ASTB23 Astrophysics of stars, galaxies and Universe

or

How do Stars and Galaxies function, form & die?

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http://wapo.st/2ig41mW

Some question we want to explore in this course:

What's inside a star and what are the physical conditions there?
Why does the sun shine?
How long does it live quietly and what happens afterwards?
How do we understand and model stars
What are the dusty disks around stars
& what's their connection to star formation?
White dwarfs
Neutron stars
Black holes
What's inside a galaxy? How does it rotate and why?
What's in the center?
What are the spiral arms? How do they depend on the type of galaxy?
What is gravitational wave astronomy?
Dark matter and dark energy

Notice

This is a fast-moving course. There is a lot of required reading: 2 textbooks (1st + parts of 2nd) and additional reading such as lecture and tutorial notes.

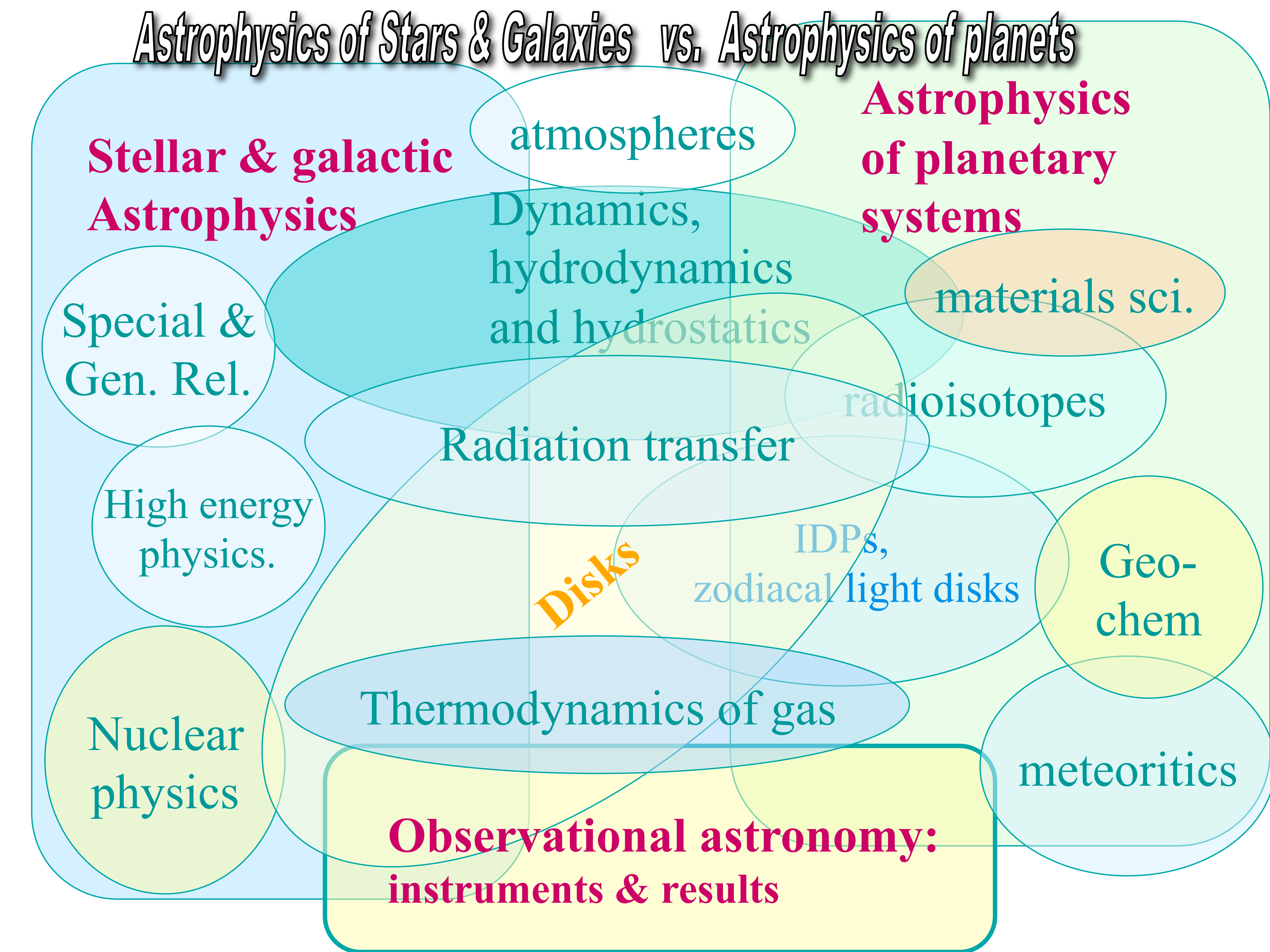
Reading these materials (e.g., next chapter of textbook) *ahead* of a lecture will enable you to get more out of every lecture, understand remarks going beyond the text of the book better and, importantly, ask questions **during the lecture or afterwards.**

Any question is valid & there are no “stupid questions” (only some answers).
So I will always address your question: either answer it right away or postpone the answer.
Sometimes the answer is contained in lecture material that lies just ahead.

In lectures, I’ll try to emphasize those things in the book that are most important.
It makes sense to be at the lectures.

In your 4 sets of assignments, you will be given adequate time to solve the problems. You are free to discuss the ideas and general methods of solution with your fellow students or an imaginary friends (GPT).

Implementation, that is developing and writing down the answers for submission must be original, i.e. entirely yours. At this stage, GPT = *double* plagiarism. Anything else, like unacknowledged citing of internet resources or a great similarity between your and your fellow student’s assignment text is a suspected plagiarism, and requires lecturer & DPES to investigate. Avoid non-intentional violations by studying what UofT considers plagiarism (cf. Academic handbook on plagiarism).


Astrophysics of Stars & Galaxies vs. Astrophysics of planets
Stellar & galactic Astrophysics
atmospheres
Astrophysics of planetary systems
Dynamics, hydrodynamics and hydrostatics
materials sci.
Special & Gen. Rel.
radioisotopes
Radiation transfer
High energy physics.
IDPs, zodiacal light disks
Disks
Geo-chem
Thermodynamics of gas
Nuclear physics
meteoritics
Observational astronomy: instruments & results

Already the Ancient [Greeks] ...

- Had a good theory of star and planet formation

and

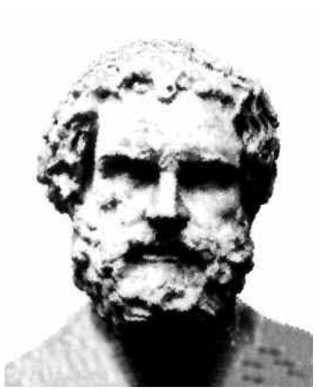
- Figured out quite cleverly & accurately the basic distances and sizes of objects in the nearby universe

- (in that order)

Already the Ancient [1]

Some of the earliest recorded physics
was very prescient & essentially correct!

Predicted: evolution (formation/decay) of worlds,
the role of disks, and diversity of "worlds".



Antique theory #1: plurality of worlds

- Kosmos: unique or multiple (infinite in number?)

Greek atomists Leucippus and Democritus considered the world

built of the same (‘solar abundance’) atomic matter that forms the Earth, subject to constant motion through vacuum, collision, and coalescence (accretion).

Who invented the so-called solar nebula: Kant & Laplace or Leucippus?

The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void;
they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.

Leucippus (480-420(?) B.C.), after Diogenes Laertios (3rd c. A.D.)

The earliest consideration of worlds (planets) around pulsars and binary stars; evolutionary aspect stressed; hot planets anticipated.

In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous.
In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture.

Democritus (ca. 460-370 B.C.), after Hyppolytus (3rd cent. A.D.)

Plurality and diversity of planetary systems reaffirmed:

There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, (...) there nowhere exists an obstacle to the infinite number od worlds.

Epicurus (341-270 B.C.)

Similar writings exist by **Lucretius (ca. 99-55 B.C.).**

Antique theory #2: a unique terrestrial system

The atomist system was eclipsed by a cohesive system of **Aristotle, (384-322 B.C.),** a student of Plato and tutor of Alexander the Great. Aristotle was not very interested in extrasolar planetary systems or their formation, or other unobservable things. But (unfortunately) he was extremely influential after 1500 yrs. His world was geocentric, unchanging and unique.

The four elements moved each to their 'natural place' with respect to the center of the world. Existence of many such centers was unthinkable:

There cannot be more worlds than one.
Aristotle [*De Caelo*]

The heliocentric system of Nicolaus Copernicus (1543) was received as supporting the plurality of planets and their systems in the Universe, though Copernicus did not discuss stellar systems too much.

Giordano Bruno was conviction about infinite number of terrestrial planets and the inhabitability of both planets and stars (non-selfluminous and self-luminous bodies) [*On the Infinite Universe and Worlds,* 1584]. In 1592, he falls into the hands of Holy Inquisition, and in 1600 dies at the stake (but **not** because of his cosmological views.)

Johannes Kepler did not believe that the stars making up the Milky Way (as surmised by Democritus and argued based on telescopic observations by Galileo) are of the similar brightness & status as our Sun, or that they have planets.

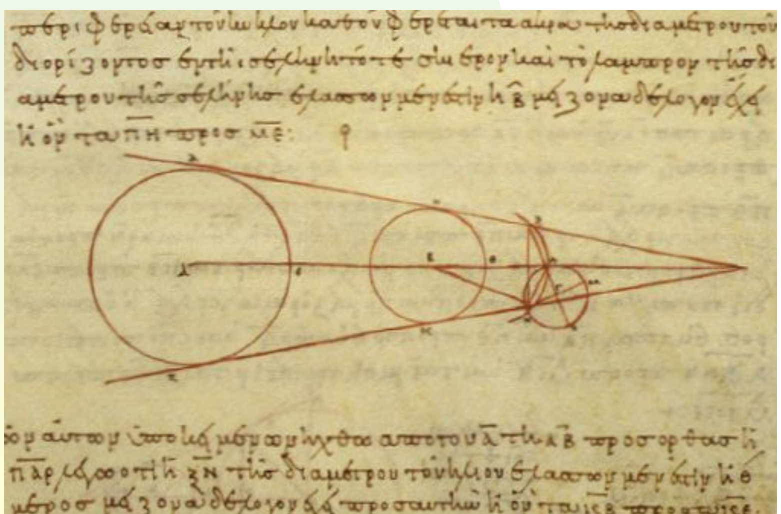
And so on... the pendulum of opinion was swinging until 1990s when observations finally settled the question.

If you want to know more about history, read lecture notes from ASTB02 posted on our web page

Already the Ancient... [2]

Greek astronomers in the Hellenistic Greece (period, which started in 323 B.C. when Alexander of Macedon died and his empire started fragmenting) possessed a fantastic ability to employ Geometry, much of which they first discovered (cf. Ευκλιδες or Euclid ~300 BC), in their study of the structure of the Solar System. They also began the Scientific Method, which bloomed 1500 years later...

You may wonder how the Ancient Greek astronomers knew so much (pretty accurate distance & size of the Moon, size of Earth etc.). Let's consider Αρισταρχος ο Σαμιος (Aristarchus of Samos, 310-230 BC)



crater Aristarchus on the Moon

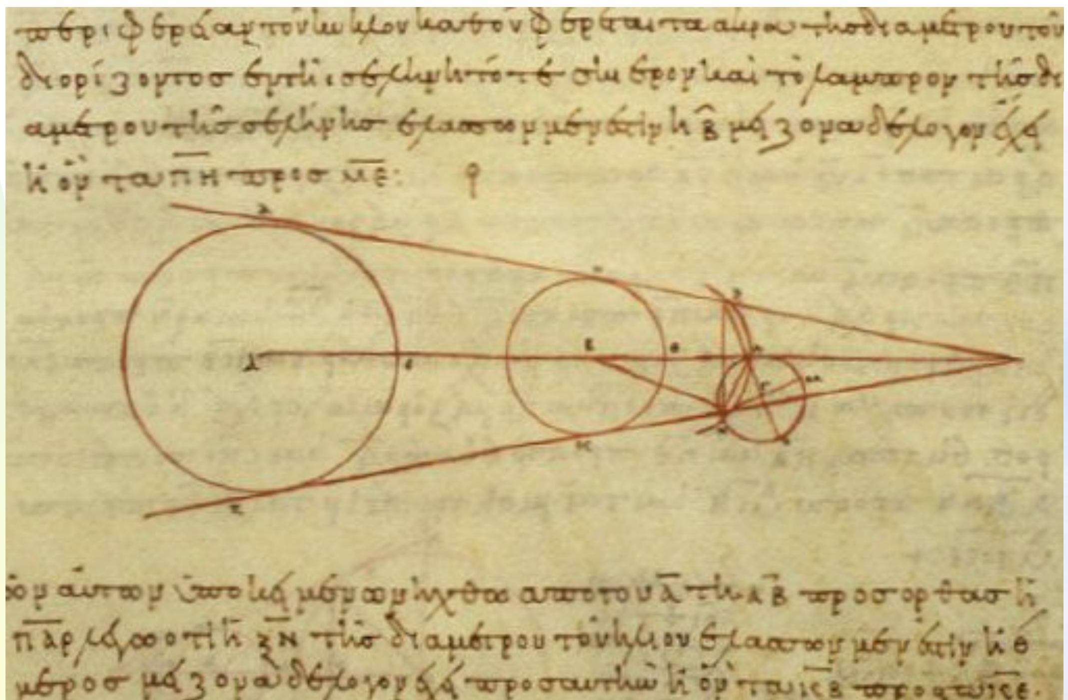
“Περὶ μεγεθῶν καὶ ἀποστημάτων [ἡλίου καὶ σελήνης]”

pron.: Perì megethôn k[a]ì apostēmátōn [h]ēlíou k[a]ì selḗnēs

“On the sizes and distances [of the] sun and moon”

The book written around 250 B.C., main work of Aristarchus of Samos, in which he calculates the quantities listed in the title. Unlike the Moon’s, the Sun’s distance was computed with a sizeable error due to one inaccurate input datum. This was corrected by Hipparcus, Eratosthenes and C. Ptolemaeus (Ptolemy). In the tutorial, you will step in Aristarchus’ shoes.. or sandals, to perform analysis similar to his.

The original is lost, but there is a 10th century A.D. copy of this book.

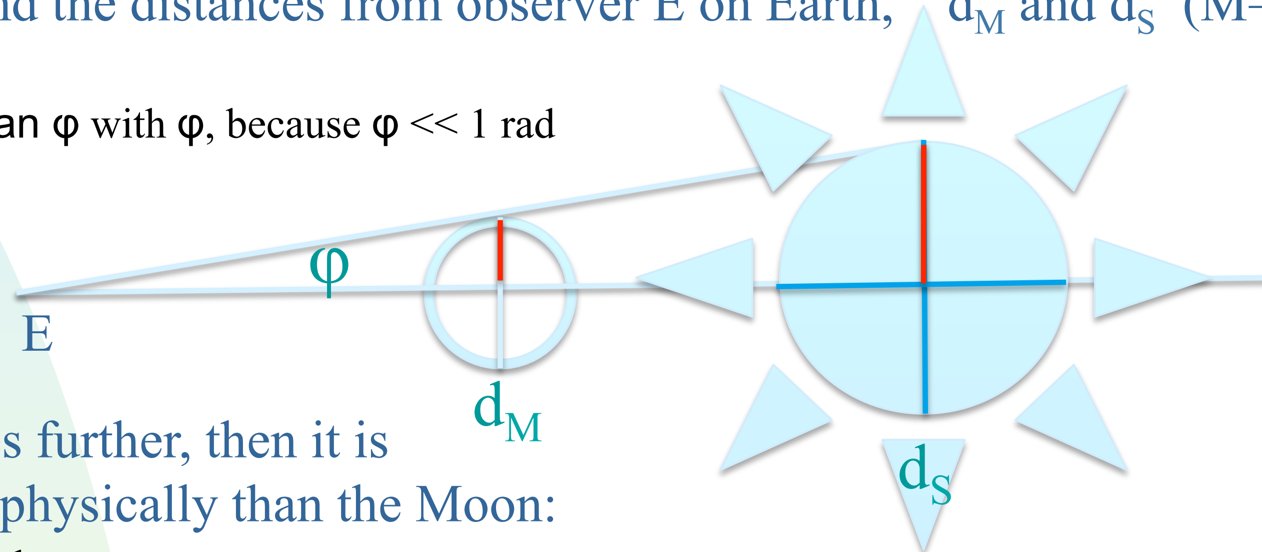


STEPS IN ARISTARCHUS'S CALCULATIONS

1. From observations of **total solar eclipses**, we know that the angular sizes of sun and moon almost exactly coincide, and that the common angular radius is equal $\varphi = ½\ 0.53°$. The value of φ in radians is a conversion factor between the physical radii R_M and R_S, and the distances from observer E on Earth, d_M and d_S (M=Moon, S=Sun):

notice that we replace tan φ with φ, because φ << 1 rad

$$R_M = \varphi\ d_M..$$
$$R_S = \varphi\ d_S.$$



If the Sun is ξ times further, then it is also ξ times larger physically than the Moon:

$\xi = R_S/R_M = d_S/d_M$. This ratio was at first unknown, but Aristarchus proposed this.

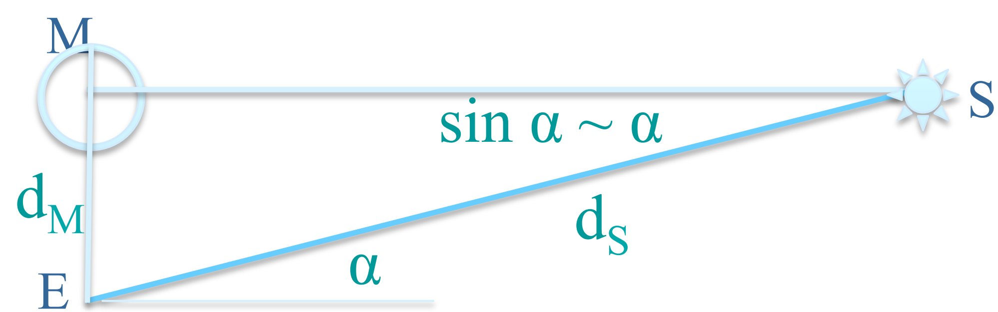
2. Sun/Moon size ratio ξ can be found from a careful observation of the Moon and Sun at the time of **exact half-Moon** provided one can measure small angle

$\alpha = 9' = (9/60)°$ (modern value)

$\alpha \sim \sin\alpha = d_M/d_S = 1/\xi$

Substituting α in radians, we get ξ.

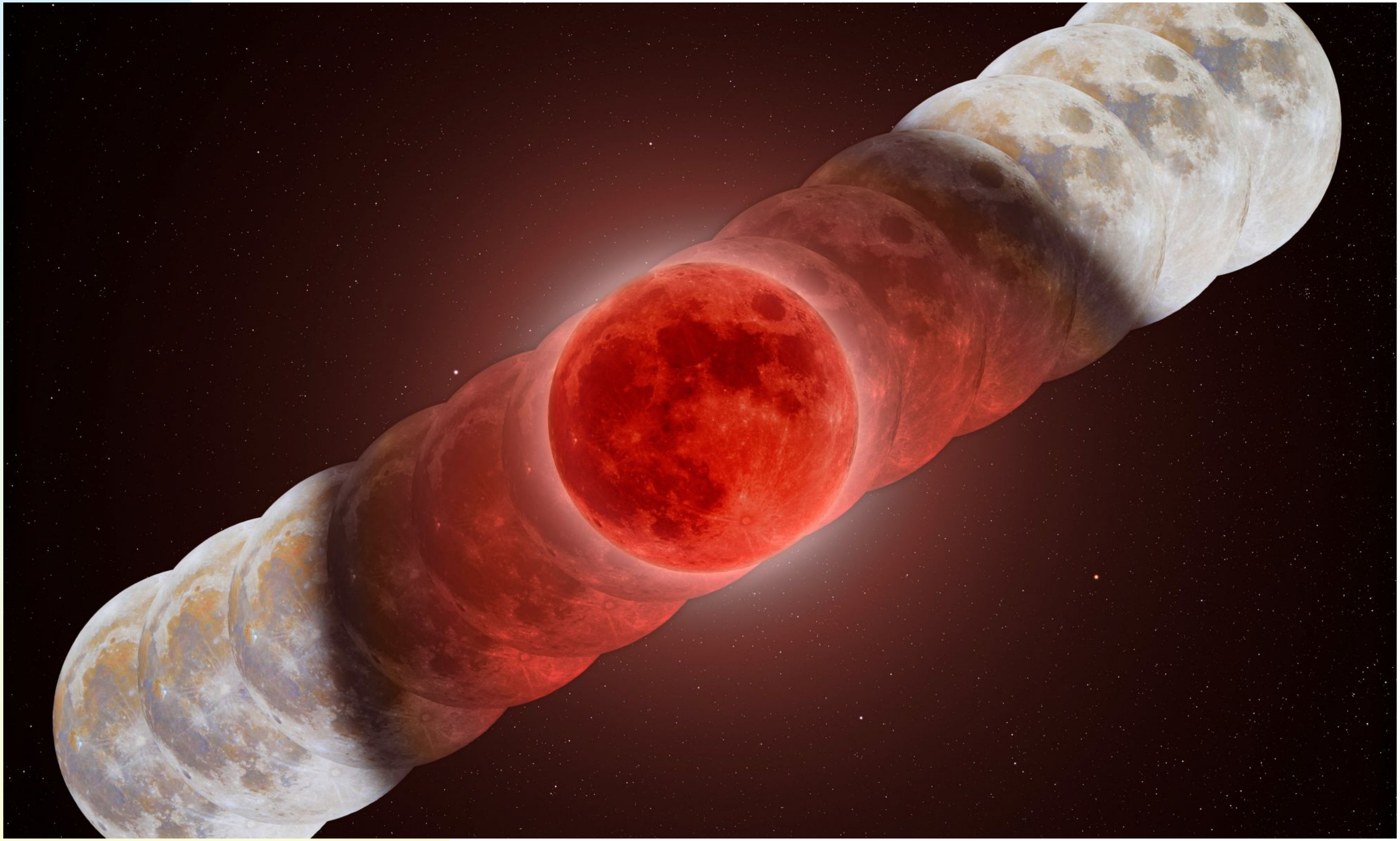
(Do it and you'll learn how much further than the Moon the Sun is.)



STEPS IN ARISTARCHUS' CALCULATIONS

3. Finally, the 3rd observation invoked by Aristarchus is the **total lunar eclipse**.

Ancient cultures including Greeks knew very well that the Earth is a sphere from such observations, showing a round outline of Earth's shadow.



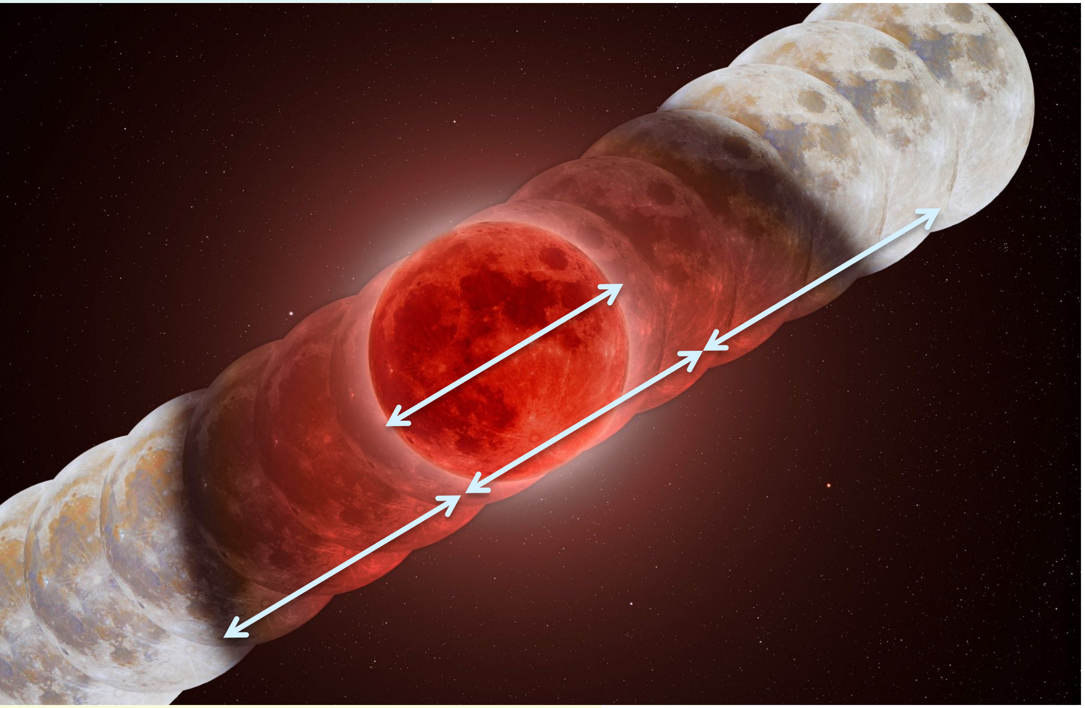
Mosaic of snapshots, total eclipse of the Moon on Nov. 8, 2022   *(c) Andrew McCarthy*

STEPS IN ARISTARCHUS' CALCULATIONS

3. Total lunar eclipse.

The angular radius of the Moon is 2.6 times smaller than the radius of Earth's shadow Some astronomers have adopted the radius of the Earth as a unit of distance, but others preferred to use more common distance units, such as *stadion* (today it'd be km).

Eratosthenes (Ερατοσθενες, 276-195 BC), chief librarian of Alexandria, computed an impressively exact radius of Earth from solstice observations at Syene, where the sun



reached zenith, and at Alexandria (800 km N of Syene), where shadows were cast at the angle of 7.2° to the vertical (1/50 of the full circle). Hence, the circumference of Earth must be 50*800 km = 40000 km

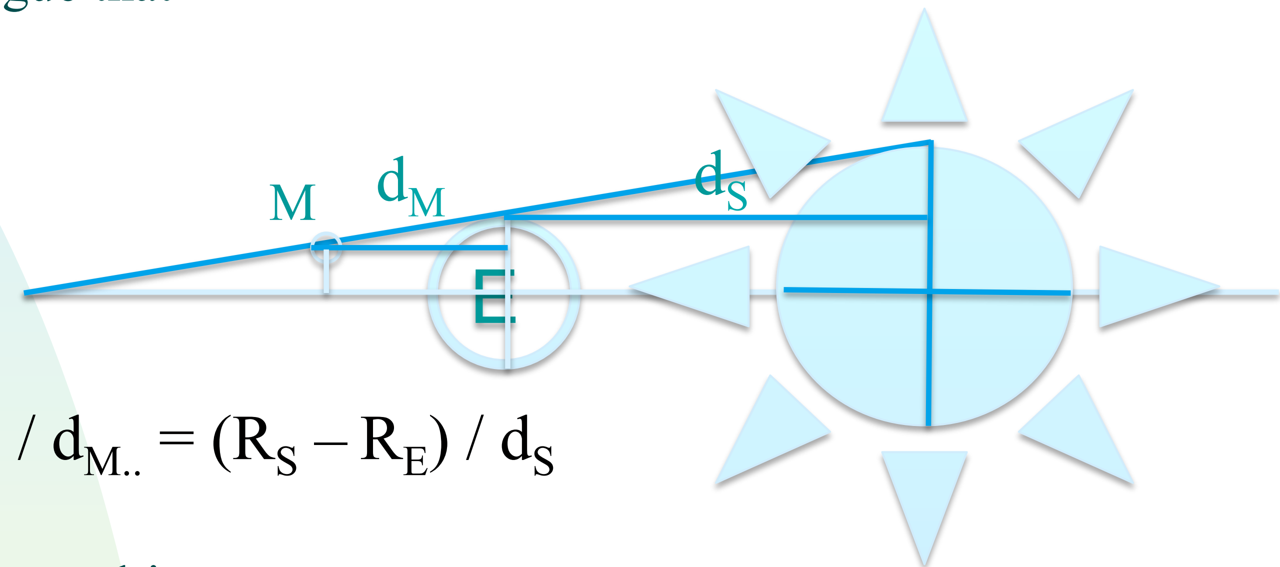
➔ R_E = 6366 km

(Actual value is 6357 km polar & 6378 equatorial, or 6371 km on average, a differ. of only 0.1%)

Great results of ARISTARCHUS'S CALCULATIONS with more modern inputs

3. From observations of **total lunar eclipse**, we know that $R_{shadow} = 2.6\ R_M$.
There are two (actually more) similar triangles in the picture.

Exercise: First argue that



$$(R_E - 2.6\ R_M) / d_{M..} = (R_S - R_E) / d_S$$

Then calculate from this:

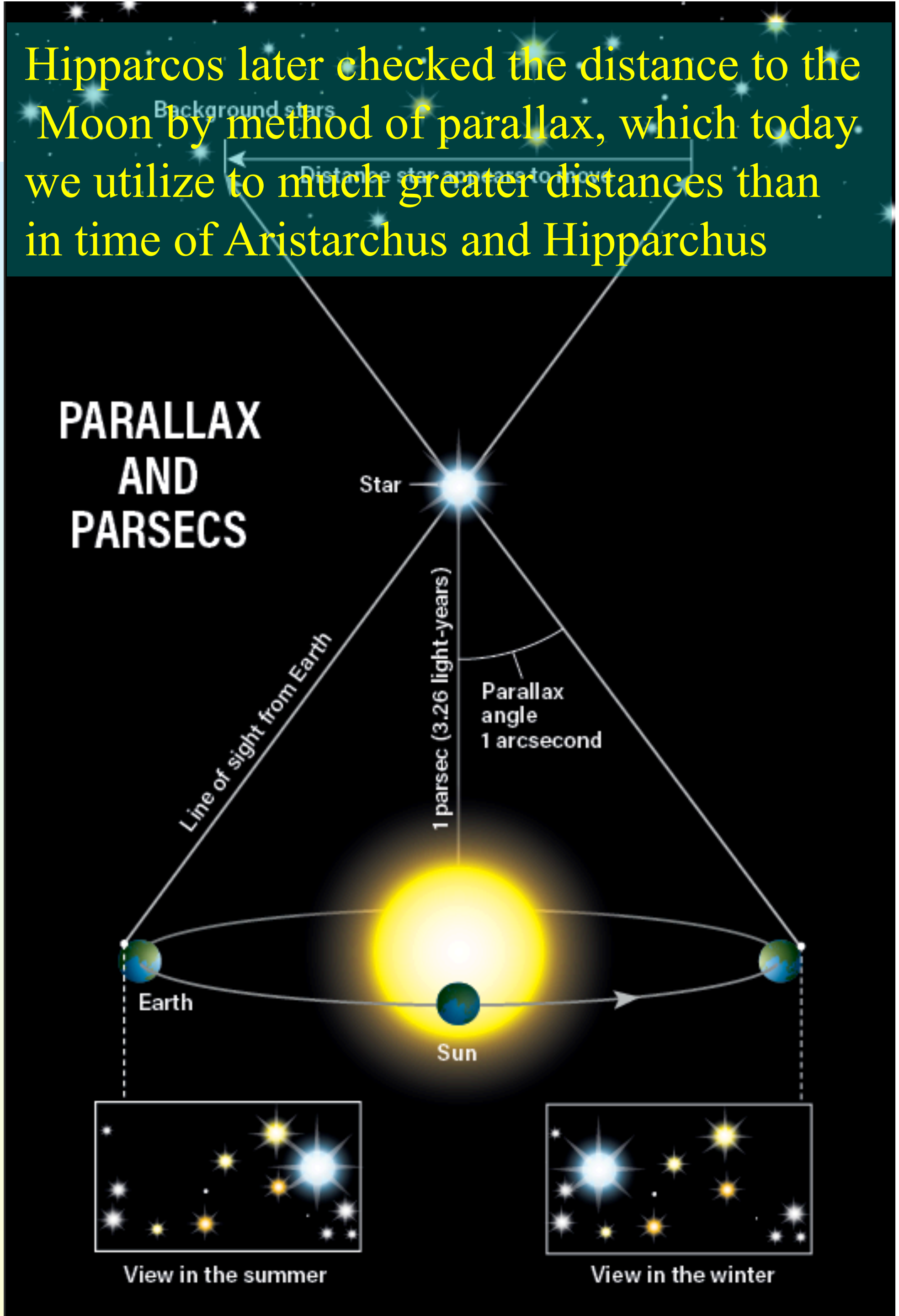
$R_M = R_E/3.6$
$R_M = 1770$ km
$d_M = 382600$ km

those values agree very well with modern measurements (today, we measure d_M by bouncing laser beams off mirrors left on the Moon's surface by American astronauts and by the Soviet Lunokhod rover)

Distance and size for the Sun are rescaled by a factor ξ. We obtain $d_S = 149.2$ mln km, which is very close to the actual average distance 1 AU = 149.5 mln km.
This and Aristarchus's reported heliocentric system (no extant works) demonstrated great mastery of astronomy by Hellenistic astronomers.

Parallax and parsecs

Hipparcos later checked the distance to the Moon by method of parallax, which today we utilize to much greater distances than in time of Aristarchus and Hipparchus



Daily parallax of the Moon is caused by Earth's rotation. Observer by moving sideways by 1 R_E (perpendicular to the line of sight) sees the Moon change the angular position on a stellar background by $R_E/d_M = 0.0166$ rad $= 0.95° = 57'$

Yearly motion of Earth around Sun and improved accuracy of parallex measured in units of arseconds (1" = 1'/60 = 1/60 of degree = 1°/3600) allowed astronomer/mathematician Bessel in 18th cent. to measure the distance to star 61 Cygni, equal 3.49 pc.

PARSEC

1 pc = 206265 AU

(nearest stars are at ~1 pc).

Def.: 1 AU at 1 pc spans 1" (arcsecond).

Name derives from:

parallax = 1 arcsecond at 1 parsec