Renaissance Astronomy

Isaac Newton, who discovered the Law of Gravity, once wrote, “If I have seen further, it is because I stood on the shoulders of giants.” This quote has a history several hundred years older than Newton's use of it. But which giants was he referring to? Copernicus, Tycho, Kepler, and Galileo.

Copernicus's book *On the Revolutions of the Heavenly Spheres* (1543) clearly stated that it was not just a hypothesis that the Earth was in motion and revolved about the Sun. While the planets preferentially moved west to east against the background of stars, each had a characteristic period when the motion was east to west. Copernicus reordered the planets from the fastest (Mercury) to the slowest (Saturn) and placed the Sun at the center of the solar system. The retrograde motion was easily explained by this reordering. The Earth was "demoted" from the center of the world. It was just one of the planets.

But what proof did Copernicus have that the Earth was actually in motion?

None, really!

There were no telescopes. The accuracy of positional measurements was about 10 to 15 arc minutes.

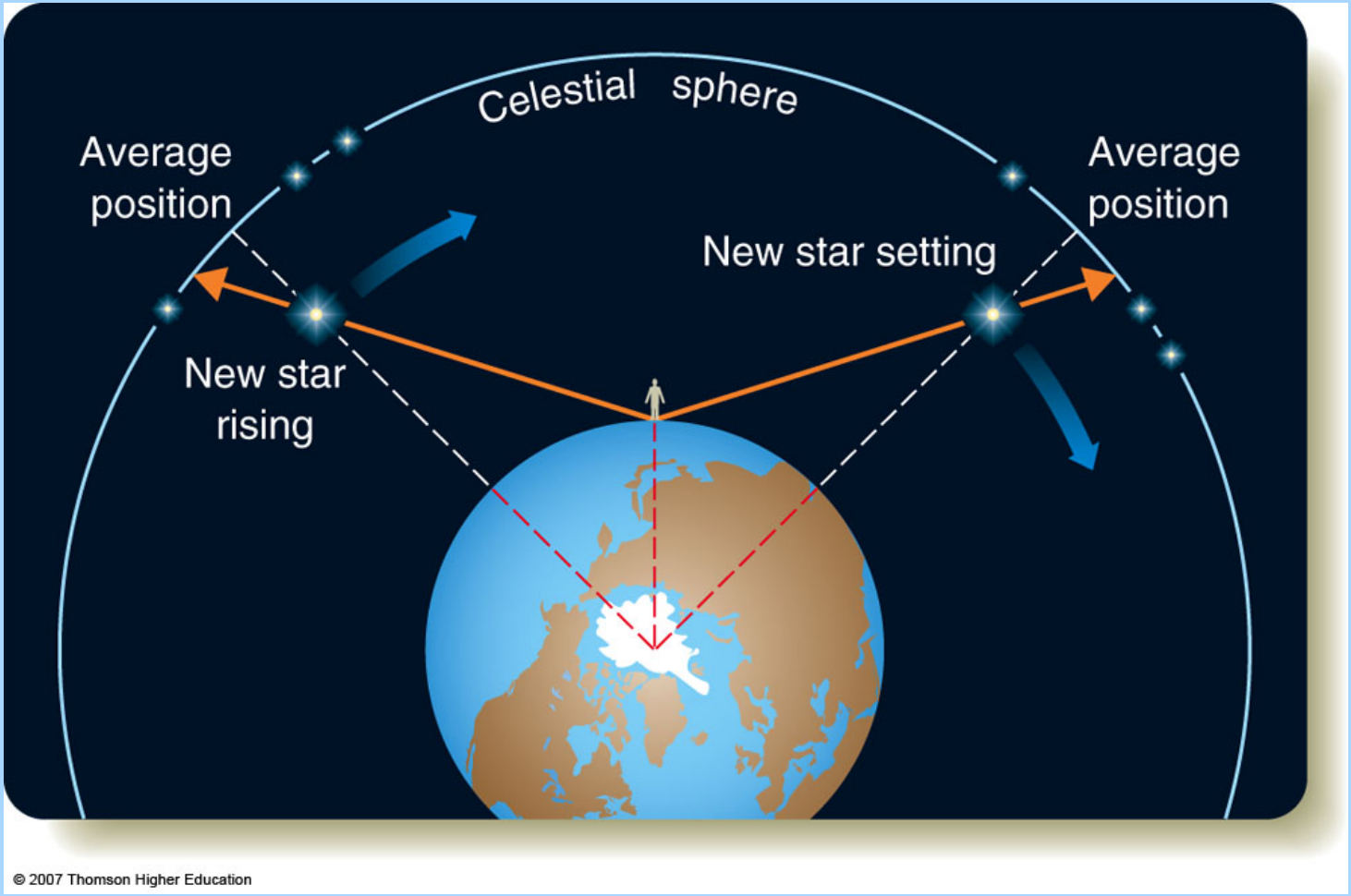
The stars did not show annual parallaxes, which they should, if the Earth were in motion.

We don't feel like we're moving.

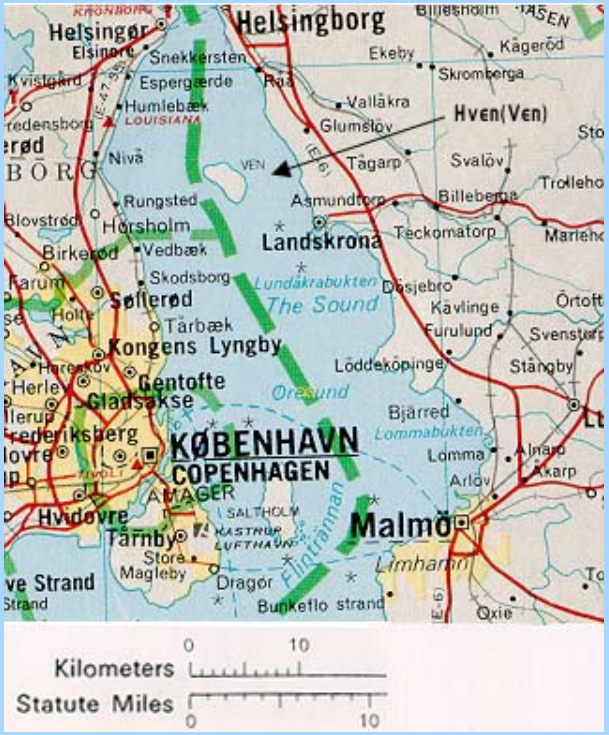
Tycho Brahe (1546-1601)

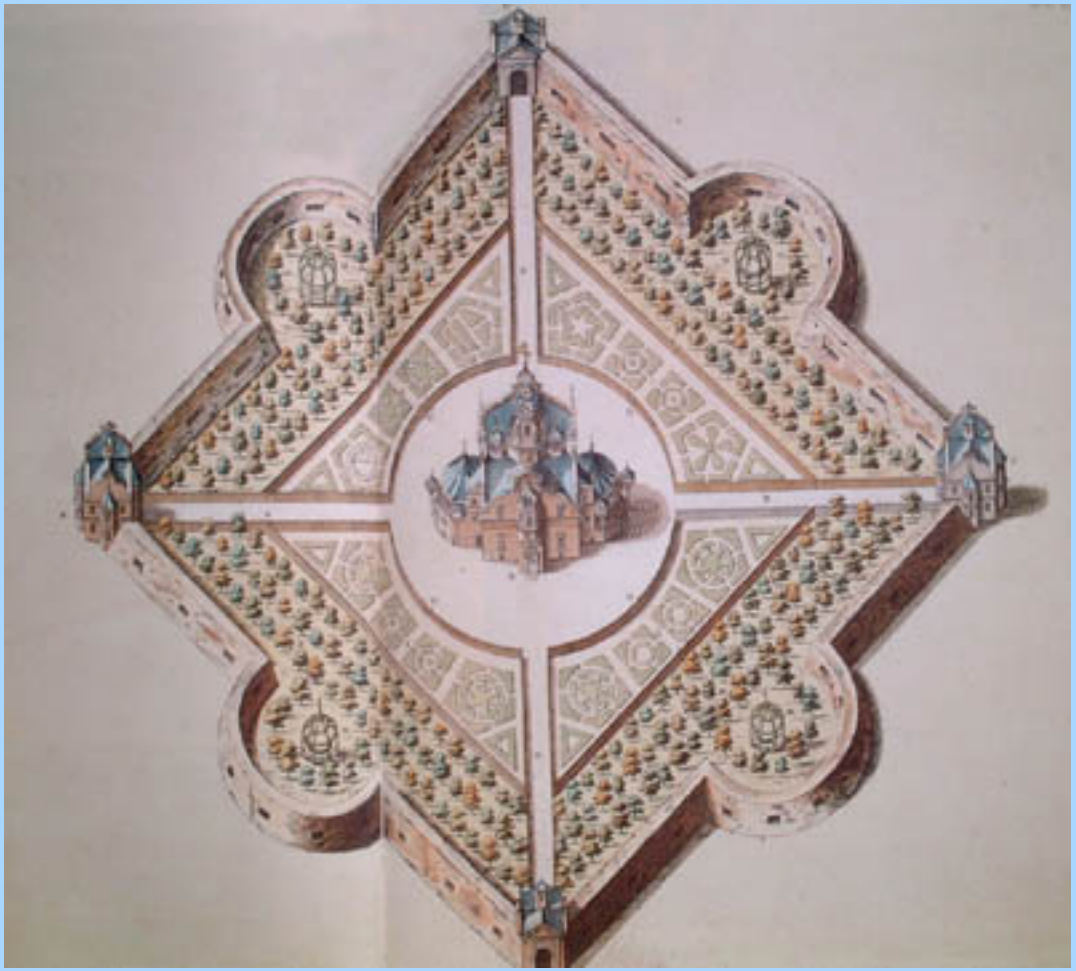
In 1572 a new star appeared in the constellation Cassiopeia. According to the ancients, the celestial realms were "perfect". The stars should not move in position, and stars should not suddenly pop into view. Was this object as far away as the stars?

If the object were between the Earth and the Moon, then its position against the background stars should shift as the object rose, reached the meridian, and set in the west. Tycho's observations showed that the new object was *not* nearby. Changes do happen in the starry realm.



Hven (Tycho's island)



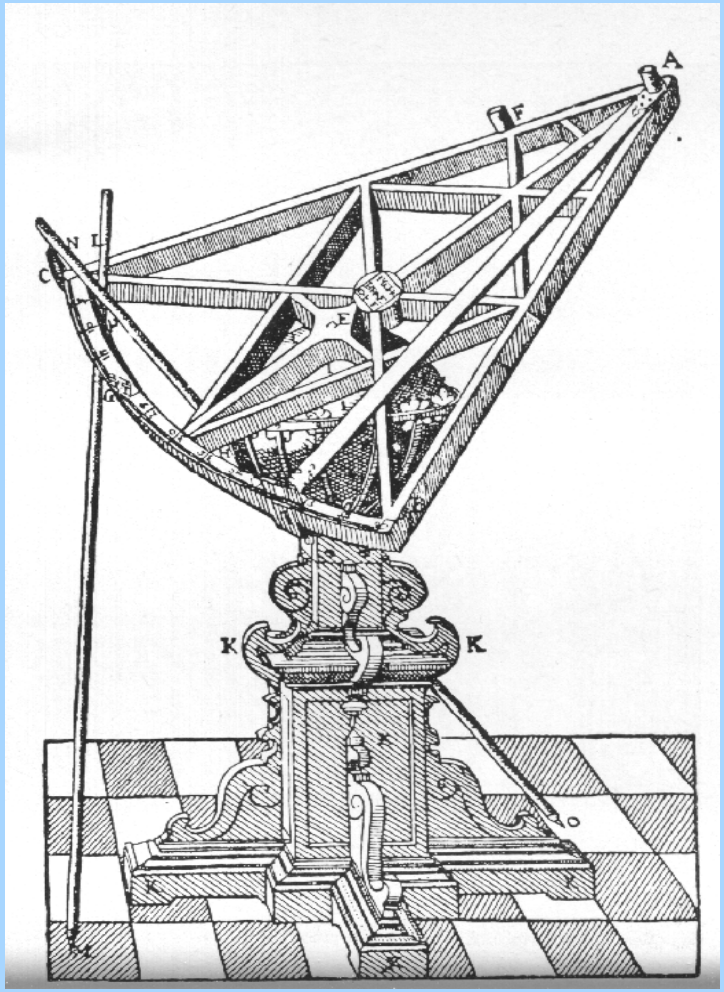


Uraniborg -

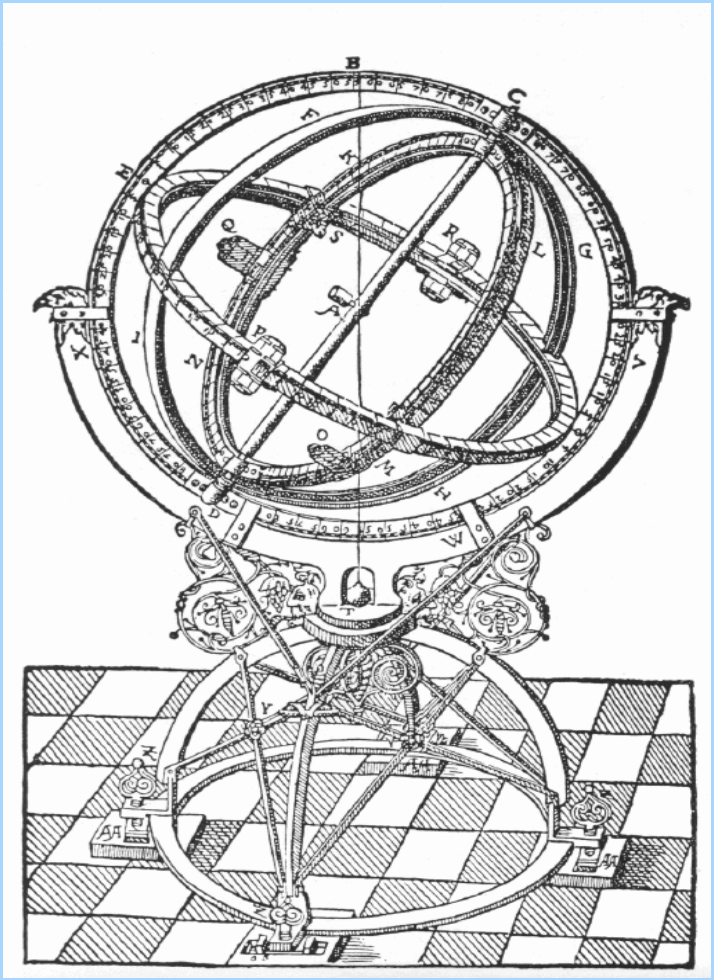
castle of the heavens

This observatory cost the equivalent of $5 billion in modern currency!

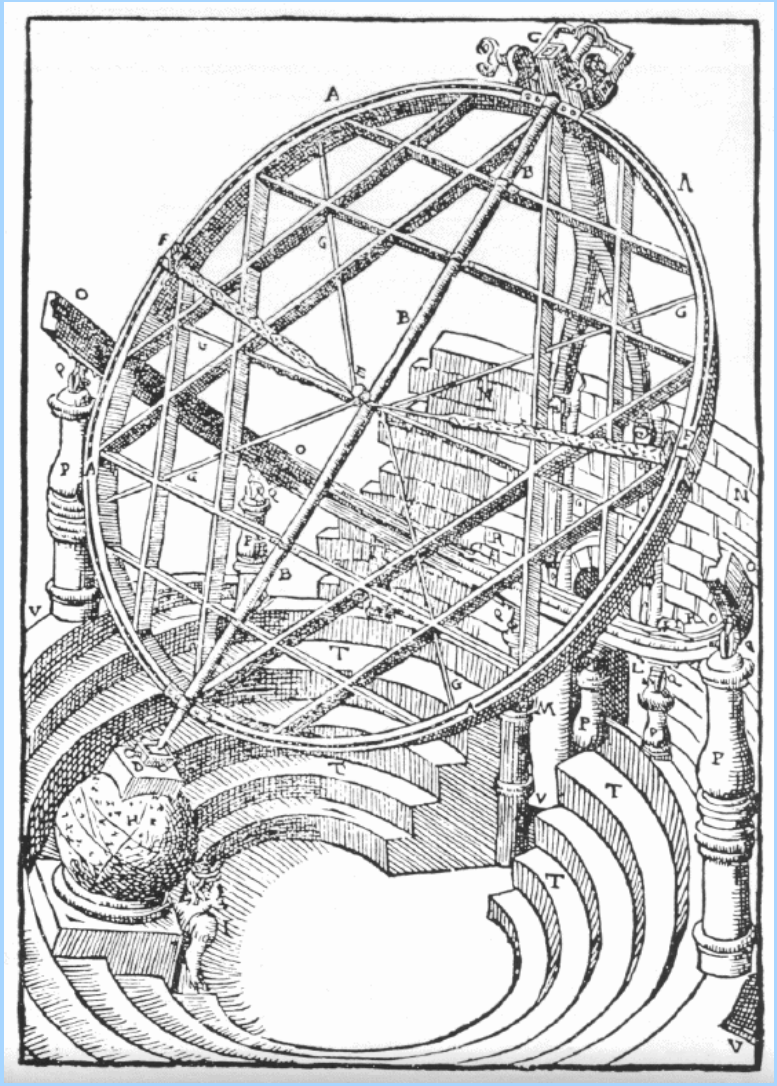
After a while they ran out of space and had to build an auxiliary observing location. Note the observatory “domes”.



sextant



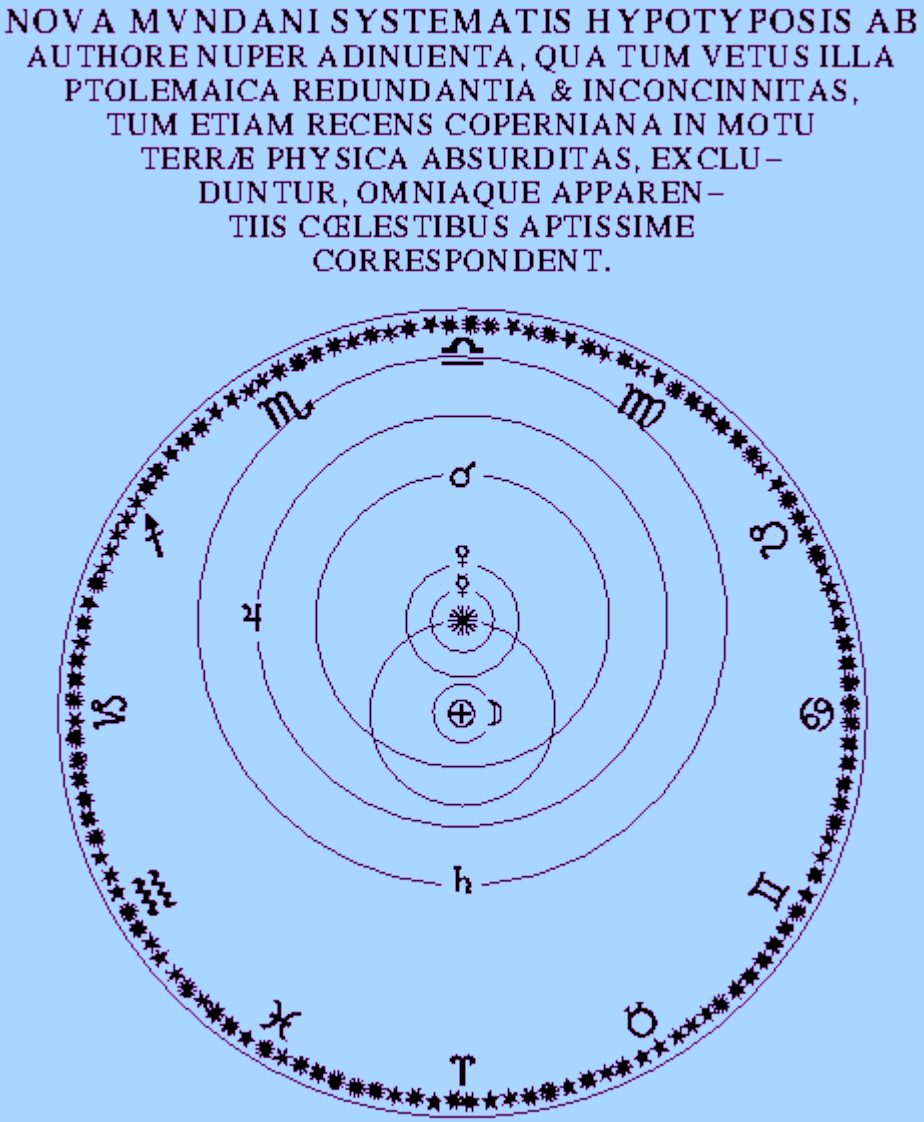
armillary sphere



large equatorial armillary

Tycho and the large mural quadrant, capable of positional measures to 1 arc minute

The accuracy of Tycho's best positional measurements was +/- 1 arc minute. This was an improvement of a factor of 10 over previous observations. If the stars were closer than 3438 Astronomical Units, Tycho should have been able to measure their trigonometric parallaxes. But he found no parallax for the stars. He then had to make one of two conclusions: 1) the stars were many thousands or even millions of AU away; or 2) the Earth was immobile and did not orbit the Sun. He chose the latter.

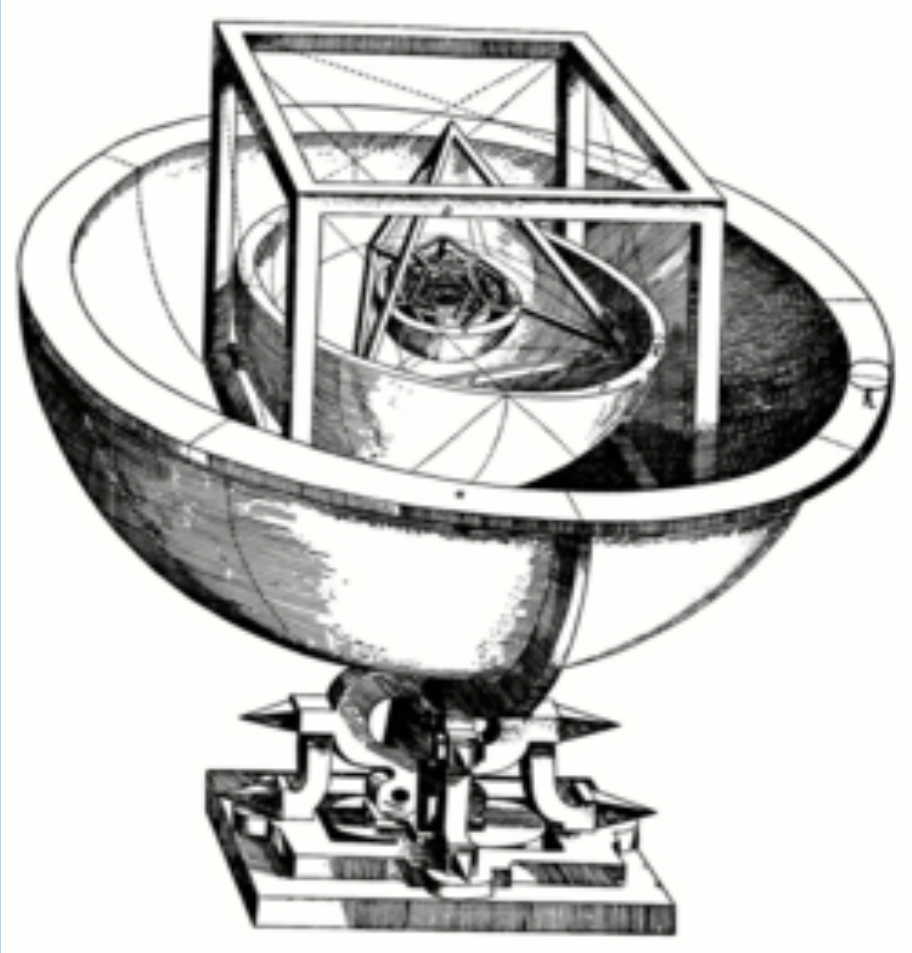


Tycho's arrangement of the solar system. The Earth is immobile. The other planets orbit the Sun, which orbits the Earth.

Tycho and his assistants produced a catalogue of 777 stars. Due to advancements in instrumentation and observing methods, their stellar positions were roughly 10 times better than the previous catalogues of Ulugh Beg and Ptolemy. Their observations of the position of Mars opened the door for a major breakthrough in the understanding of planetary motions.

Tycho's motto was: "*Nec fasces, nec opes, sola artis sceptra perennant.*" (Neither wealth, nor power, but only knowledge, alone, endures.)

Johannes Kepler (1571-1630) was Tycho's principal assistant once Tycho moved from Denmark to Prague.



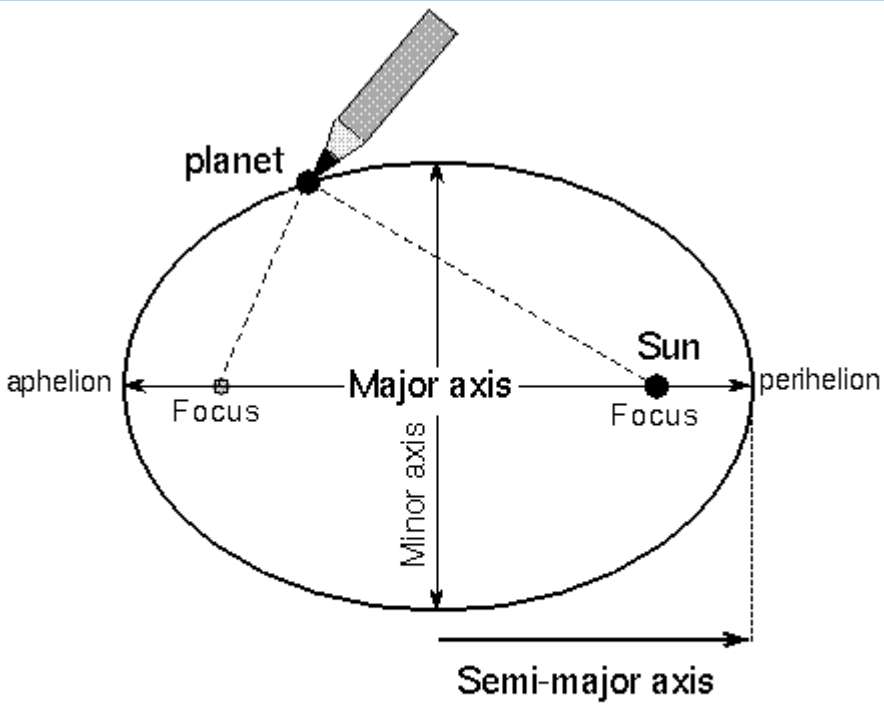
In 1595 Kepler tried to account for the different sizes of the orbits of the planets, using nested spheres and regular geometric solids. But it didn't quite work.

Once he started working on the orbit of Mars, Kepler realized that its orbit could not be circular. He next tried an egg-shaped (ovoid) curve. That worked better, but the data were best fit by an ellipse. He discovered three laws of planetary motion.

1) the orbit of a planet is an ellipse, with the Sun at one focus

2) a line from a planet to the Sun sweeps out equal areas in equal times

3) a planet's orbital period squared is proportional to its orbit size cubed

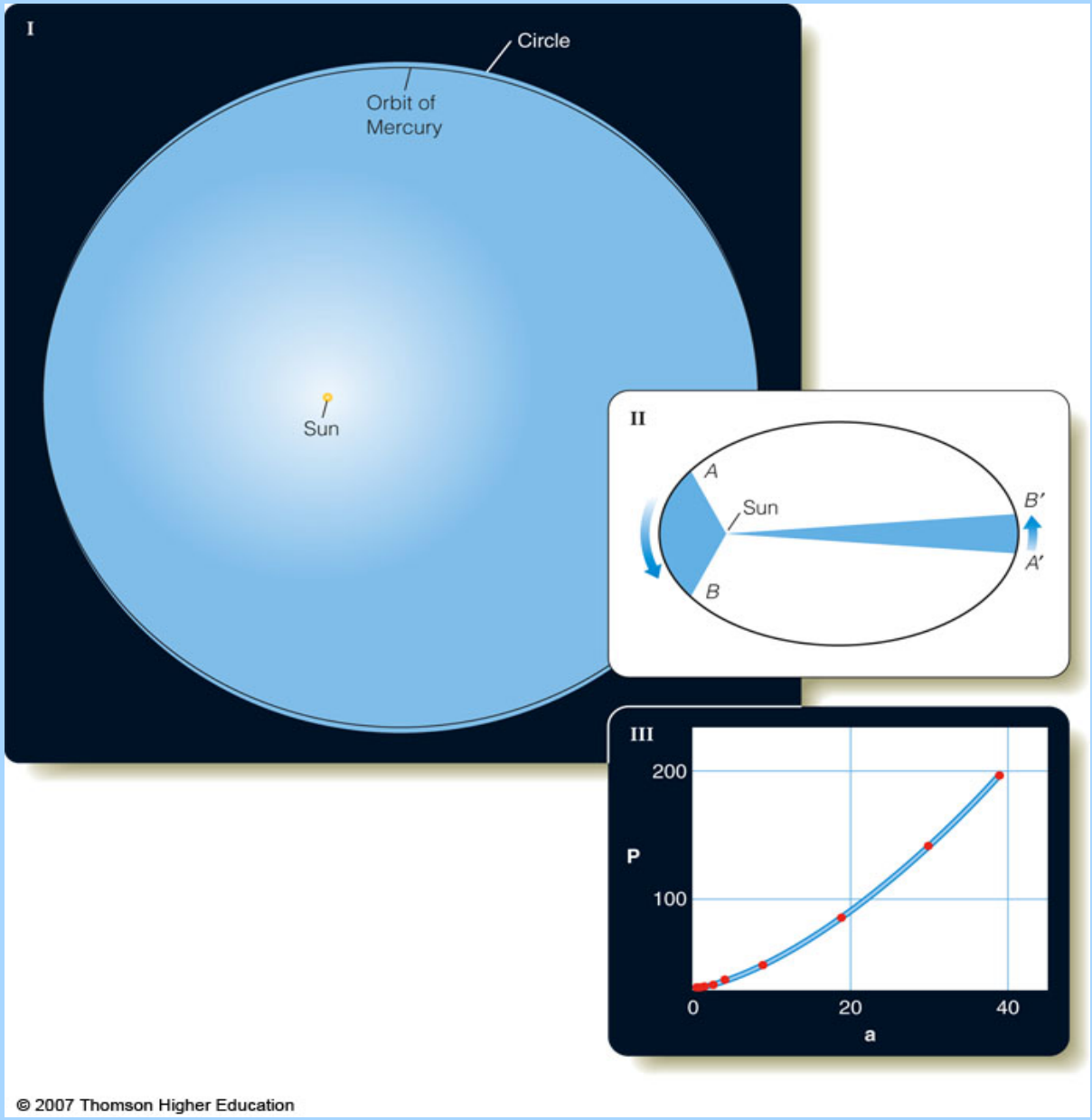


Drawing an **ellipse**: loop string around thumb tacks at each **focus** and stretch string tight with a pencil while moving the pencil around the tacks. The Sun is at one focus.

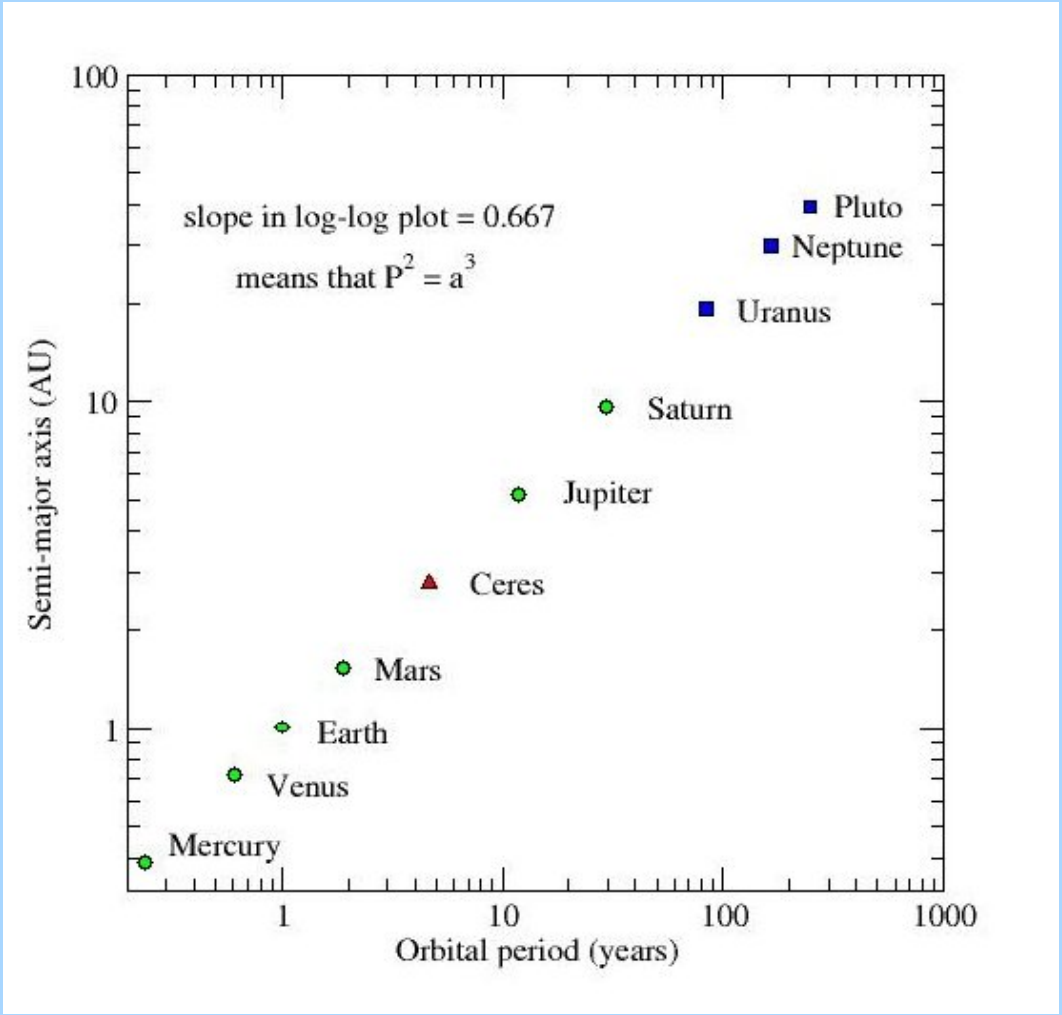
Kepler's First Law: each planet has an elliptical orbit, with the Sun at one focus of the ellipse

Here we have not carried a full orbital determination for Mars, which involves ***simultaneously*** solving for the semi-major axis size (a = 1.523 AU), the eccentricity (0.093), the inclination of the orbit to the ecliptic plane, the time of perihelion, and two other parameters. Here we have only shown that by using a correctly ***eccentric*** orbit of the right eccentricity and size, with perihelion occurring on October 24, 2016, we can accurately fit the observed ecliptic longitudes. One other simplification we made was to assume that the Earth's orbit is perfectly circular. It's not.

The orbital model can be used to ***predict*** future positions of Mars. Comparing data yet-to-be-obtained to a model is the essence of the scientific method.



Kepler's
Second and
Third Laws



If $P^2 = a^3$, then
$2 \log P = 3 \log a$.

We get a straight line if we plot log a vs. log P or log P vs. log a.

Kepler knew about Mercury, Venus, Earth, Mars, Jupiter, and Saturn, but not know Ceres, Uranus, Neptune, or Pluto.

If we measure the orbital period *(P)* of a planet in years and the orbit size *(a)* in astronomical units (AU), Kepler's Third Law can be stated as:

$$(P_{yr})^2 = (a_{AU})^3$$

For example, for Jupiter's orbit $a = 5.20$ AU. That cubed is 140.6. The square root of that is 11.8, which is the period of Jupiter's orbit in Earth years.

(Technically, the "orbit size" *a* is half the length of the major axis of the ellipse, the "semi-major axis".)

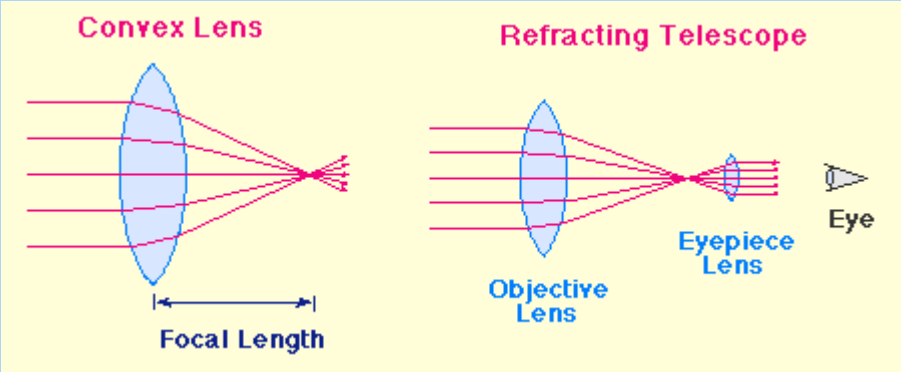
In 1627 Kepler published the *Rudolphine Tables,* which were tables of motion of the Moon and planets, based on his analysis of Tycho's observations. In this engraving from the frontispiece, he shows Hipparchus, Ptolemy, Copernicus, and Tycho.

Why were there no telescopes prior to 1600?

Consider the following passage, from the *Opus Majus* of Roger Bacon (1267): "Greater things than these may be performed by refracted vision. For it is is easy to understand by the canons above mentioned that the greatest things may appear exceeding small, and the contrary. For we can give such figures to transparent bodies, and dispose them in such order with respect to the eye and the objects, that the rays shall be refracted and bent towards any place we please; so that we shall see the object near at hand, or at a distance under any

angle we please. And thus from an incredible distance we may read the smallest letters, and may number the smallest particles of dust and sand, by reason of the greatness of the angle under which we may see them; and on the contrary, we may not be able to see the greatest bodies close to us, by reason of the smallness of the angle under which they may appear; for distance does not affect this kind of vision except by accident, but the magnitude of the angle does so. And thus a *boy may appear to be a giant, and a man as big as a mountain...Thus also, the sun, moon, and stars may be made to descend hither in appearance...*"

Even though reading glasses were known in the 13th century, apparently no one actually turned a spyglass to the heavens prior to Galileo in January of 1610. He had heard that such a device had been invented in Holland a couple years prior. So he learned the basics of lens making and produced his own telescopes.



1475-1564 Michelangelo

1564-1642 Galileo

1642-1727 Isaac Newton

Galileo

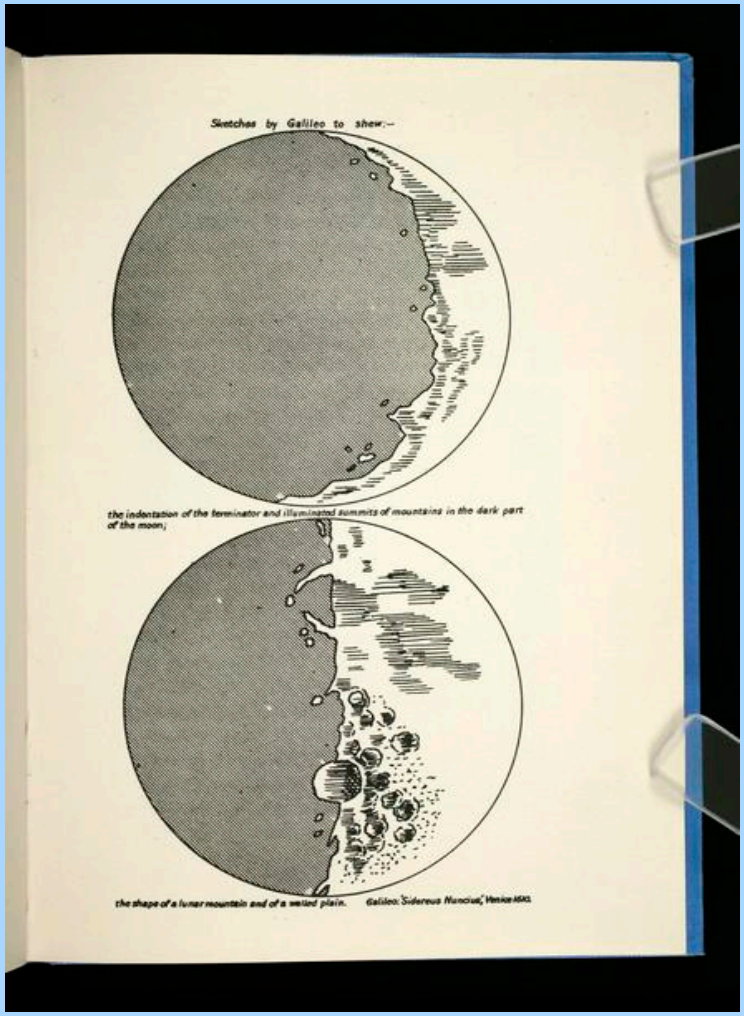
"Philosophy is written in this grand book, the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letters in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles and other geometric figures...Without these one wanders about in a dark labyrinth."

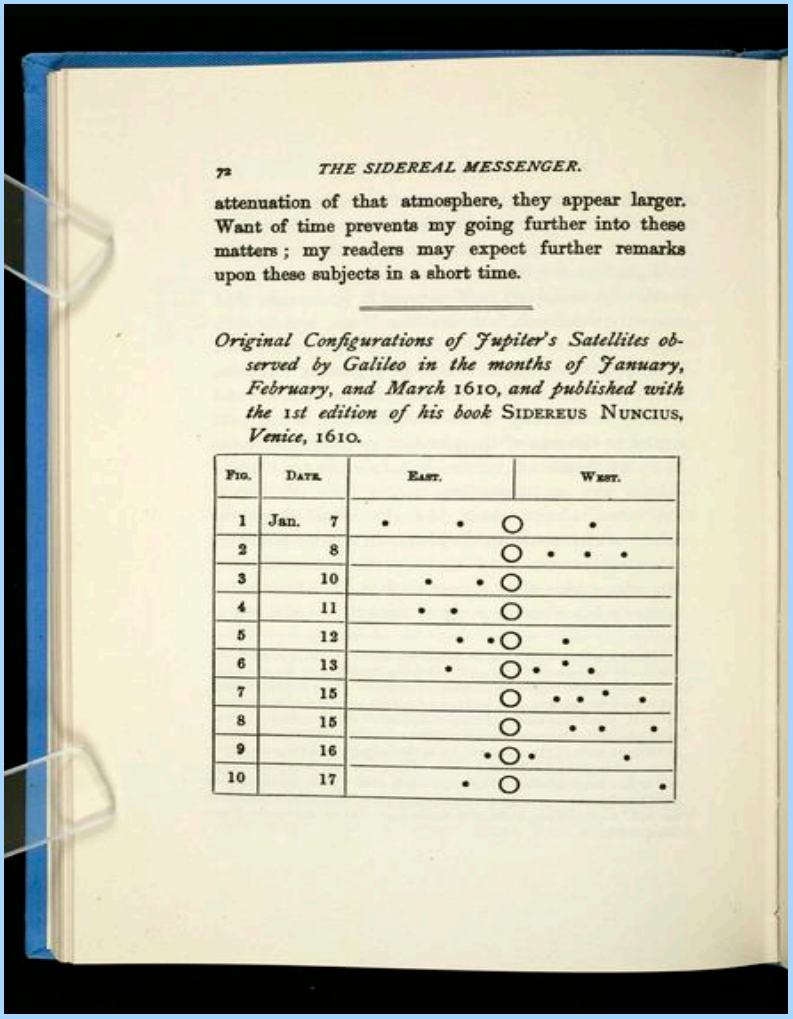
- Galileo (*The Assayer*, 1618)

When Galileo turned his newly made refracting telescopes to the night skies he discovered that he could see fainter stars than with his unaided eye. The band of the Milky Way was made of faint stars, never before seen by humans.

He discovered that the Moon had mountains, like the Earth. Contrary to ancient Greek notions, the Moon was not perfectly smooth.

He discovered four moons that revolved around Jupiter. Here was proof that not all objects had to revolve around the Earth. He named them the "Medicean stars" and got himself appointed court mathematician to the rulers of Florence.





attenuation of that atmosphere, they appear larger. Want of time prevents my going further into these matters; my readers may expect further remarks upon these subjects in a short time.

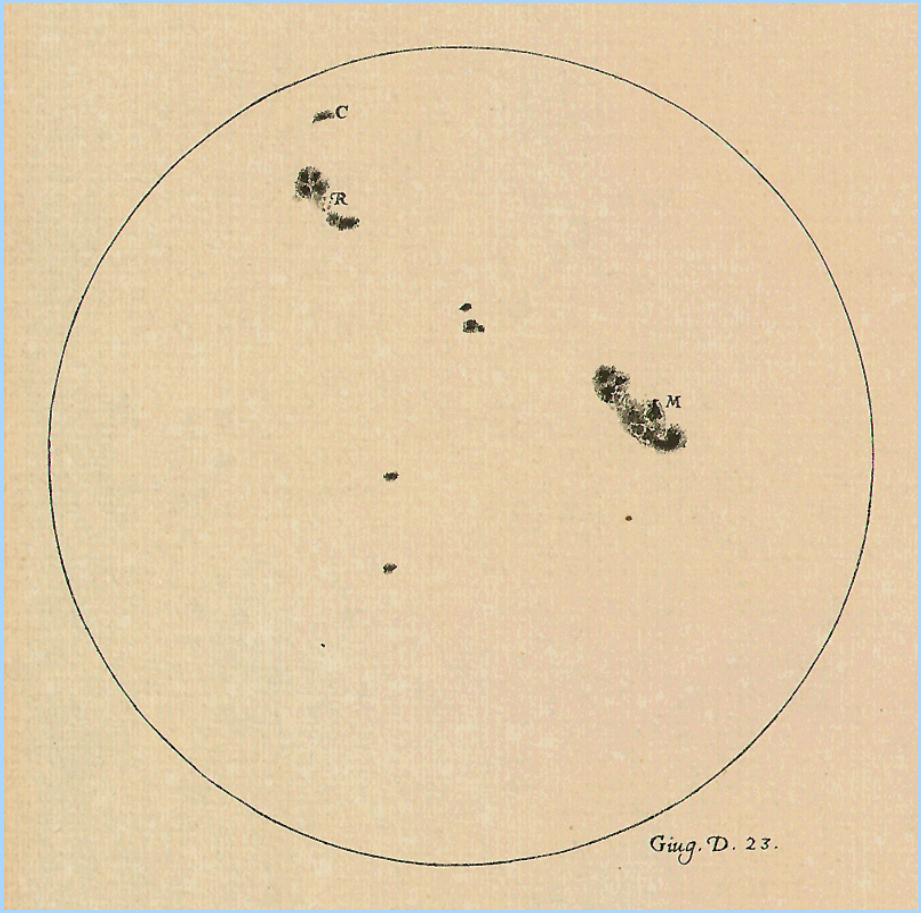
Original Configurations of Jupiter's Satellites observed by Galileo in the months of January, February, and March 1610, *and published with the 1st edition of his book* SIDEREUS NUNCIUS, *Venice*, 1610.

FIG.	DATE.	EAST.	WEST.
1	Jan. 7	• • ○ •	
2	8	○ • • •	
3	10	• • ○	
4	11	• • ○	
5	12	• • ○ •	
6	13	• ○ • • •	
7	15	○ • • • •	
8	15	○ • • •	
9	16	• ○ • •	
10	17	• ○ •	

Two pages from Galileo's best seller, the *Sidereal Messenger* (1610)

A couple years later he discovered that Venus exhibits all the phases of the Moon (i.e. crescent, quarter, gibbous, and full). A colleague had pointed out to him that Ptolemy's epicyclic theory would keep Venus between the Sun and Earth at all times, giving it a perpetual crescent shape. He interpreted the observation of the range of phases to Venus to be proof against Ptolemy's theory and in favor of the Copernican theory.

He also discovered that the Sun had spots. It was not a “perfect” sphere either.



Galileo was a publicity seeker, and while he impressed a lot of people, he rubbed a lot of other people the wrong way. He was fond of saying things like, "Of all hatreds, there is none greater than that of ignorance against knowledge."

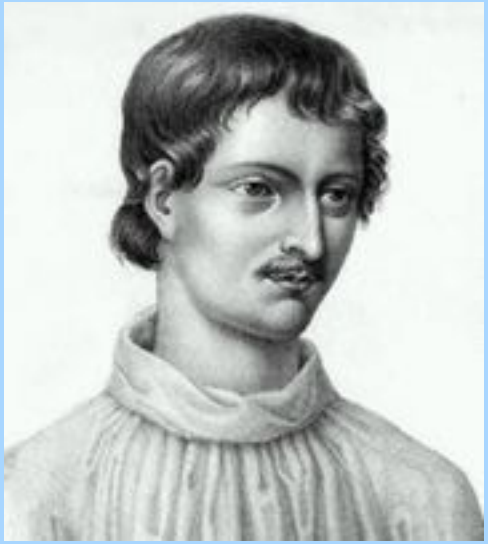
He was fond of quoting Cardinal Baronius, the librarian of the Vatican: "S*piritui Sancto mentem fuisse nos docere quomodo ad coelum eatur, non quomodo coelum gradiatur.*" (The Holy Spirit shows us how to go to Heaven, not how the heavens go.)

Galileo was summoned to Rome in 1616 and met with the leading Catholic theologian of the day, Cardinal Bellarmine.

Galileo was told that the Copernican hypothesis (that the Earth revolved about the Sun) was suspect. The Holy Congregation of the Index decided not to ban Copernicus's book. But, to use the book and stay in the Church's good graces, one had to censor certain passages.

Very few copies of *De Revolutionibus* outside of Italy were emended.

Expressing opinions contrary to the Church was serious business. In 1600 the philosopher Giordano Bruno was burned at the stake in Rome. He was accused of holding views counter to Catholic doctrine (e.g. on the Trinity, the Divinity of Jesus, and the Virginity of Mary). He also believed in metempsychosis and the plurality of worlds -- that there are many inhabited planets in the universe, some with intelligent beings like us.



In 1624 a new pope was elected. Cardinal Maffeo Barberini, a personal friend of Galileo's, and a liberal supporter of Galileo's prior scientific endeavors, became Pope Urban VIII.

Once again Galileo went to Rome, and he asked his friend the Pope for permission to write a book that objectively discussed the pros and cons of the Copernican theory. Eight years later Galileo finished writing the *Dialogue on the Two Chief Systems of the World.* It was published with minor revisions required by the censors of the Inquisition.

The *Dialogue* is a conversation amongst three characters, an advocate of Copernicanism, an advocate of the Ptolemaic theory, and a sceptic willing to listen objectively.

Unfortunately for Galileo, he named the advocate of the Earth-centered system Simplicio, and that character often said things very similar to the official Church position. Some of his enemies decided to take him on, and they discovered a document from 1616 which warned Galileo not to discuss Copernicanism *in any way whatsoever*. When Pope Urban VIII found out, he felt that Galileo had deceived him about the proceedings of 1616.

There is evidence that this key phrase was added some years after 1616 in order to set a trap for Galileo.

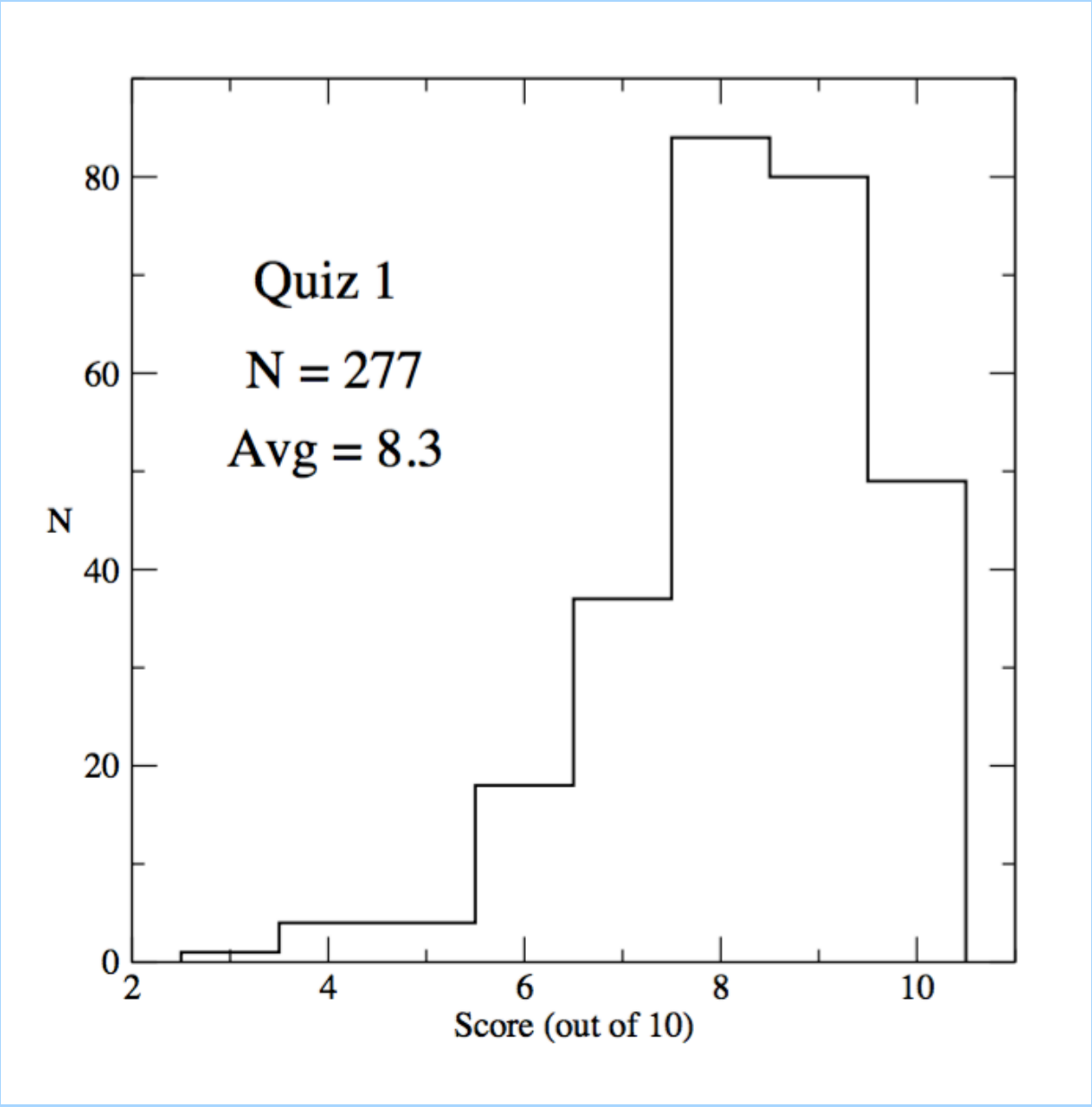
This is why Galileo was put on trial by the Inquisition in 1633. He was tried not so much for heresy as for disobeying orders.

In 1979 Pope John Paul II expressed the hope that a commission be constituted, under the authority of the Pontifical Academy of Sciences, to "study the Galileo case more deeply and, in frank recognition of wrongs from whatever side they come, dispel the mistrust that still opposes, in many minds, a fruitful concord between science and faith." The commission was constituted in 1981 and presented their report in 1992.

In the 1992 commission summary Cardinal Paul Poupard reviewed some of the facts. Galileo had failed to prove the revolution of the Earth around the Sun and its daily rotation about its axis. He thought he had found a proof in the tides, but he was mistaken in this.

In 1725 the Englishman James Bradley discovered the aberration of light, which was actually the first proof of the motion of the Earth.

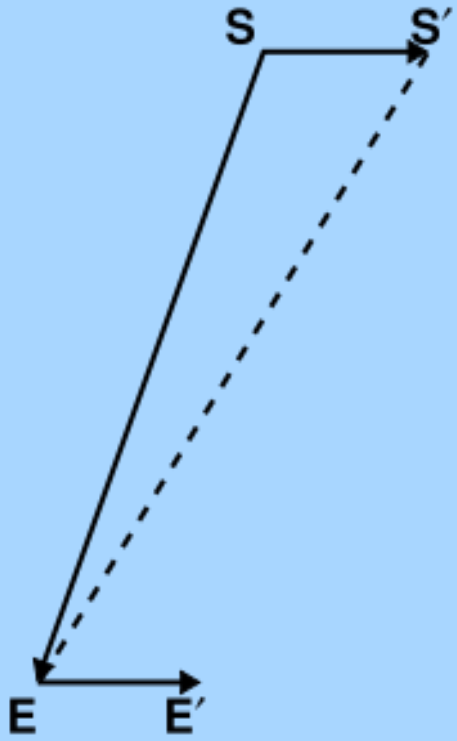
In the 1830's W. Struve, W. Bessell, and T. Henderson measured the first three stellar parallaxes. This was the first mechanical proof of the Earth's motion.


Quiz 1
N = 277
Avg = 8.3
N
0
20
40
60
80
2
4
6
8
10
Score (out of 10)

You should now have read chapters 1, 2, and 3 of *The Essential Cosmic Perspective*, and should start chapter 4.

Chapter 2 online HW was due today (9/9). Chapter 3 is due next Wednesday.

You should have read chapters 1, 7, 9, and 10 of *A Guide to Wider Horizons*, and should now read chapter 3 ("the energy budget").



The aberration of light. Because of the Earth's motion around the Sun, a star at position S appears to be sending us its light from location S'. The star position is shifted 20 arc seconds.

After the discovery of the optical proof of the Earth's motion (aberration), in 1741 the Vatican approved the publication of Galileo's complete works.

In 1757 books favoring heliocentric theory were removed from the Index of prohibited books.

In 1822 the Catholic Church agreed that works could be published that presented Copernican astronomy as a *thesis*, not just a mere hypothesis.

The 1992 report concludes: “...a re-reading of the archival documents shows once more that all those involved in the trial, without exception, have a right to the benefit of good faith, in the absence of extra-procedural documents showing the contrary. The philosophical and theological qualifications wrongly granted to the then new theories about the centrality of the sun and the movement of the earth were the result of a *transitional situation* in the field of astronomical knowledge, and of an exegetical *confusion* regarding cosmology. Certain theologians, Galileo's contemporaries, being heirs of a unitarian concept of the world universally accepted until the dawn of the 17th century, failed to grasp the profound, non-literal, meaning of the Scriptures when they describe

the physical structure of the created universe. This led them unduly to transpose a question of factual observation into the realm of faith.

It is in that historical and cultural framework, far removed from our own times, that Galileo's judges, incapable of dissociating faith from an age-old cosmology, believed, quite wrongly, that the adoption of the Copernican revolution, in fact not yet definitively proven, was such as to undermine Catholic tradition, and that it was their duty to forbid its being taught. This subjective error of judgment, so clear to us today, led them to a disciplinary measure from which Galileo 'had much to suffer.' These mistakes must be frankly recognized.”

Galileo was sentence in house arrest in 1633. Basically, he was grounded for the next 9 years. And then he died. But he did dictate one final book, which was published in Amsterdam.

We don't have anything to worry about regarding the Inquisition, right? Well, for 24 years under Pope John Paul II the head of the Congregation of the Doctrine of the Faith was Cardinal Joseph Ratzinger. He became Pope Benedict XVI. What used to be called the Inquisition is now called the Congregation of the Doctrine of the Faith!