How do you discover that you live in a Solar System?

- What is our solar system? What does it consist of?
  - Discussion of basic facts & geography. What d'ya know?

- How would you discover it? Determine its basic properties? Focus on key elementary (naked eye) observations.

  - Star patterns stay together --> constellations.

  - Stars move across the sky through the night (Earth rotates).

  - Stars change with the season, "constellation of the month" --> the Sun apparently drifts through the stars.

  - Moon moves through the stars with mo(o)nthly phases.

  - Planets = brightest stars (apparently!) = ancient wanderers
    - also move through the stars (with less regular seasons).
    - stay near the ecliptic, Zodiacal plane.
    - have very long term periodicities.

- Systematic observations and mapping of cycles needed before these things could be understood. To obtain these we need coordinate systems...

Modern (Copernican) Understanding of Motions on the Sky

• Most of the apparent motions of stars and galaxies across the sky are to the many motions of the Earth. These include:

	Periods
Rotation on axis:	23 hr. 56 min. (sidereal)24 hr. (synodic)
Revolution around Sun:	365.26 days
Precession and nutation:	26,000 yr., and 18.6 yr.

• The apparent motions of the planets and Moon include substantial contributions from their own motions.

• A small part of the apparent motion of the stars is also due to the Sun and star's relative motion through the galaxy (stellar proper motion).

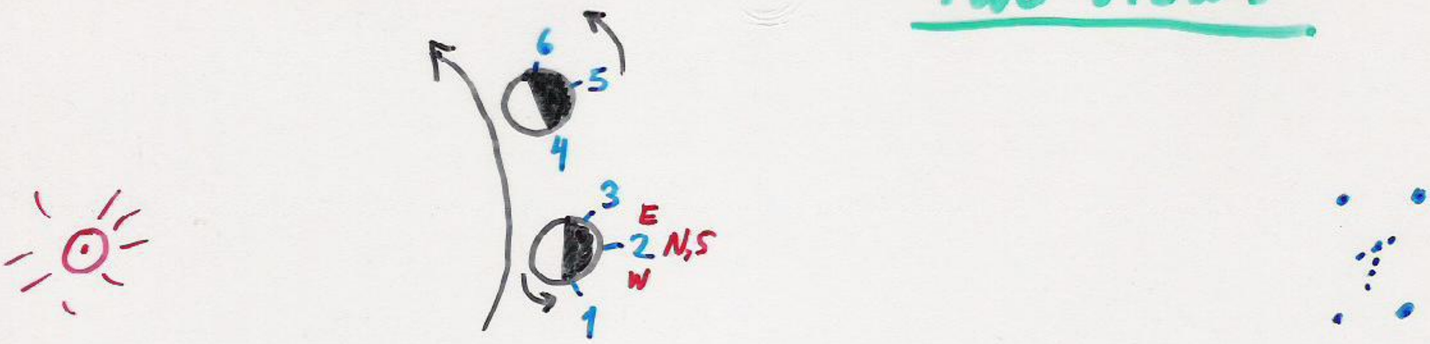
• Relative motions of the galaxies and the Milky Way on the sky are not directly observable (but stay tuned!).

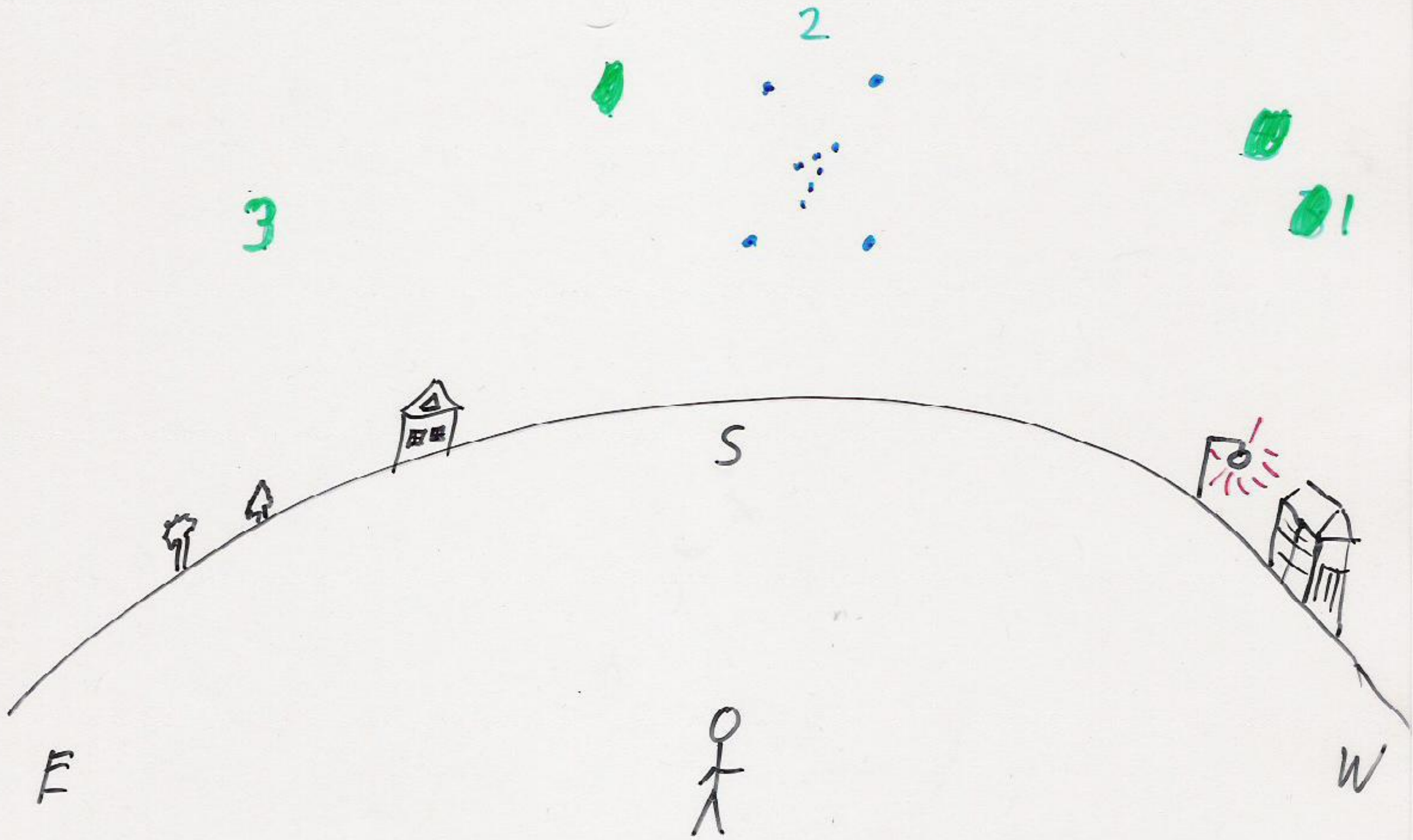
It is useful to keep 2 different points of view in mind:

1. The sky as viewed from an arbitrary point on Earth.
2. The view from a point above (north) the fundamental (ecliptic) plane of the solar system.

II 2a

Two Views





Coordinate Systems

Astronomers use 2 main systems.

The Horizon System:

Altitude – degrees (0 – 90°) above the horizon.

Azimuth – degrees (0 – 360°) around the horizon from the north point.

This coordinate system serves to answer the question – where is a particular star, planet or other object at one moment, at one location.

See picture.

Examples:

	Altitude	Azimuth
Zenith	90°	-
South Point	0°	180°
Polaris	Latitude	0°

These coordinates serve to answer the question – where is that star, planet, etc.? – at one moment, at one location.

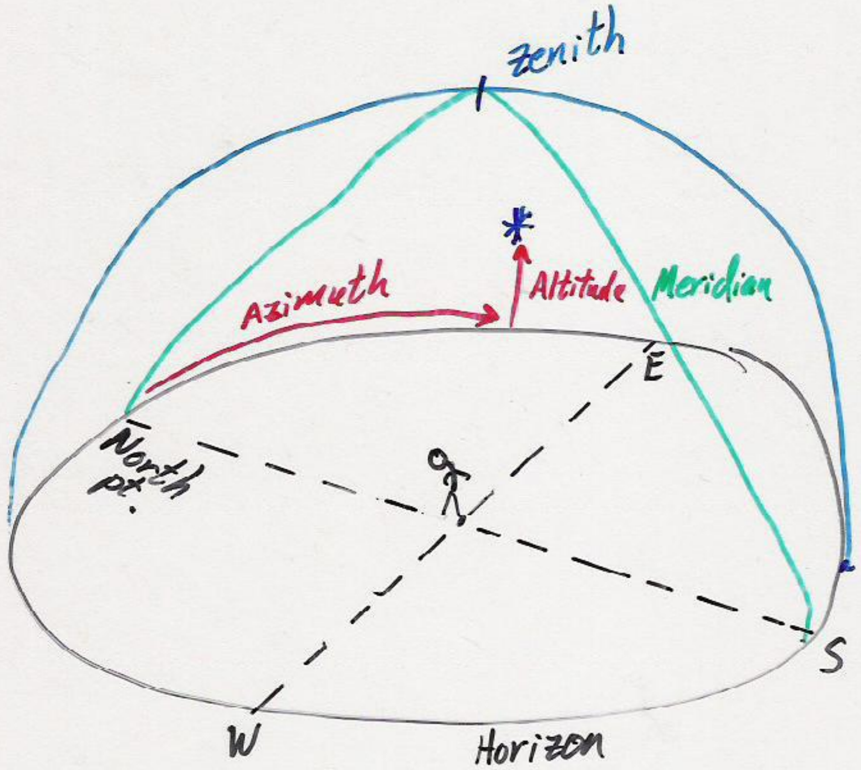


Fig. 2-2, SJ

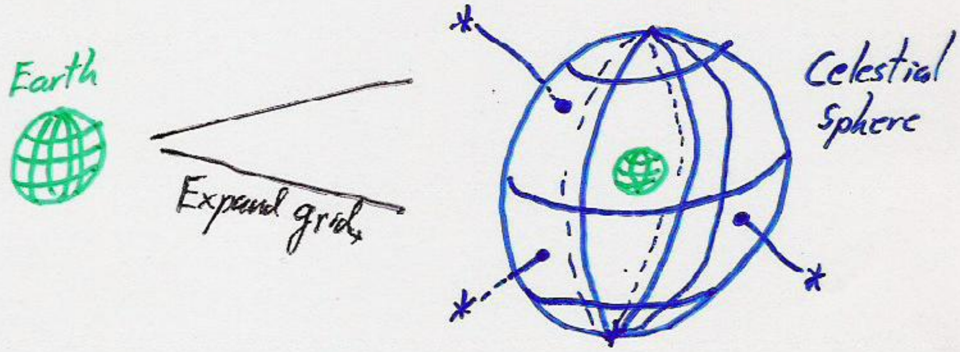
Examples:

	Alt.	Az.
Zenith	90°	–
South point	0°	180°
Polaris	Latitude	0°

Celestial Equatorial System:

A generalization of the longitude-latitude system. Except, the coordinate grid is not fixed to the rotating Earth; it's fixed on the celestial sphere.

See picture.



Some terms:

Vernal Equinox ♈ – origin of the coordinate system. Defined as the point where the ecliptic crosses the celestial equator with the Sun moving northward (i.e., spring).

Right Ascension – like longitude. It is measured eastward in hours (0-23), minutes and seconds from the vernal equinox. (Time units are convenient for east-west measurements. Why?)

Declination - like latitude. It is measured from the equator in degrees (0 – 90°), minutes, seconds of arc.

- The C.E. system "factors out" the rotation of the Earth, and its revolution around the Sun.

- It does not factor out precession. The Earth's equator, and thus the C.E., wobble with a period of 26,000 yr. relative to the ecliptic. The wobbling of the C.E. coordinate grid relative to the fixed stars requires astronomers to update catalog positions about every 50 yrs. Computer programs provide more accurate corrections, as needed.

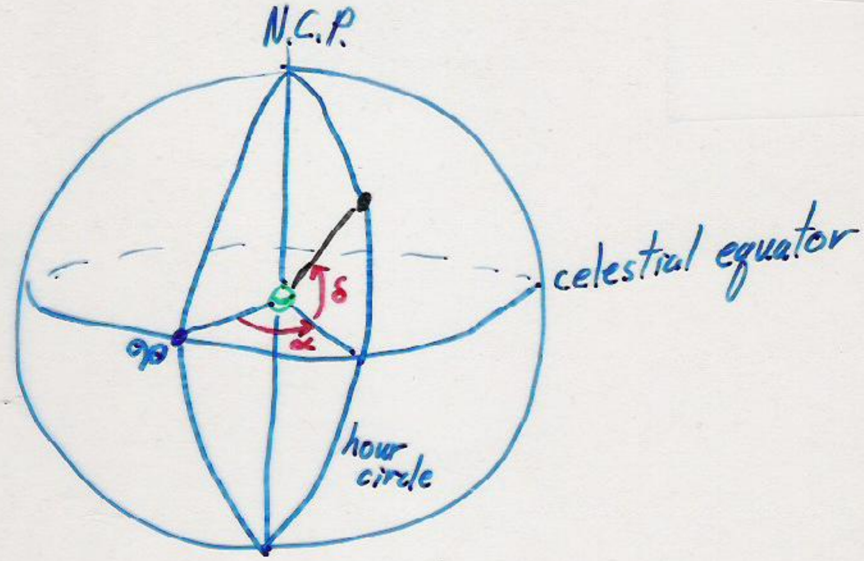


Fig. 2-3

A position given as (α, δ) or (α(1950), δ(1950)).

II 6

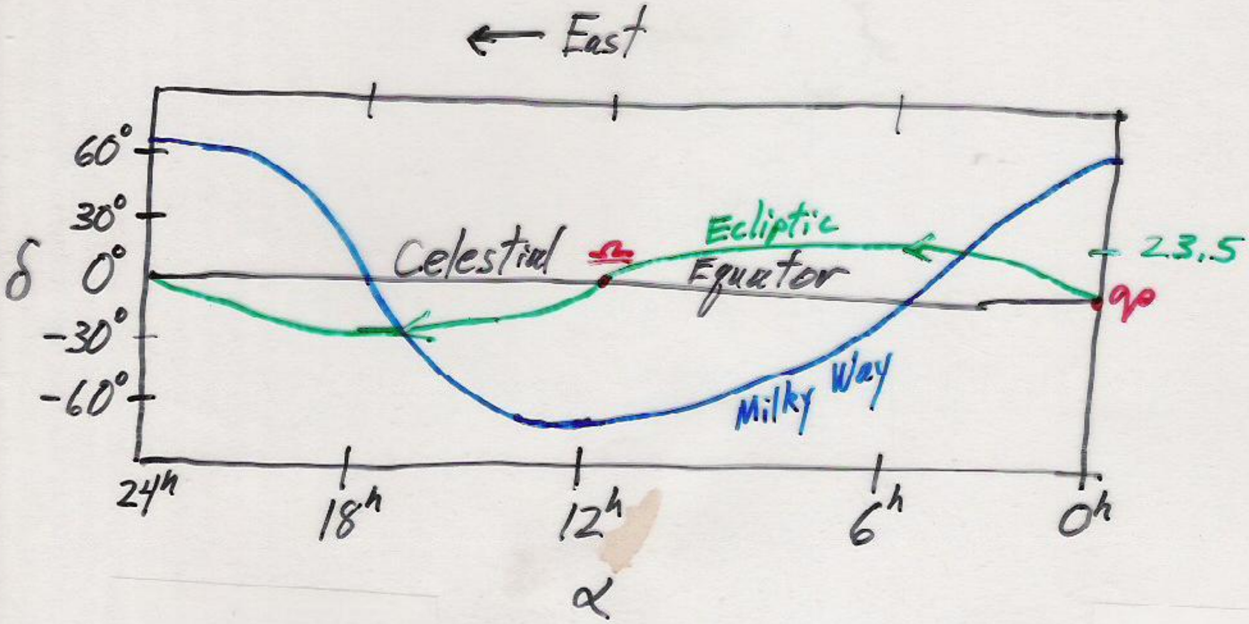
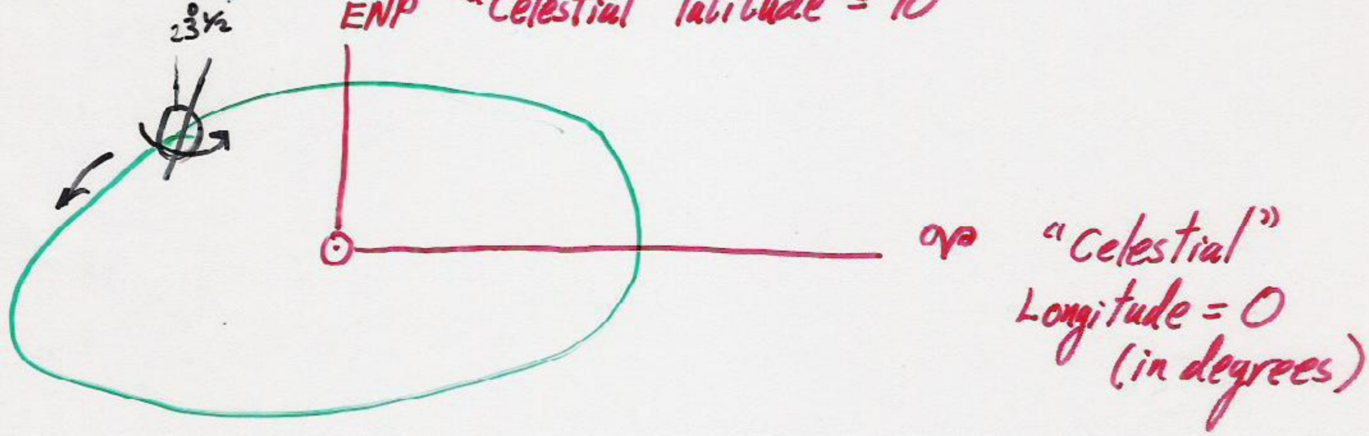


Fig. 2-4

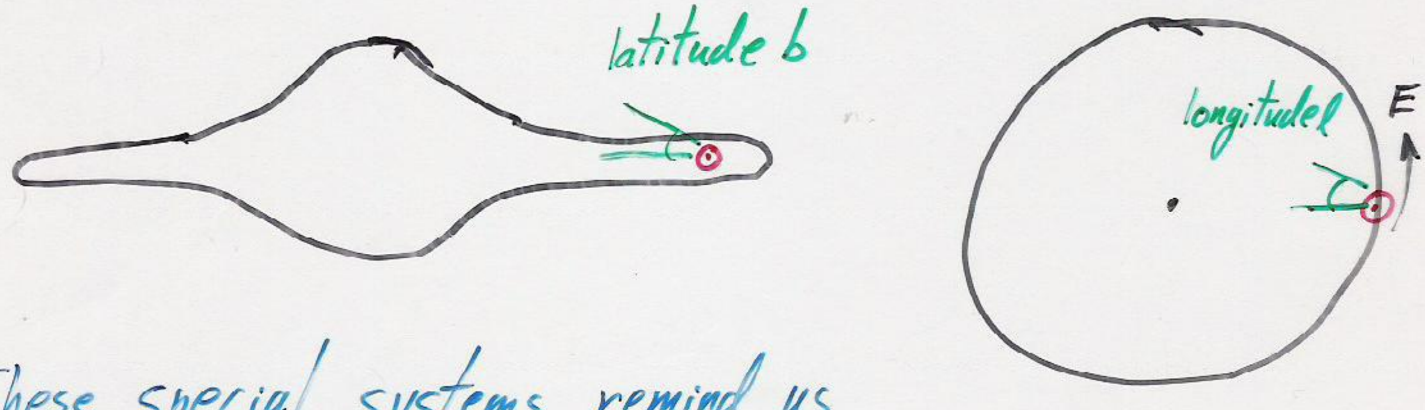
Other Coordinate Systems

Several other systems are convenient for special purposes.

Ecliptic System



Galactic System



These special systems remind us that coordinates are ad hoc, simply defined to facilitate the study of a particular structure.

Finding the Distances to the Stars

- First, best technique = surveying (or trigonometric parallax)

see picture

- Classical Greeks attempted this observation, but failed.

  - Stars are too far!

- Tycho Brahe thought he detected it with naked eye observations, but no.

  - Need a telescope!

- After Newton, intense telescopic searches for 150 years

  - Not only is the effect small, but other, similar effects are bigger.

  - Aberration of starlight = 20.5" per year (Bradley 1729).

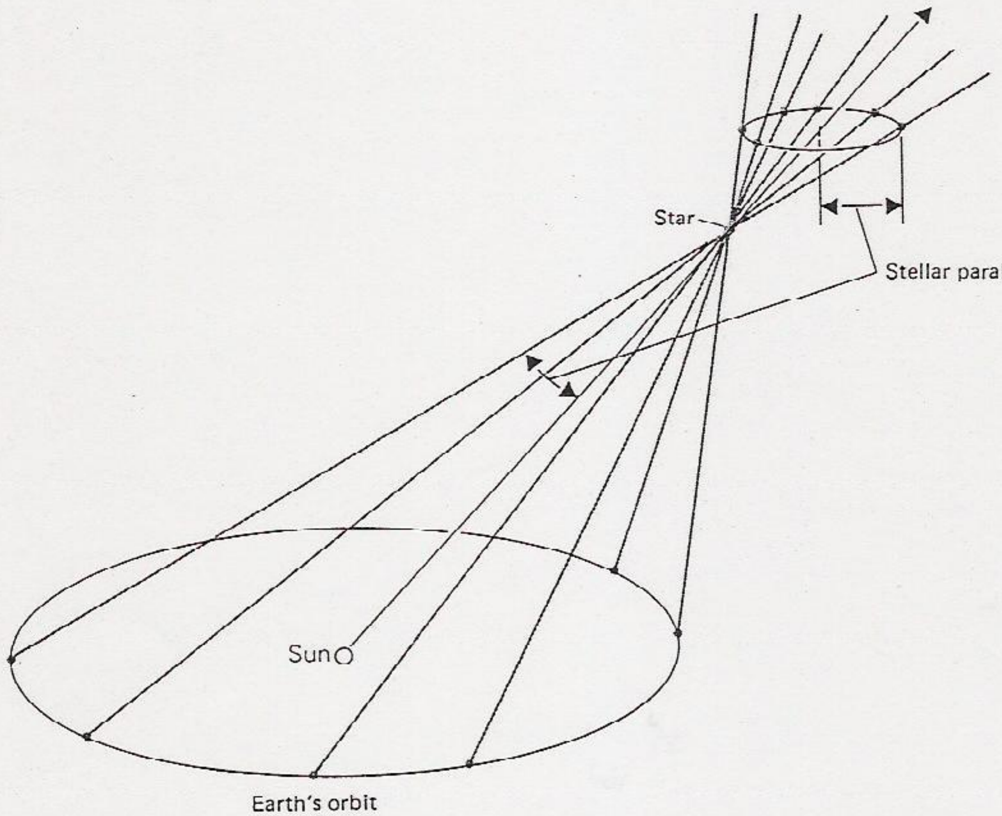


Figure 22.5 The parallax

- Finally, success,

F. Bessel	1838 (Germany)	(61 Cygni)
T. Henderson	1838 (Cape of Good Hope)	
F. Struve	1838 (Russia)	

- In the 1990s, accurate parallaxes available from the Hipparcos satellite.

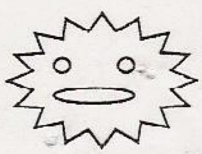
  - "High Precision Parallax Collecting Satellite" (ESA), see http://astro.estec.esa.nl/SA-general/Projects/Hipparcos/hipparchos.html

  - Launched 1989, lasted 4 yrs. Observed 120,000 stars with 0.002-0.004" accuracy, and over a million with lower accuracy.

- Other methods of distance determination involve the use of "standard" candles.

Preliterate Astronomy

- **Neolithic:** we know very little.
  - Evidence that moon phases were tracked 30,000 yrs. ago. Before math or agriculture were developed.
  - Chambered tombs, passage graves and stone circles of different epochs in Europe preferentially aligned east-west, or SW-NE along solstice lines.
  - Megalith builders are especially notable, e.g.,
    - » Newgrange in Ireland, circa 3000 B.C.
    - » Standing stones in the Hebrides, Scotland. Charting declination extremes of the moon.
    - » Stonehenge, beginning about 3200 B.C. and developed for several thousand years. (Not very exact alignments.)
    - » Similar monuments from France to Romania.
    - » Many later cultures erected monuments along solsice line, e.g. Mayans, ancient Egyptian.
- **Bronze age onward:**
  - Artifacts show that Sun and sky worship began very early.
    - » Gimbutas and other anthropologists argue that "Old European" religion was Earth-mother centered.
    - » Sky gods brought by "Indo-Europeans"?
    - » Sun god important to ancient greeks, celts, and germans.



Measurements by Greek Astronomers

Aristarchus (310-230 B.C.) - relative distance of the Moon and Sun.

- relative sizes of Earth, Moon and Sun from eclipse observations. (also Hipparchus.)
- Earth goes around the Sun.

Eratosthenes (276-195 BC) - size of the Earth.

Hipparchus (160-127 BC) - relative positions and magnitudes of stars.

- precession
- solar motion (eccentric)
- lunar motion (regression of nodes)

Ptolemy (~140 A.D.) - distance to moon by surveying.

also - Almagest, epicycle models.

- **Aristarchus**
  - Relative distance of Moon and Sun:
    - » Estimated angle MEM' = 2 x ang.e MES (Fig.1.8) Given two angles in a triangle can get ratio of sides.

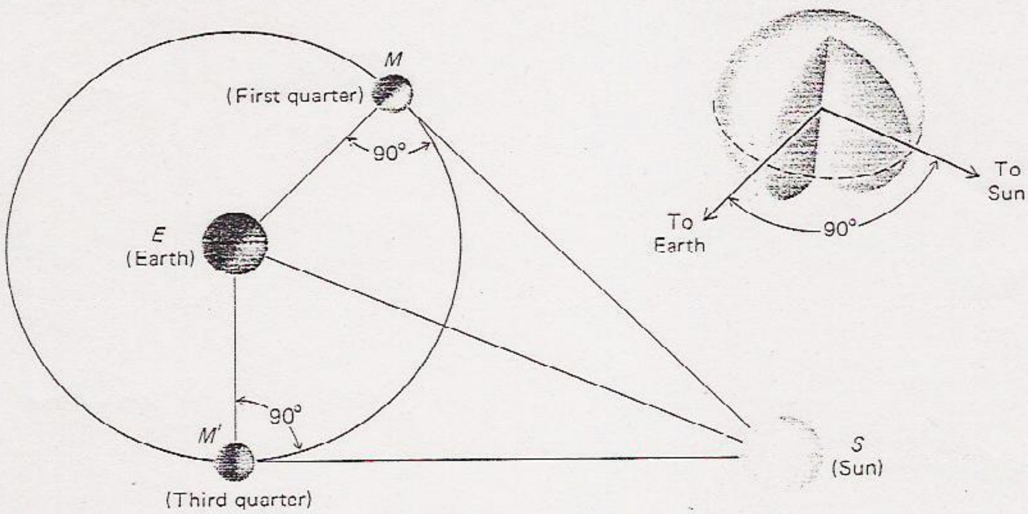


FIGURE 1.8 Aristarchus' method of determining the relative distances of the Sun and Moon from the Earth.

  - Got size of Moon by comparison to Earth's shadow in eclipse (Fig. 1.9). Use relative distances of Sun and Moon to determine how much smaller the shadow size is than the Earth's diameter. Got inaccurate values.

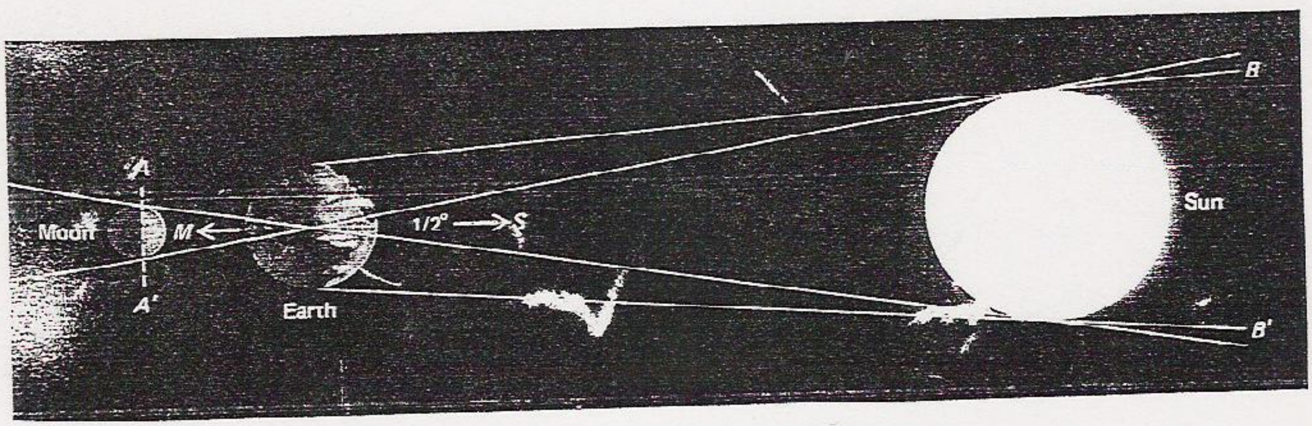


FIGURE 1.9 The principle by which Aristarchus could determine the relative sizes of the Sun, Moon, and Earth.

- **Hipparchus: accurate measurements + geometry**
  - According to Pliny, he set out to "enumerate the stars for posterity" after seeing a new star (probably a comet recorded by the Chinese).
  - ~~Table of chords: equivalent to trig. tables.~~
  - Used *eccentric* to account for solar motion as uniform circular motion (see Fig. 6.6 Thurston).

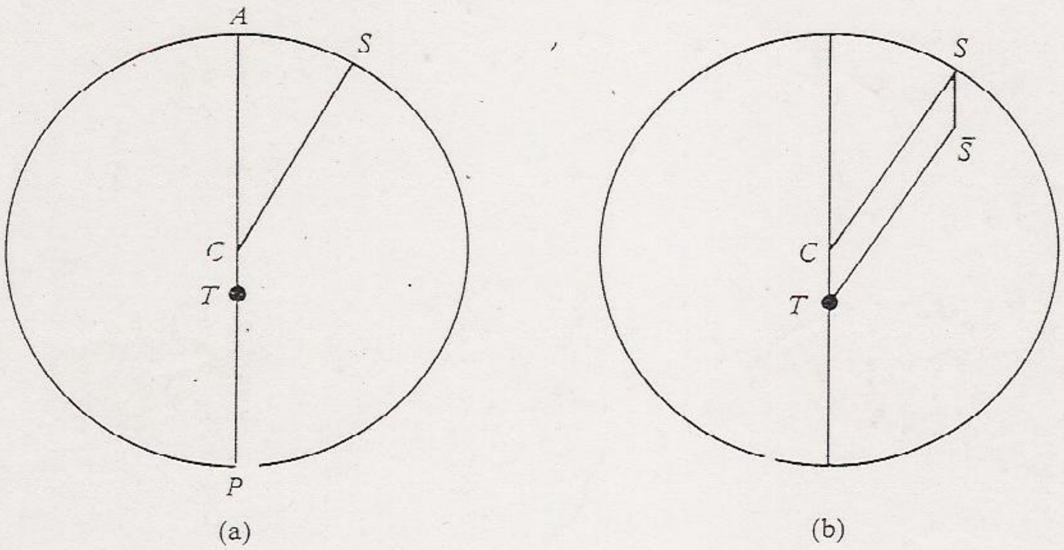


FIGURE 6.6

  - Eccentric + pseudo-epicycle for Moon (Thurston Fig. 6.8).

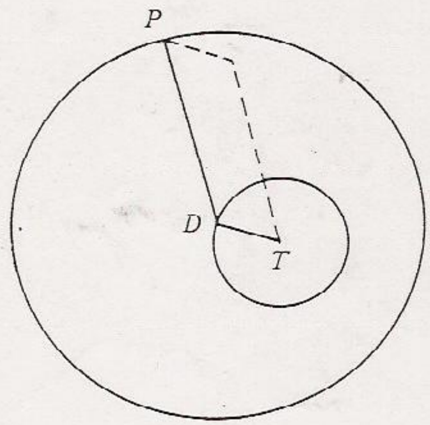


FIGURE 6.8.

  - Discovered equinox had moved 2° in 150 years (derived from position of Spica at lunar eclipse).

- **Ptolemy:** lived in Alexandria, Almagest = Megiste syntaxis, Great Compendium, originally Mathematical Compendium.....in 13 vols.
  - Famous cosmology - Earth-centered a la Aristotle (No parallax, therefore if the Earth moved, stars must be infinitely distant. Moreover, "animals and other bodies left hanging in air..."
  - Based much on Hipparchus, but used regular epicycles.
  - Some observations and a variety of clever calculations, like Moon's parallax.
  - Many of Ptolemy's quoted observations may have been faked! I.e. calculated; got results he wanted. E.g. his equinox was off by a day, probably based on Hipparchus + his own models). But superb calculations!

Renaissance Astronomy

Copernicus, Tycho, Galileo, Kepler

- **New and Revived Cosmological Ideas**
- **More accurate instruments, regular observatories**
- **The Telescope**
- **New and Revived Mathematical techniques**
  - Geometry
  - Logarithms
  - Calculus predecessors
- **Mechanics**

Copernicus (1473-1543)

Born and lived in Prussian kingdoms of northern Poland. Trained in law, religion, and medicine in Italy. Physician and assistant to his uncle the bishop.

- **Heliocentric system,** but with uniform motion & epicycles.
  - Context: debates on Pythagorean vs. Ptolemaic views in Italy.
  - Placed known planets in proper order out from Sun.
  - Noticed closer to Sun, greater orbit speed.

- **Evidences:**
  - Phases of Venus (Copernicus didn't see them though).
  - Configurations of Superior planets vs. Inferior (Fig. 2.3)
  - Retrograde motion for Superior planets (Fig. 1.15)
  - Get relative distances from quadrature triangles.
  - Ptolemy could also account for retrograde motion, but less "naturally".

Tycho Brahe (1546 - 1601)

- **Danish nobleman,** gained patronage of Frederick II, King of Denmark
  - Uraniborg Observatory on island of Hveen 1576-1597
  - Court astronomer for Rudolph II in Prague. Hired Kepler.

- **Important observations**
  - Observed comet (1577), but no parallax ----> not luminous "airey vapours". Concluded it was greater than 3 times as distant as the Moon.
  - Very accurate positional observations (≈ 1 arcmin.) of stars and planets. Continuous 20 yr. record of observations. Noticed many empirical regularities.

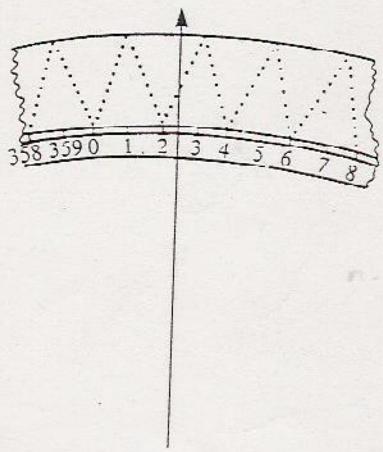


FIGURE 10.7.

- **Cosmology**
  - Halfway to Copernicus, but couldn't observe parallax. Concluded that Earth is fixed. Thought he resolved stars.

Galileo Galilei (1564 - 1642)

Didn't finish college, but got a professorship
....Pisa --> Padua --> Tuscany

- **Mechanics**
  - experiments were a new idea: pendulums, balls on planes, falling objects.
  - **Gravitational acceleration** independent of mass.
  - **Law of inertia:** body resists change in motion. Rest is not the only natural state.

- **Astronomy**
  - made telescopes, 30x magnification, *found:*
  - many faint stars, star clusters.
  - Milky Way = stars
  - Galilean moons of Jupiter, i.e. other centers of motion.
  - Phases of Venus.
  - Structure of Moon: maria, mountains, i.e. imperfect surface.
  - Supspots, Sun is imperfect, temporary. Solar rotation.

- **Heliocentric Cosmology:** strong advocate of Copernicus.

Johannes Kepler (1571 - 1630)

- Son of a "reckless soldier of fortune" and "the undisciplined and ill-educated" daughter of the burgomaster of Eltingen (1927 Encyclopedia Brittanica).

- Recovered from smallpox at age 4 with crippled hands, and eyesight permanently impaired.

- Enrolled in seminary at age 13, entered university at age 17.

- Gave up theology for science professorship (in Ptolemaic *astrology*) at Gratz.

- Because of religous disturbances in Gratz, took job with Tycho at Prague. Succeeded Tycho in 1601 as court astronomer or mathematician.

- Picked up the study of **Mars**. Long struggle with traditional orbit models, though from early on he considered the **Law of Areas.** Finally stumbled on a model that behaved in some ways like an ellipse.

- Published **Astronomia Nova** in 1609 with orbit for Mars and first 2 laws.

- Got telescope in 1610 and did optical studies (theory of refraction).

- Published **De Harmonice Mundi** in 1619 with **third law** and theory of the harmony of the spheres.

- Mother arrested for witchcraft in 1620 (Wurttemberg).

- Linz beseiged, obtained permission to move "Rudolphine Tables" types to Ulm. Published in 1627.

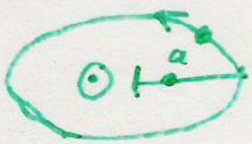
Orbital Motion: Kepler

We will not have time to discuss the historical context, despite the fact that this is one of the most interesting chapters in the history of science (see Abell, Morrison and Wolff).

Kepler: Over a period of about 20 years Kepler worked on models, based on the Copernican system, to fit Tycho Brahe's extensive observations of Venus and Mars. The result was a set of 3 fundamental laws of planetary motion.

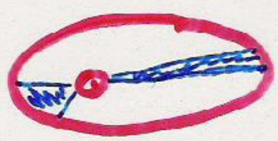
Kepler's Laws (quoted from Abell) **The 1-body problem.**

1. Each planet moves about the sun in an orbit that is an ellipse, with the sun at one focus of the ellipse.



$$r = \frac{a(1-e^2)}{1+e\cos\theta}, \quad e^2 = \frac{a^2-b^2}{a^2}$$

2. (Law of Areas) The straight line joining a planet and the sun sweeps out equal areas in the orbital plane in equal intervals of time.



3. The squares of the sidereal periods of the planets are in direct proportion to the cubes of the semimajor axes of their orbits.

$$\left(\frac{P}{1\,\text{yr.}}\right)^2 = \left(\frac{a}{1\,\text{a.u.}}\right)^3$$

More generally, $P^2 = \frac{4\pi^2}{GM} a^3$ (e.g. MKS)