 'You made that bungler your husband, Kingu! You gave him the rank, not his by right, of Anu. You have abused the gods my ancestors, in bitter malevolence you threaten Anshar, the king of all the gods. 'You have marshaled forces for battle, prepared the war-tackle. Stand up alone and we will fight it you, you and I alone in battle.'

When Tiamat heard him her wits scattered, she was possessed and shrieked aloud, her legs shook from the crotch down, she gabbled spells, muttered maledictions, while the gods of war sharpened their weapons. Then they met: Marduk, that cleverest of gods, and Tiamat grappled alone in singled fight. The lord shot his net to entangle Tiamat, and the pursuing tumid wind, Imhullu, came from behind and beat in her face. When the mouth gaped open to suck him down he drove Imhullu in, so that the mouth would not shut but wind raged through her belly; her carcass blown up, tumescent.

She gaped- And now he shot the arrow that split the belly, that pierced the gut and cut the womb. Now that the Lord had conquered Tiamat he ended her life, he flung her down and straddled the carcass; the leader was killed, Tiamat was dead, her rout was shattered, her band dispersed.

Those gods who had marched beside her now quaked in terror, and to save their own lives, if they could, they turned their backs on danger But they were surrounded, held in a tight circle, and there was no way out. He smashed their weapons and tossed them into the net; they found themselves inside the snare, they wept in holes and hid in corners suffering the wrath of god. When they resisted he put in chains the eleven monsters, Tiamat's unholy brood, and all their murderous armament. The demoniac band that has marched in front of her he trampled in the ground.

But Kingu the usurper, he chief of them, he bound and made death's god. He took the Tables of Fate, usurped without right, and sealed them with his seal to wear on his own breast. When it was accomplished, the adversary vanquished, the haughty enemy humiliated; when the triumph of Anshar was accomplished on the enemy, and the will of Nudimmud was fulfilled, then brave Marduk tightened the ropes of the prisoners. He turned back to where Tiamat lay bound, he straddled the legs and smashed her skull (for the mace was merciless), he severed the arteries and the blood streamed down the north wind to the unknown ends of the world.

When the gods saw all this they laughed out loud, and they sent him presents. They sent him their thankful tributes. The lord rested; he gazed at the huge body, pondering how to use it, what to create from the dead carcass. He split it apart like a cockle-shell; with the upper half he constructed the arc of sky, he pulled down the bar and set a watch on the waters, so they should never escape. He crossed the sky to survey the infinite distance; he station himself above apsu, that apsu built by Nudimmud over the old abyss which now he surveyed, measuring out and marking in. He stretched the immensity of the firmament, he made Esharra, the Great Palace, to be its earthly image, and Anu and Enlil and Ea had each their right stations.

(b) Genesis

Gen.1

[**1**] In the beginning God created the heavens and the earth.
[**2**] The earth was without form and void, and darkness was upon the face of the deep; and the Spirit of God was moving over the face of the waters.
[**3**] And God said, "Let there be light"; and there was light.
[**4**] And God saw that the light was good; and God separated the light from the darkness.
[**5**] God called the light Day, and the darkness he called Night. And there was evening and there was morning, one day.
[**6**]
And God said, "Let there be a firmament in the midst of the waters, and let it separate the waters from the waters."

[**7**] And God made the firmament and separated the waters which were under the firmament from the waters which were above the firmament. And it was so.
[**8**] And God called the firmament Heaven. And there was evening and there was morning, a second day.
[**9**]And God said, "Let the waters under the heavens be gathered together into one place, and let the dry land appear." And it was so.

[**10**] God called the dry land Earth, and the waters that were gathered together he called Seas. And God saw that it was good.
[**11**] And God said, "Let the earth put forth vegetation, plants yielding seed, and fruit trees bearing fruit in which is their seed, each according to its kind, upon the earth." And it was so.
[**12**] The earth brought forth vegetation, plants yielding seed according to their own kinds, and trees bearing fruit in which is their seed, each according to its kind. And God saw that it was good.
[**13**] And there was evening and there was morning, a third day.

[**14**]And God said, "Let there be lights in the firmament of the heavens to separate the day from the night; and let them be for signs and for seasons and for days and years,

[**15**] and let them be lights in the firmament of the heavens to give light upon the earth." And it was so.
[**16**] And God made the two great lights, the greater light to rule the day, and the lesser light to rule the night; he made the stars also.
[**17**] And God set them in the firmament of the heavens to give light upon the earth,
[**18**] to rule over the day and over the night, and to separate the light from the darkness. And God saw that it was good.
[**19**] And there was evening and there was morning, a fourth day.
[**20**]And God said, "Let the waters bring forth swarms of living creatures, and let birds fly above the earth across the firmament of the heavens."

[**21**] So God created the great sea monsters and every living creature that moves, with which the waters swarm, according to their kinds, and every winged bird according to its kind. And God saw that it was good.
[**22**] And God blessed them, saying, "Be fruitful and multiply and fill the waters in the seas, and let birds multiply on the earth."
[**23**] And there was evening and there was morning, a fifth day.
[**24**]And God said, "Let the earth bring forth living creatures according to their kinds: cattle and creeping things and beasts of the earth according to their kinds." And it was so.

[**25**] And God made the beasts of the earth according to their kinds and the cattle according to their kinds, and everything that creeps upon the ground according to its kind. And God saw that it was good.
[**26**]Then God said, "Let us make man in our image, after our likeness; and let them have dominion over the fish of the sea, and over the birds of the air, and over the cattle, and over all the earth, and over every creeping thing that creeps upon the earth."

[**27**] So God created man in his own image, in the image of God he created him; male and female he created them.
[**28**] And God blessed them, and God said to them, "Be fruitful and multiply, and fill the earth and subdue it; and have dominion over the fish of the sea and over the birds of the air and over every living thing that moves upon the earth."
[**29**] And God said, "Behold, I have given you every plant yielding seed which is upon the face of all the earth, and every tree with seed in its fruit; you shall have them for food.
[**30**] And to every beast of the earth, and to every bird of the air, and to everything that creeps on the earth, everything that has the breath of life, I have given every green plant for food." And it was so.
[**31**] And God saw everything that he had made, and behold, it was very good. And there was evening and there was morning, a sixth day.

Gen.2

[**1**]Thus the heavens and the earth were finished, and all the host of them.

[**2**] And on the seventh day God finished his work which he had done, and he rested

on the seventh day from all his work which he had done.
[**3**] So God blessed the seventh day and hallowed it, because on it God rested from all his work which he had done in creation.
[**4**]These are the generations of the heavens and the earth when they were created. In the day that the LORD God made the earth and the heavens,

[**5**] when no plant of the field was yet in the earth and no herb of the field had yet sprung up -- for the LORD God had not caused it to rain upon the earth, and there was no man to till the ground;
[**6**] but a mist went up from the earth and watered the whole face of the ground --
[**7**] then the LORD God formed man of dust from the ground, and breathed into his nostrils the breath of life; and man became a living being.
[**8**] And the LORD God planted a garden in Eden, in the east; and there he put the man whom he had formed.
[**9**] And out of the ground the LORD God made to grow every tree that is pleasant to the sight and good for food, the tree of life also in the midst of the garden, and the tree of the knowledge of good and evil.
[**10**] A river flowed out of Eden to water the garden, and there it divided and became four rivers.

[**11**] The name of the first is Pishon; it is the one which flows around the whole land of Havilah, where there is gold;
[**12**] and the gold of that land is good; bdellium and onyx stone are there.
[**13**] The name of the second river is Gihon; it is the one which flows around the whole land of Cush.
[**14**] And the name of the third river is Tigris, which flows east of Assyria. And the fourth river is the Euphrates.
[**15**] The LORD God took the man and put him in the garden of Eden to till it and keep it.

[**16**] And the LORD God commanded the man, saying, "You may freely eat of every tree of the garden;
[**17**] but of the tree of the knowledge of good and evil you shall not eat, for in the day that you eat of it you shall die."
[**18**] Then the LORD God said, "It is not good that the man should be alone; I will make him a helper fit for him."

[**19**] So out of the ground the LORD God formed every beast of the field and every bird of the air, and brought them to the man to see what he would call them; and whatever the man called every living creature, that was its name.
[**20**] The man gave names to all cattle, and to the birds of the air, and to every beast of the field; but for the man there was not found a helper fit for him.
[**21**] So the LORD God caused a deep sleep to fall upon the man, and while he slept took one of his ribs and closed up its place with flesh;
[**22**] and the rib which the LORD God had taken from the man he made into a woman and brought her to the man.
[**23**] Then the man said, "This at last is bone of my bones
and flesh of my flesh;
she shall be called Woman,
because she was taken out of Man."
[**24**] Therefore a man leaves his father and his mother and cleaves to his wife, and

they become one flesh.
[**25**] And the man and his wife were both naked, and were not ashamed.

Gen.3

[**1**] Now the serpent was more subtle than any other wild creature that the LORD God had made. He said to the woman, "Did God say, `You shall not eat of any tree of the garden'?"
[**2**] And the woman said to the serpent, "We may eat of the fruit of the trees of the garden;
[**3**] but God said, `You shall not eat of the fruit of the tree which is in the midst of the garden, neither shall you touch it, lest you die.'"
[**4**] But the serpent said to the woman, "You will not surely die.
[**5**] For God knows that when you eat of it your eyes will be opened, and you will be like God, knowing good and evil."
[**6**] So when the woman saw that the tree was good for food, and that it was a delight to the eyes, and that the tree was to be desired to make one wise, she took of its fruit and ate, and she also gave some to her husband who was with her, and he ate.

... and with that simple act of disobedience and curiosity, the enterprise and style of SCIENCE was born!

More on... TIMEKEEPING AND THE CALENDAR

Down the long road of history, the timekeeping issue that really matters is the calendar. Why? Because it's so critical to ***food production***! Whether your society is agricultural (crops have to be planted) or hunter-gatherer (plants and animals have to be exploited at the right time of year), you just need a good calendar. Egypt furnishes a good example. It's too dry to support much agriculture, except in the Nile valley. So they had a choice: either build immense irrigation works, or plan to exploit the annual flooding of the Nile. They did both, but since the flooding comes for free, it was the favored method. You have to get your fields plowed and seeded at just the right time... but how would they know what the right time is? The rule was: the flood starts at the “heliacal rising” of Sirius. Any old rube can recognize Sirius, the Dog Star, and heliacal rising means: the first glimpse of Sirius in the pre-dawn sky (after several months of invisibility due to the glare of sunlight). Nowadays this occurs in mid-August, but in ancient Egypt it would have been about June 25 (the difference arises from *precession*). When you first see Sirius in the pre-dawn sky, the flood is coming soon.

“Days" and "years" are the major (regular) milestones of time, and everyone knows what they mean. Astronomers, however, reserve the right to make small but necessary quibbles about their meaning. Namely these...

1. The day is the interval between the *Sun's* crossings of the meridian, not the interval between successive crossings of *stars* (which is the Earth's true rotation period). The stars cross every 23h 56m, but the Sun crosses every 24h. Or, in an equivalent version, the Earth has to rotate an extra degree (corresponding to 4 m of time) to catch up with the Sun, which moves about one degree per day.

We must do it this way, because the day's important events arise from the Sun, not the stars. During a strange and nerdy moment many years ago, I actually bought a watch that kept sidereal time (basically telling what stars are in the sky right now, rather than the Sun). After about a year of missing appointments, I came to realize the folly of that. (Still, I have to admit... I miss it.)

2. Because of precession, the correct year is the so-called "tropical year", not the time it takes the Earth to go 360 degrees around the Sun. The latter is the *sidereal* year, which is 365.2566 days. The former, which is defined as the interval between the Sun's crossings of the celestial equator, is 365.2422 days. Mighty close, but if you punch a few calculator

keys, you'll see that this 21 minute difference accumulates to 1 year in... 26,000 years. Or half a year in 13,000 years. Aha. So if you don't make this correction, then it snows in July 13000 years later... but then comes back to normal in another 13000 years.

I assume that the Babylonians, who knew this 26000 year number pretty accurately, didn't base it on 26000 years of observation and failed agriculture. How did they learn about it, and how long a baseline of records did they need? Could be an interesting paper topic (I dunno the answer).

OK, that's the scientific part. Basically known 3000 years ago. But many cultures also choose to recognize the Moon as a keeper of time. The reasons are minor, and, for that matter, not really known. Tides, perhaps... nocturnal hunting... fertility... and maybe just to have a convenient unit of time intermediate between a day and a year. Anyway, enter the MONTH.

BTW I leave out discussion of the week - I have no idea why we have weeks. The seven days do seem to honor the seven planets:

Sun - day domingo
Moon - day lunes
Tues - day martes Mars
Woden - day miercoles Mercury
Thor - day jueves Jupiter (Jove)
Fri - day viernes Venus
Satur - day sabado Saturn

A few whiffs of Norse and Spanish... and basically similar all over Europe.

Back to the month. What matters is the SYNODIC month (interval between full moons), and that's 29.531 days. It doesn't divide evenly into 365.2422 d, so we have to do some fancy steppin' to keep months synched to the year. We need a time-keeping system which will enable people, especially farmers and tax-collectors, to reckon where each day falls in the year. It must be systematic, accurate, and understandable. In 46 BC, Julius Caesar's astronomers concocted the *Julian calendar*. They said the following. The year has 365.25 d, so we'll have six short months (30 d) and six long months (31 d), alternating and starting with January which is long. That's one too many days, so we'll rob February, which knocks it down to 29. After Caesar Augustus died, they wanted to name a month after him (no airports were then available), and named the eighth month August. But August was a short month – definitely no way to treat so august a personage! So February, already the weak sister of the bunch, had to cough up an extra day.

That only gets you to 365 d, and the Roman astronomers certainly knew about the extra 0.25. Enter the leap year: every four years, February gets an extra day. All years divisible by 4 are leap years. That's the Julian calendar.

This was good enough for many centuries, but an error still remains: this interval of 365.25 d is TOO LONG, by 0.0078 d = 11 min 14 sec. This accumulated to 1 day in 128 years, and 12 days by the mid-16th century. The true vernal equinox had slipped to about March 10.

Rumors that the calendar was wrong started to circulate, possibly spread by astronomers and by farmers (who certainly kept their own weather records). By itself that was no big problem; who cares about the eggheads and the hayseeds? The biggest problem was the date of Easter: the first Sunday after the first full moon after the spring equinox. Which spring equinox, the real one or the calendar version? This was kind of embarrassing. Catholicism had lost a lot of grip in northern Europe (Luther nailed up his 95 theses in 1517), and was trying hard to win converts in South America. So Pope Gregory XIII challenged Christopher Clavius, a famous astronomer and Jesuit priest, to reform the calendar.

And he did. Recognizing the error of 1 day per 128 years, Clavius abolished 3 out of every 100 leap days. Thus the new year lost 3 days in 400 years, or on average 1 day per 133 years. Whew - almost perfect! Thus was born the "Gregorian calendar", still in use today. Its distinguishing new feature was that century years need to be divisible by 400, not merely 4, to be leap years. Thus 1600 and 2000 were leap years, but 1700, 1800, and 1900 were not.

Clavius and Pope Gregory also needed to fix the 10 days which had already slipped (10 rather then 12, because they were trying to calibrate everything to the Council of Nicaea in 325 AD). In 1582, they did that by announcing in a papal bull (pardon the expression) that Thursday 4 October should be followed by Friday 15 October.

Brave guys! People felt they would suffer from this, and sometimes they did – some landlords and tax-collectors got a little greedy concerning their take in October 1582. But most of Catholic Europe adopted the change right away. Not so the Protestants, who weren't about to endorse anything associated with "Papism". England and the colonies didn't adopt the change until 1752. So although we commemorate Washington's birthday as February 22, 1732, a wall calendar in the birthing room would have read February 11, 1731. (The English, and many other cultures, adopted the vernal equinox as the start of the year. Months and years were somewhat decoupled; January started with January 1, and March with March 1, but by tradition the *year* started on March 25.) And Czarist Russia never adopted the Gregorian calendar; that's why the "October Revolution" took place in November.

So that's the whole story on calendars – everything relevant for farmers, citizens, etc. There are some other calendar hijinks out there (e.g. the Jewish and Islamic calendars, which accord much more respect to the month, and therefore have to cope with 354-day years); but the whole world of commerce – as far as I know – is now on the Gregorian calendar.

For real time enthusiasts *in extremis*, there are many super-subtle wrinkles today: leap seconds, atomic clocks, changes in Earth's rotation, etc. But nothing further that is relevant to our story.

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Now for ECLIPSES...

Another subject of enormous import for ancient astronomy, and still with great scientific impact as late as the 1970s... but now with interest shading more towards the artistic than the scientific.

The attached pages show the basic eclipse geometries and other info. Here are five things you should know, all simple but more or less in order of increasing subtlety.

1. Lunar = moon goes through Earth's shadow cone. Gotta happen exactly at full moon, and at night. Half the Earth sees it (everyone who sees the Moon).

2. Solar = moon occults the Sun, and casts a tiny shadow on the Earth, about 40 miles wide. Gotta happen exactly at New Moon, and in the day (cuz you hafta see the Sun).

3. Solar eclipses happen because the Sun is 400 times bigger than the Moon, and 400 times farther away... so they have the same angular size in the sky (about half a degree). A nice cosmic coincidence. If the Moon were more distant or physically smaller, we'd never see the dramatic spectacle of darkness at noon. If it were closer, a solar eclipse would occur every month at new moon.

4. For both eclipses, the Moon has to line up with the Sun... and for that line-up

to be close, the full/new moon has to be near a NODE, or an "ecliptic node", in its orbit. The Moon's orbit is inclined to the ecliptic by 5 degrees, so it's usually *not* near a node; it needs to be within about 1 degree of the ecliptic, so each full moon carries about a 1/5 chance of making a lunar eclipse, and each new moon carries about a 1/5 chance of making a solar eclipse.

5. Lunar eclipses are widely seen, but very few people have ever seen a total solar. The Moon's shadow cone is tiny, averaging about 30 miles wide; it sweeps thousands of miles across the Earth, which helps a lot, but the total area covered is still small. If you never make an effort by travelling to a predicted eclipse track, you have to wait about 400 years for it to come to you. And if it's cloudy... wait for another 400.

If you know these things, you really know a lot about eclipses. Personally I'm tempted by the arcana and mathematical lure of eclipse prediction... and amazed that this was known to some of the Greeks, and likely some of the Babylonians too. And that's sort of our subject, so I'll go further along this road. Warning: very technical stuff ahead – but strictly optional!

Two numbers govern the mathematics of eclipse prediction. Full and new moons occur every 29.5306 days – the *synodic month*. But the Moon returns to its ecliptic node (the place where the orbital planes of Sun and Moon intersect) every 27.2122 days – the "nodical" month.

Suppose everything is perfectly lined up today: moon is full or new, and at the node. You get a total eclipse – very nice. 27.2122 days later, the Moon is again at the node, but it's 2.3 days too early: no hope for an eclipse. Another 27.2122 days, and it's 4.6 days too early: zero hope then too. Then 6.9, yadda yadda yadda. We say that the clocks are not "resonant" – a language we'll use many times in this class. But if you keep banging your calculator into submission, you'll eventually find an interval (a long one) which is an integer number of BOTH CYCLES. I'm sure you see it instantly. It's

223 synodic months = 6585.32 d
242 nodical months = 6585.35 d

Now we're in business. After 6585.33 d, the configuration of Sun and Moon will repeat very precisely – and thus a "very similar" total eclipse will occur. That's 18 years 11 days 8 hours. This is the famous "saros" cycle.

Three more comments.

1. This is a decent resonance, but not perfect. The 0.03 d error means that after 30 saros cycles, the error grows to 0.9 d, and that will kill the eclipse – maybe you'll get a partial, but nothing worth writing home about. After another 30 cycles, it's totally dead.

2. The gradual loss of resonance implies that other configurations, now not quite resonant, will in the future give us great eclipses, which will hang in there for maybe 500-year runs. Even the worst possible mismatch between lunar node and lunar phase (nodical crossing at *quarter* moon) will get its act together in about 10000 years. The last shall be first. At any given time there might be a coupla dozen saros cycles producing eclipses – some just getting warmed up, some in mid-career, and some fading away. That's how we manage to get – somewhere on Earth – several eclipses every year.

3. A fascinating aspect of this is the "0.33" part of the 6585.33 d cycle. Even if you see one solar eclipse at age 20 and live an additional 18 years and 11 days, and every day is clear, will you see the next one in the series (and thereby have a hope of learning the periodicity)? No you won't, because the Earth needs to rotate another 1/3 of a revolution – so people living 8 hours west of you (Polynesians) will see it. You'll have a fighting chance 54 years and 34 days later... but how would you know that the true cycle is 18 years 11 days? And if you're lucky enough to see an eclipse from some other series, how could you tell it belonged to a different series?

Boggles the mind. Those amazing Babylonians. As for Stonehengers... well, OK, them too, maybe. Whoever they were.

BTW all of this material on calendars and eclipses is treated, with pretty pikshers and the like, in introductory texts. Be sure to read about these matters.

Now we're about to leave all this geometrical/stargazing/numerology stuff behind, and return to more of C1610's main story, the history of cosmology.

The Great Copernicus Chase

OWEN GINGERICH

When my astrophysicist friends ask me why I no longer compute model stellar atmospheres, I tell them that I'm the victim of anniversaries. In 1971 the astronomer Johannes Kepler had his four hundredth birthday, closely followed by the Copernican quinquecentennial in 1973. As an astronomer with strong historical interests, I knew I would be expected to have an opinion on these men, but I hoped, by taking at least a small look at some original sources, to avoid the time-honored clichés about their lives and discoveries.

Kepler was an enthusiast, a man who wrote a five-foot shelf of books and who left scores of surviving letters and unexamined manuscripts. In contrast, Copernicus was essentially a one-book author. No personal letters survive, and precious few working manuscripts. To study Copernicus means studying his *De revolutionibus orbium coelestium*, a formidably technical treatise published in 1543, just in time to reach the Polish astronomer on his deathbed.

But did anyone really read Copernicus's magnum opus? He wrote in an age when merely being able to understand Ptolemy's *Almagest* was considered the highest achievement of an astronomer. Copernicus's own treatise, heavily dependent on Ptolemy's fourteen-hundred-year-old work, was no easier to read. It is entirely possible that more people alive today have read through *De revolutionibus* than in the entire sixteenth century. Or so my fellow Copernicanist, Gerald Ravetz, and I decided in a bull session one night in York in 1970.

Two days after that discussion, I found myself at the Royal Observatory in Edinburgh, and there I took the occasion to examine its first edition Copernicus. To my astonishment, the book was carefully annotated from beginning to end. If there were so few knowledgeable readers in the sixteenth century, then by no decent probability should I have found so quickly a copy with errors perceptively marked to the very last page. As I weighed the possibilities, it occurred to me that, by an improbable chance, I might just have in hand a copy from the small group of Lutheran scholars who were responsible for getting the book printed.

There was, first, young Georg Joachim Rheticus, the twenty-two-year-old radical professor who went off to northern Poland to persuade the aging and reluctant Copernicus to publish his work. I call him a radical because anyone who adopted heliocentrism in those days had to be something of a revolutionary, but it was more than that. Neither Joachim nor Rheticus (meaning "from the Rhine") was his real family name. He was christened Iserin, but when he was still a teenager, his father was charged with sorcery and beheaded, and the lad was forced to adopt a new name. Later on, after he was driven from his post as astronomy professor at Leipzig following a drunken homosexual incident, he left astronomy and became a medical doctor. As a doctor he adopted Paracelsianism, which in medicine was just as radical as heliocentrism was in astronomy. If a little more biographical data were available, Rheticus would make a prime subject for a psychobiography.

In any event, the well-annotated *De revolutionibus* I had found in Edinburgh had not been worked over by Rheticus. I might have pinned down the annotator more promptly had I seen, on folio 96, a Latin note citing "Our Joachim . . . ," clearly a reference by

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one of his near-colleagues. As it was, I soon found the owner's initials stamped among the decorations on the cover: E R S, which I eventually realized stood for Erasmus Reinhold Salveldensis—that is, Erasmus Reinhold from Saalfeld. Reinhold was the senior professor of mathematics and astronomy at Wittenberg; at the time of his Polish trip, Rheticus was the junior professor there. Unlike Rheticus, Reinhold was a solid, conservatively oriented man who steadily worked his way up the academic ladder, finally becoming rector, a much admired teacher, and the most influential astronomer in the Lutheran world. As for Copernicus's treatise, he ignored the newfangled heliocentric cosmology while immersing himself in such safe technical questions as the motion of the moon (which in any system went around the earth) and the slow precessional motion of the starry firmament. That he held such an attitude is quite precisely revealed by the places where he did and where he did not annotate his *De revolutionibus*.

The significance of having available the annotated *De revolutionibus* of the foremost astronomy teacher of the mid-sixteenth century was not lost on me, for I realized that such annotations provided an ideal way to find out how teachers and students of that era approached Copernicus's astronomy. Fortunately, the mid-1500s were still close enough to the tradition of the Middle Ages, when marginal glossing of manuscripts was a common practice; also fortunately for me, the *De revolutionibus* was printed with generous margins, despite the fact that paper was the major expense for publishers. And so, with the discovery of Reinhold's *De revolutionibus*, the Great Copernicus Chase began.

In 1970 no one had much of an idea about how many copies of the *De revolutionibus* had been printed, or how many survived. An obviously incomplete list of seventy copies had been published in 1943, and that provided a starting point, especially for the German libraries. When Rheticus brought the manuscript of Copernicus's book back to Germany, the obvious printer was Johannes Petreius in Nuremberg. In the 1540s Petreius had become the leading publisher of scientific texts, and his press had both the facilities and the distribution network to cope with a major technical treatise.

It has always seemed anomalous to me that Nuremberg, where the *De revolutionibus* was originally printed, no longer has a copy from the first edition. Although still a cultural mecca, Nuremberg has long since yielded the intellectual centrum to Munich, the Bavarian capital. Munich still has two first editions in the Staatsbibliothek, but two other copies at the university perished in the air raid of July 1944—a tragedy at least partly the fault of the librarian, who, I am told, refused to protect the books on the grounds that such pessimism would be unpatriotic. In Berlin and Frankfurt copies were also lost, but elsewhere in both West and East Germany more than three dozen copies survive. Germany is the only place in Europe where first editions outnumber the second, still reflecting the original saturation from the Nuremberg printing.

The 1943 list of seventy first editions provided a particularly strong compendium for Germany, but the task of ferreting out copies elsewhere in Europe and America required other detective techniques: letters of inquiry, consultation with dealers, advertising in bibliophilic journals. In Oxford and in Cambridge there existed central lists for the libraries—something which is not the case for London, so it took several years before I realized that London outstripped either of the traditional university towns. Who would have guessed that Dr. Williams's Library, rich in theology, would also hold an *editio princeps* of the *De revolutionibus*? Or that the Victoria and Albert Museum would hold another?

Finding the copy at the V & A was something of a victory for dogged, systematic sleuthing. In an effort to ferret out as many copies as possible, I went through the Book Auction Records from their inception in 1888, and under 1897 I found the sale of a Copernicus in a Grolier binding. Jean Grolier, an illustrious French bibliophile of the sixteenth century, was noted for the distinguished book bindings in his library, which are nowadays great collector's items. My eyes jumped to attention when I saw the citation in the auction index, for I realized that I had never seen a Copernicus in a Grolier binding. An examination of the original Sotheby's auction catalogue cast more light on the sale. "The bindings," read the description, "though quite modern, are historically correct—they are, in fact, modern imitations of very high quality." What Sotheby's delicately called imitations, most modern collectors have unhesitatingly called forgeries. The sale included fakes of a wide variety of distinguished libraries, all cleverly made by the French forger Hagué. Eventually my investigation traced the faked Grolier copy to the Victoria and Albert, which had purchased it for their decorative arts collection. And there I found it, complete with genuine but entirely irrelevant old bookplates that Hagué had captured from who knows where.

Because the intellectual capital of France is so obviously Paris, it has come as something of a surprise for French savants to realize that there are even more copies of the *De revolutionibus* in the provinces than in Paris itself, despite the fact that there are more Copernicuses in Paris than in any other city—twelve first editions and as many seconds by my latest count. The key to the French provinces was nevertheless held by the Bibliothèque Nationale, which contains printed catalogues from most of the outlying libraries. My systematic search in the BN turned up numerous locations, and simultaneously scholars at the Centre Alexandre Koyré in Paris queried the provincial libraries. Eventually, in a series of field trips, I visited virtually every French library known to hold a copy of the first or second edition. Many of the provincial libraries have remarkable collections of early books, generally taken over from monasteries or Jesuit colleges at the time of the French Revolution. When I congratulated the librarian at Verdun on owning a Copernicus, she said, "C'est rien. You should see our manuscripts!" And she promptly led me into the manuscript room and handed me the most exquisite illuminated manuscript that I have ever examined.

But owning a Copernicus *is* something, as far as printed books are concerned, and I have little doubt that the first edition Copernicus in some of these libraries represents the most valuable book in their collection, a fact probably unknown to the majority of the librarians. I must admit that I was startled in one of the libraries in southern France. Their copy had a particularly distinguished provenance from one of the sixteenth-century Pléiade, and I wanted to photograph its title page. The match-box sized library was literally too small to provide an area sufficiently bright, and after some negotiation it was decided that I should take the book onto the front steps facing the town square and use the sunlight there.

The price of the *De revolutionibus* has climbed steeply in recent years, upward of $40,000, and will no doubt climb even higher now that the Japanese have entered the bidding. (Three of the last ten copies to enter the market have gone to universities in Japan.) The price for the first edition was considerably enhanced in 1974 following the Sotheby's auction of the first part of the scientific collection formed by Harrison Horblit. There, in a psychological configuration extremely favorable to the seller, his copy was pushed to $110,000, the highest price ever paid for a printed work in the history of science. The Horblit copy was and is the most important example in private hands. In the absence of a copy autographed by Copernicus himself, the next best "association copy" is a presentation from Rheticus, Copernicus's only direct disciple, and such is the copy that set the record-breaking price.

To me, this pricey copy has a feature that is much more interesting than Rheticus's signature. On the flyleaf is a long Greek poem written in 1543 by Joachim Camerarius, the leading professor at Leipzig, and inscribed into the book by Camerarius himself. "What is this book?" asks the stranger in the poetic dialogue. "A new one, with all kinds of good things in it," replies the philosopher. "O Zeus! How great a wonder do I see! The earth whirls everywhere in aethereal space," the stranger cries out. "But," warns the philosopher, "do not merely wonder, nor condemn a good thing as the ignorant do before they understand, but examine and ponder all these things."

Such laudatory poems were commonplace in scholarly books of the sixteenth century, and their absence in the *De revolutionibus* is conspicuous. Could Camerarius's poem have been commissioned by Rheticus for the book? Rheticus, lured by a particularly attractive salary, had left the Nuremberg printery before the front matter was finished, leaving the final part of the proofreading in the hands of Andreas Osiander, a local and learned preacher. To Rheticus's consternation, the final work contained no introductory poems, but an anonymous foreword from Osiander that cautioned the reader to treat the new cosmology as hypothetical, "not necessarily true nor even probable." In annoyance and anger Rheticus crossed off Osiander's foreword with a red crayon before sending the book to his friend Andreas Aurifaber, then dean at Wittenberg. Was Rheticus disturbed by the philosophy, or mostly just cross that Camerarius's poem had not been used? From this distant epoch, we can hardly even guess.

While Harrison Horblit still owned the Rheticus copy, I took Jerzy Dobrzycki, a colleague from Warsaw, down to Connecticut to see it. Professor Dobrzycki immediately realized that the Greek poem was the source of a Latin poem that Kepler had written into his own copy of the *De revolutionibus*. Kepler's copy and the poem had long been known to scholars. I have seen and photographed it in Leipzig a couple of times. Kepler signed the poem "I K," but until Dobrzycki made the connection, no one realized that the initials stood not only for Iohannes Kepler but for the Greek iota-kappa of Ioachim Camerarius—a charming example of the wordplays that so delighted Kepler. (One of his anonymous books contains three consecutive anagrams of his name on the title page!)

The Rheticus and the Kepler copies both rate three stars in my census, but such extraordinary annotations are comparatively rare. More common are minor, rather uninspired, marginal tracks: catchwords that provide a running index. Usually such notes peter out after the first few chapters. Sometimes the remarks are more substantive, and occasionally even highly critical. Christopher Clavius, the Jesuit astronomer who engineered the Gregorian calendar reform, wrote beside a faulty trigonometric theorem, "Here Copernicus is dreaming!" ("Hallucinatur hic Copernicus"). At least two annotators quoted the Sicilian astronomer Maurolycus, who had said that Copernicus "deserved whips and lashes" for his unorthodox cosmology. In the richly annotated Yale copy, a long Latin critique finally breaks off into German: "Der Himmel ist aber zum Narren worden, er musz gehn wie Copernicus will" ("The heavens would behave like a clown if they had to go as Copernicus wants"). However, the next owner added an ameliorating postscript; he noted that there was indeed a typographical error in the text, but it didn't matter because Copernicus actually used the correct number in subsequent calculations.

Despite the paucity of really well-annotated copies, there have been just enough to keep up the excitement of the chase. And gradually a major and unexpected result emerged from the survey: not only did several score books contain significant notes, but these notes ran in related families. Marginal clarifications and criticisms were passed from tutor to pupil, sometimes through several generations. For example, parts of Reinhold's comments have propagated into over a dozen specimens, and another independent set of notes appears in six more far-flung volumes. The critique in the Yale copy appears elsewhere thrice more, always untempered by the Yale postscript. These secondhand annotations reveal that even if Copernicus's revolutionary new doctrine failed to find a place in the regular university curriculum, a network of astronomy professors scrutinized the text and their protégés carefully copied out their remarks, setting the notes onto the margins of fresh copies of the book with a precision impossible by aural transmission alone. Clearly the students sat with the master book before them as they transcribed key words, data, diagrams, or whole paragraphs of elucidation. How wrong Ravetz and I were in supposing that only a handful of sixteenth-century readers were familiar with the book!

Even as the personal examinations drew to a close, well-annotated copies occasionally turned up. One of the last first editions for which information became available—from Debrecen in Hungary—turned out to have marginalia matching copies in Pisa, Soissons, and Ann Arbor. Another, from a specially unlocked safe in London, was filled with glosses, apparently quite independent of any other copy, made by a sixteenth-century Spanish bishop. However, the unannotated copies of the *De revolutionibus* are far more common, and, apart from their bindings and state of preservation, they are as alike as peas in a pod and nearly as uninteresting. Often the circumstances of seeing a book are far more memorable than the book itself.

The visit to a secluded castle—one of three English buildings still surrounded by a water-filled moat—was all the more sweetly savored with the knowledge that no historian of science had been allowed to enter its precincts for several decades. At that time the Tate Gallery in London had mounted a two-million-dollar campaign to save two bucolic Stubbses for England, and so it was with double interest that we sat in the castle's drawing room and counted half a dozen splendid oils by George Stubbs on the walls.

In Budapest I was actually handed a first edition to take to my room overnight; I slept with the precious volume under my bed. And at the university in Vienna I was assured that the book couldn't be fetched until the next day—a day I did not have. There ensued a delicate maneuvering for position, and it quickly became clear that they were waiting for me to announce myself as a professor. Then the magic sprang into effect. Yes, I could have the books within an hour in the professorial aula and, if I wanted, they would be available at any time till eight P.M. "We're not so efficient as American libraries," a charming young assistant confided. "Our rules go back to Franz Josef." "Never mind," I replied, knowing full well that there are few university libraries in America where one can examine a *De revolutionibus* at night.

In the professors' room that evening, all alone and unsupervised, I carefully made a rubbing of the blind-stamped binding of the Vienna Copernicus, and I mused on the fact that I hadn't been asked to produce a shred of evidence that I really was a professor. Had I shown them my Harvard dazzler letter, maybe they would have furnished tea and pastry as well!

I'm not sure if the Harvard dazzler is a uniquely Harvard phenomenon, but somehow I have trouble envisioning a Yale dazzler or a Princeton dazzler. The Harvard dazzler comes on an engraved letterhead of the president and fellows, with a gold seal bright enough to compete with the crown jewels. The corporation secretary certifies the bearer's professional credentials and expresses appreciation for any courtesies that the relevant libraries, museums, and consular officers can offer.

Only one and a half times was the dazzler letter really indispensable. I had always envisioned the École Polytechnique as the MIT of France, the home of Pasteur and Gay-Lussac. In reality it is more like the United States Military Academy, but considerably more formidable than West Point, where I had little difficulty in seeing *their* first edition Copernicus. The gate of the École Polytechnique was barred by three officers behind wickets, who assured me that I needed permission from the commandant to see a book in the library. I followed their instructions to the next gate, where the porter simply sent me directly to the library. The librarian was horrified: were I to publish anything about their Copernicus, the commandant was sure to find out and he would demand to know how I had got in without his permission. So, armed with my dazzler, I tracked back to the commandant's office, where a suitably dazzled officer promptly issued me a pass. I think the speed of this transaction left the librarian a bit chagrined. It must have been decades since anyone had asked to see the *De revolutionibus*, and there was considerable scurrying before the volume was eventually produced for my inspection.

The other time when the dazzler seemed at least half needed was at the Bibliotheca Apostolica Vaticana. Casual visitors to Saint Peter's or to the Sistine Chapel are protected from the fact that Vatican City is a political enclave of its own, and fully as bureaucratic as Italy itself. To visit the library, a form and a visa are demanded at the gate to the City, and then a pass from the secretariat. The check-in procedure gives one a locker key, which subsequently entitles its holder to see three books per day. Special permission from the prefect allows more books to be examined, but the book fetchers will look affronted by anyone audacious enough to suppose he can read more than three volumes in a day! Special permission will also allow foreign scholars to work in the afternoon as well. Since that is a privilege accorded only male researchers, in the afternoon a professor is allowed to read the books without wearing his jacket.

Not only has the trail led to great institutional libraries such as the Vatican (which has three first editions, as do Turin, Princeton, Glasgow, Trinity College in Cambridge, and the Bibliothèque Nationale) and to small provincial libraries, but also to a score of private collections.

Fortunately for the census taker, American collectors are not particularly secretive, an attribute probably closely tied with the comparative honesty of our income tax structure.

Nevertheless, tracking down these copies has required a lot of generous help from rare-book dealers, and has had its moments of tragicomedy. I was, for example, barred from a West Coast collection on the grounds that I came from Massachusetts, the only state that had had the audacity not to cast its electoral votes for Mr. Nixon. On another occasion, I was literally *smuggled* into the library of a collector who had grown senile, an act surreptitiously carried out while the nurse was taking the owner on his daily outing. But otherwise the collectors have all accepted my visits with good humor and splendid hospitality.

The list of memorable visits to private collections included one in Pittsburgh, where we met the man who brought neon advertising signs to the world. Henry Posner told us how, in his younger years, he had met the inventor of a new kind of light, the neon bulb, and he had asked the inventor what he intended to use it for. Well, said the inventor, it would be very good on an automobile to detect if the spark was active. "It gives a very bright light, doesn't it?" Posner observed, and shortly thereafter he installed the first outdoor neon sign for a large Parisian department store. Posner invested his ensuing fortune in rare books of all sorts, from Copernicus to Omar Khayyám, from one of two known copies of the first printing of the Bill of Rights to—so he assured us—a Gutenberg Bible kept in a safe in the cellar. By that time Posner was advanced in age and occasionally not too exact in his claims, so I mentally dismissed his Gutenberg Bible as a mild delusion of grandeur. A couple of years later I was chagrined to discover that he really did have most of Gutenberg's Old Testament, now the only major part of the first printed edition still in private hands.

It is comparatively easy to know where the Gutenberg Bibles are, because this is one of the few books for which a comprehensive census exists. Surprisingly, only three other major books have their locations listed with any serious claims to completeness: the first folio of Shakespeare (over one-third of the copies are in the Folger Shakespeare Library in Washington), the elephant folios of Audubon's birds, and now the first two sixteenth-century editions of Copernicus's *De revolutionibus*. As a subsidiary result of the Copernicus census, bibliographers will have extensive information on the provenances and movements of an important early scientific book.

For example, there are forty-seven first editions of the *De revolutionibus* in America. The second edition, which was issued in Basel in 1566, presumably after the 1543 edition went out of print, is virtually as rare as the first, and forty-four copies are currently recorded in this country. The first *De revolutionibus* to come to the Americas, as far as anyone knows, arrived on a ship that docked in Veracruz in 1600. That such details were recorded in the bill of lading, and that the bill of lading survives, completely astonishes me. It is only sad that the book itself can no longer be found. Apparently the earliest surviving copy was the third edition, brought over at the request of James Logan in Philadelphia around 1700, and his second edition may have come as early as 1709. The earliest first edition is undoubtedly the one in the Boston Athenaeum, which arrived around 1825. Thomas Jefferson bought a second edition for the University of Virginia, and Harvard had one at an unknown time in the nineteenth century. The larger movement of these books to America did not take place until the twentieth century—a migration of such proportion that there are more first editions here than in any other country. There are also probably more copies in private hands in America than anywhere else, but the number is rapidly declining as the books are handed over to institutional libraries. Whether the tide has turned on the flow of Copernicus books to America is hard to say, but a first edition auctioned by Philadelphia's Franklin Institute (to help pay off its Bicentennial debt) recrossed the Atlantic to the Old World once again, perhaps a harbinger of the Gutenberg Bibles that have since returned to Mainz and to Stuttgart. More recently two more copies of the *De revolutionibus*, from the Robert Honeyman collection, have followed suit—with the result that the United Kingdom has now almost nudged out the United States as the leading repository of the first edition, as it has been of the second.

Keeping track of the movements of the *De revolutionibus* has proved quite an obstacle to the formation of a complete census, although most dealers and private owners, recognizing the uniqueness of the Copernican survey, have been exceptionally cooperative. After the distinguished Rheticus presentation copy was bought in 1974 by a combine of dealers in New York and London, such was the secrecy of its disposition that when the book eventually found a buyer (at a suitably augmented price), even the London owners did not know its destination. Nonetheless such things are hard to keep secret, and eventually the book world buzzed with rumors that the new owner lived in Cambridge, Massachusetts. I dropped the putative collector a note about my interests, but had no response for several months. Then one day the phone rang, and to my surprise the new owner was on the line telling me about his remarkable collection of great works in the history of ideas.

Meanwhile I often wondered about the earlier provenance of this distinguished copy. What had happened to it after its recipient, Andreas Aurifaber, had died in Danzig? There seemed to be no evidence of ownership between the sixteenth century and the early 1950s, when the volume had turned up on the London book market without an intervening pedigree. And all this leads, strangely enough, to the libraries of Italy.

At the end of the sixteenth century, the ownership pattern of the *De revolutionibus* was quite different in Italy from that in Germany. There was no teaching tradition for the book in Italy, and few copies from the Nuremberg edition came down from Lutheran territory to the cisalpine regions. The 1566 Basel edition was apparently much easier for Italians to obtain and hence became widespread in the libraries of the Italian universities and religious orders. The evidence for this distribution has been preserved in an unexpected way: through the censorship of the book.

Early in the seventeenth century a brilliant but controversial physicist named Galileo Galilei began to argue that ultimate truth might be found not only in the Book of Scripture but in the Book of Nature—in other words, that cosmological theories might represent physical truth rather than mere hypotheses.

As a direct result of Galileo's polemics, Copernicus's *De revolutionibus* was in 1616 placed on the *Index of Prohibited Books* "until suitably corrected." Such was the sensitivity of the affair that for this book, and for this book only, the changes were exactly specified. The corrections, duly announced in 1620, have much in common with the recent rewriting of California high school biology textbooks. The Inquisition ordered a dozen statements that sounded too positive to be replaced by weaker sentences confirming that the cosmology was meant only as a hypothesis, not as a fact or a physical law. Of the thirty copies of the second edition now in Italian libraries, nearly 60 percent have been censored. The number includes Galileo's own copy, which has the offending text only lightly canceled but with the corrections written in his own hand. Perhaps he corrected the book while under house arrest to demonstrate his good behavior. On the other hand, of the first editions only 14 percent have been censored. The conclusion follows naturally that the majority of the first editions now in Italy came after 1700, when heliocentrism was no longer a burning issue. Circumstantial evidence suggests that the Rheticus-Aurifaber copy participated in this southern migration.

According to its catalogue, the Biblioteca Palatina in Parma should have a first edition, but when I visited that library a few years ago an assistant showed me an empty space on the shelf and through the fuzzy filter of the language barrier I understood that the copy couldn't be found. The empty slot suggested that the loss was recent, although in retrospect I realize that the shelves in question were laden with marvelously bound old books that would seldom, if ever, get moved. The catalogue seemed to say something about a manuscript note on the preface attributing it to Camerarius, and I mentally filed this away in case I should ever find such a copy in another collection.

Recently I asked the librarian at Parma to send me a copy of the catalogue description of the still-missing Copernicus, and then I promptly realized that the Latin did not say the *preface* was attributed to Camerarius but that a manuscript poem about the book by Camerarius was *prefixed* to the book. Precisely the description of the Rheticus copy! How the copy given by Rheticus to Aurifaber got to the Parma Palace Library was a mystery, but at least it would have been in keeping with the movement of first editions into

Italy after the seventeenth century.

I was rather curious about all this, so I arranged to have a closer look at the copy. One Saturday morning the present owner brought it around to my observatory office, and there, armed with an ultraviolet lamp, we thoroughly scrutinized the volume, searching for evidence of erased inscriptions or library stamps. The ultraviolet light revealed an early and now faded signature, illegible even under the probing of the short wavelengths. However, absolutely no physical evidence emerged for an earlier ownership by the Italian library—no missing end leaves, no telltale remnants of bookplate paste, no trace of the Parma shelf mark. Nevertheless the circumstantial evidence provided by the old catalogue description suggests that Parma had been its resting place for at least a century.

Whatever its previous homes, the present location of the Rheticus-Aurifaber copy is but another manifestation of the continual movement of rare books—a movement that puts books of English provenance into Poland, books of Polish provenance into Scotland, and books of Scottish provenance into England. This movement, although guaranteeing a built-in obsolescence for any census, at least has often the merit of making the books visible.

More troubling to any census maker is the thought of any number of copies sequestered in remote monasteries, in quiescent private collections, or even in major institutions. Recently I learned of a previously missed second edition at the University of Liverpool. When the curator of rare books there sent me its description, he remarked, "I assume you are only interested in this edition, as we also have two of the first." With that offhand comment, my census of the 1543 edition went from 243 to 245.

I am often asked how many copies were printed in the first place. Disappointingly little information survives concerning press runs in the fifteenth and sixteenth centuries. However, an interesting way to reconstruct empirically the original number of *De revolutionibus* copies goes as follows: Make a list of possible sixteenth-century owners, and then check how many of their copies have actually been found. Since about half of the expected ownerships have turned up, this method suggests that at least half of the entire first edition is now accounted for. Hence, a printing of four hundred to five hundred copies seems likely.

Because Copernicus's book was quickly recognized as a classic, few copies would have been thrown away, and since it was formidably technical, not many copies would have worn out from overuse. But how do books disappear? In principle by fire and flood, but apart from those lost in modern warfare, cases are hard to document. Pirates threw at least one Copernicus into the Mediterranean because they were so outraged that the cargo they had just captured consisted of nothing but books. And it is quite possible that a few copies went up in smoke in the Great Fire of London, although specific evidence is still lacking.

For better or for worse, I am reconciled to producing an incomplete census, and I know that clever book dealers will keep turning up unrecorded copies. But there remains a bittersweet comfort: the Great Copernicus Chase will go on!

SCENE 3

January ten, sixteen ten:
Galileo Galilei abolishes heaven.

Galileo's study at Padua. It is night. GALILEO *and* SAGREDO *at a telescope.*

SAGREDO (*softly*): The edge of the crescent is jagged. All along the dark part, near the shiny crescent, bright particles of light keep coming up, one after the other, and growing larger and merging with the bright crescent.

GALILEO: How do you explain those spots of light?

SAGREDO: It can't be true . . .

GALILEO: It *is* true: they are high mountains.

SAGREDO: On a star?

GALILEO: Yes. The shining particles are mountain peaks catching the first rays of the rising sun while the slopes of the mountains are still dark, and what you see is the sunlight moving down from the peaks into the valleys.

SAGREDO: But this gives the lie to all the astronomy that's been taught for the last two thousand years.

GALILEO: Yes. What you are seeing now has been seen by no other man besides myself.

SAGREDO: But the moon can't be an earth with mountains and valleys like our own any more than the earth can be a star.

GALILEO: The moon *is* an earth with mountains and valleys, and the earth *is* a star. As the moon appears to us, so we appear to the moon. From the moon, the earth looks something like a crescent, sometimes like a half globe, sometimes a full globe, and sometimes it is not visible at all.

SAGREDO: Galileo, this is frightening.

An urgent knocking on the door.

GALILEO: I've discovered something else, something even more astonishing.

More knocking. GALILEO *opens the door and the* CURATOR *comes in.*

CURATOR: There it is—your "miraculous optical tube." Do you know that this invention he so picturesquely termed "the fruit of seventeen years' research" will be on sale tomorrow for two scudi apiece at every street corner in Venice? A shipload of them has just arrived from Holland.

SAGREDO: Oh, dear!

GALILEO *turns his back and adjusts the telescope.*

CURATOR: When I think of the poor gentlemen of the Senate who believed they were getting an invention they could monopolize for their own profit. . . . Why, when they took their first look through the glass, it was only by the merest chance that they didn't see a peddler, seven times enlarged, selling tubes exactly like it at the corner of the street.

SAGREDO: Mr. Priuli, with the help of this instrument, Mr. Galilei has made discoveries that will revolutionize our concept of the universe.

CURATOR: Mr. Galilei provided the city with a first-rate water pump and the irrigation works he designed function splendidly. How was I to expect this?

GALILEO (*still at the telescope*): Not so fast, Priuli. I may be on the track of a very large gadget. Certain of the stars appear to have regular movements. If there were a clock in the sky, it could be seen from anywhere. That might be useful for your shipowners.

CURATOR: I won't listen to you. I listened to you before, and as a reward for my friendship you have made me the laughingstock of the town. You can laugh—you got your money. But let me tell you this: you've destroyed my faith in a lot of things, Mr. Galilei. I'm disgusted with the world. That's all I have to say. (*He storms out.*)

GALILEO (*embarrassed*): Businessmen bore me, they suffer so. Did you see the frightened look in his eyes when he caught sight of a world not created solely for the purpose of doing business?

SAGREDO: Did you know that telescopes had been made in Holland?

GALILEO: I'd heard about it. But the one I made for the Senators was twice as good as any Dutchman's. Besides, I needed the money. How can I work, with the tax collector on the doorstep? And my poor daughter will never acquire a husband unless she has a dowry, she's not too bright. And I like to buy books—all kinds of books. Why not? And what about my appetite? I don't think well unless I eat well. Can I help it if I get my best ideas over a good meal and a bottle of wine? They don't pay me as much as they pay the butcher's boy. If only I could have five years to do nothing but research! Come on. I am going to show you something else.

SAGREDO: I don't know that I want to look again.

GALILEO: This is one of the brighter nebulae of the Milky Way. What do you see?

SAGREDO: But it's made up of stars—countless stars.

GALILEO: Countless worlds.

SAGREDO (*hesitating*): What about the theory that the earth revolves round the sun? Have you run across anything about that?

GALILEO: No. But I noticed something on Tuesday that might prove a step towards even that. Where's Jupiter? There are four lesser stars near Jupiter. I happened on them on Monday but didn't take any particular note of their position. On Tuesday I looked again. I could have sworn they had moved. They have changed again. Tell me what you see.

SAGREDO: I only see three.

GALILEO: Where's the fourth? Let's get the charts and settle down to work.

They work and the lights dim. The lights go up again. It is near dawn.

GALILEO: The only place the fourth can be is round at the back of the larger star where we cannot see it. This means there are small stars revolving around a big star. Where are the crystal shells now, that the stars are supposed to be fixed to?

SAGREDO: Jupiter can't be attached to anything: there are other stars revolving round it.

GALILEO: There is no support in the heavens. (SAGREDO *laughs awkwardly.*) Don't stand there looking at me as if it weren't true.

SAGREDO: I suppose it is true. I'm afraid.

GALILEO: Why?

SAGREDO: What do you think is going to happen to you for saying that there is another sun around which other earths revolve? And that there are only stars and no difference between earth and heaven? Where is God then?

GALILEO: What do you mean?

SAGREDO: God? Where is God?

GALILEO (*angrily*): Not there! Any more than He'd be here—if creatures from the moon came down to look for Him!

SAGREDO: Then where is He?

GALILEO: I'm not a theologian: I'm a mathematician.

SAGREDO: You are a human being! (*Almost shouting:*) Where is God in your system of the universe?

GALILEO: Within ourselves. Or—nowhere.

SAGREDO: Ten years ago a man was burned at the stake for saying that.

GALILEO: Giordano Bruno was an idiot: he spoke too soon. He would never have been condemned if he could have backed up what he said with proof.

SAGREDO (*incredulously*): Do you really believe proof will make any difference?

GALILEO: I believe in the human race. The only people that can't be reasoned with are the dead. Human beings are intelligent.

SAGREDO: Intelligent—or merely shrewd?

GALILEO: I know they call a donkey a horse when they want to sell it, and a horse a donkey when they want to buy it. But is that the whole story? Aren't they susceptible to truth as well? (*He fishes a small pebble out of his pocket.*) If anybody were to drop a stone—(*drops the pebble*)—and tell them that it didn't fall, do you think they would keep quiet? The evidence of your own eyes is a very seductive thing. Sooner or later everybody must succumb to it.

SAGREDO: Galileo, I am helpless when you talk.

A church bell has been ringing for some time, calling people to mass. Enter VIRGINIA, *muffled up for mass, carrying a candle, protected from the wind by a globe.*

VIRGINIA: Oh, father, you promised to go to bed tonight, and it's five o'clock again.

GALILEO: Why are you up at this hour?

VIRGINIA: I'm going to mass with Mrs. Sarti. Ludovico is going too. How was the night, father?

GALILEO: Bright.

VIRGINIA: What did you find through the tube?

GALILEO: Only some little specks by the side of a star. I must draw attention to them somehow. I think I'll name them after the Prince of Florence. Why not call them the Medicean planets? By the way, we may move to Florence. I've written to His Highness, asking if he can use me as Court Mathematician.

VIRGINIA: Oh, father, we'll be at the court!

SAGREDO (*amazed*): Galileo!

GALILEO: My dear Sagredo, I must have leisure. My only worry is that His Highness after all may not take me. I'm not accustomed to writing formal letters to great personages. Here, do you think this is the right sort of thing?

SAGREDO (*reads*): "Whose sole desire is to reside in Your Highness' presence—the rising sun of our great age." Cosimo de' Medici is a boy of nine.

GALILEO: The only way a man like me can land a good job is by crawling on his stomach. Your father, my dear, is going to take his share of the pleasures of life in exchange for all his hard work, and about time too. I have no patience, Sagredo, with a man who doesn't use his brains to fill his belly. Run along to mass now.

VIRGINIA *goes.*

SAGREDO: Galileo, do not go to Florence.

GALILEO: Why not?

SAGREDO: The monks are in power there.

GALILEO: Going to mass is a small price to pay for a full belly. And there are many famous scholars at the court of Florence.

SAGREDO: Court monkeys.

GALILEO: I shall enjoy taking them by the scruff of the neck and making them look through the telescope.

SAGREDO: Galileo, you are traveling the road to disaster. You are suspicious and skeptical in science, but in politics you are as naïve as your daughter! How can people in power leave a man at large who tells the truth, even if it be the truth about the distant stars? Can you see the Pope scribbling a note in his diary: "Tenth of January, 1610, Heaven abolished"? A moment ago, when you were at the telescope, I saw you tied to the stake, and when you said you believed in proof, I smelt burning flesh!

GALILEO: I am going to Florence.

Before the next scene, a curtain with the following legend on it is lowered:

> BY SETTING THE NAME OF MEDICI IN THE SKY, I AM BESTOWING IMMORTALITY UPON THE STARS. I COMMEND MYSELF TO YOU AS YOUR MOST FAITHFUL AND DEVOTED SERVANT, WHOSE SOLE DESIRE IS TO RESIDE IN YOUR HIGHNESS' PRESENCE, THE RISING SUN OF OUR GREAT AGE.
>
> —GALILEO GALILEI