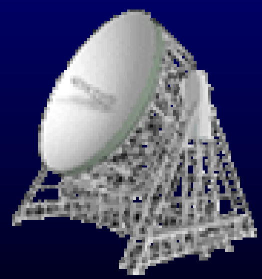
An Introduction to Astronomy and Cosmology

1) Astronomy - an Observational Science

MANCHESTER
1824
Jodrell Bank Observatory



Why study Astronomy 1

- A fascinating subject in its own right.
  - The origin and Evolution of the universe
    - The Big Bang – formation of Hydrogen and Helium
    - Dark Matter and Dark Energy
  - The life of stars
    - Nuclear synthesis – forming heavier elements
    - Ending their lives as exotic objects such as black holes in massive explosions that enrich the stellar environment
    - So allowing planetary systems to form
  - And thus providing the conditions for life to evolve.

Why Study Astronomy 2

- A great environment for studying Physics
  - The Solar System
    - Kepler’s Laws of Planetary Motion
    - Newton’s Law of Gravitation – tidal forces
    - Wein’s and Stephans’s Radiation Laws
  - Stars
    - Nuclear Fusion and synthesis of elements.
    - Exotic states of Matter
  - Big Bang
    - Elementary Particle Physics.

Why Study Astronomy 2

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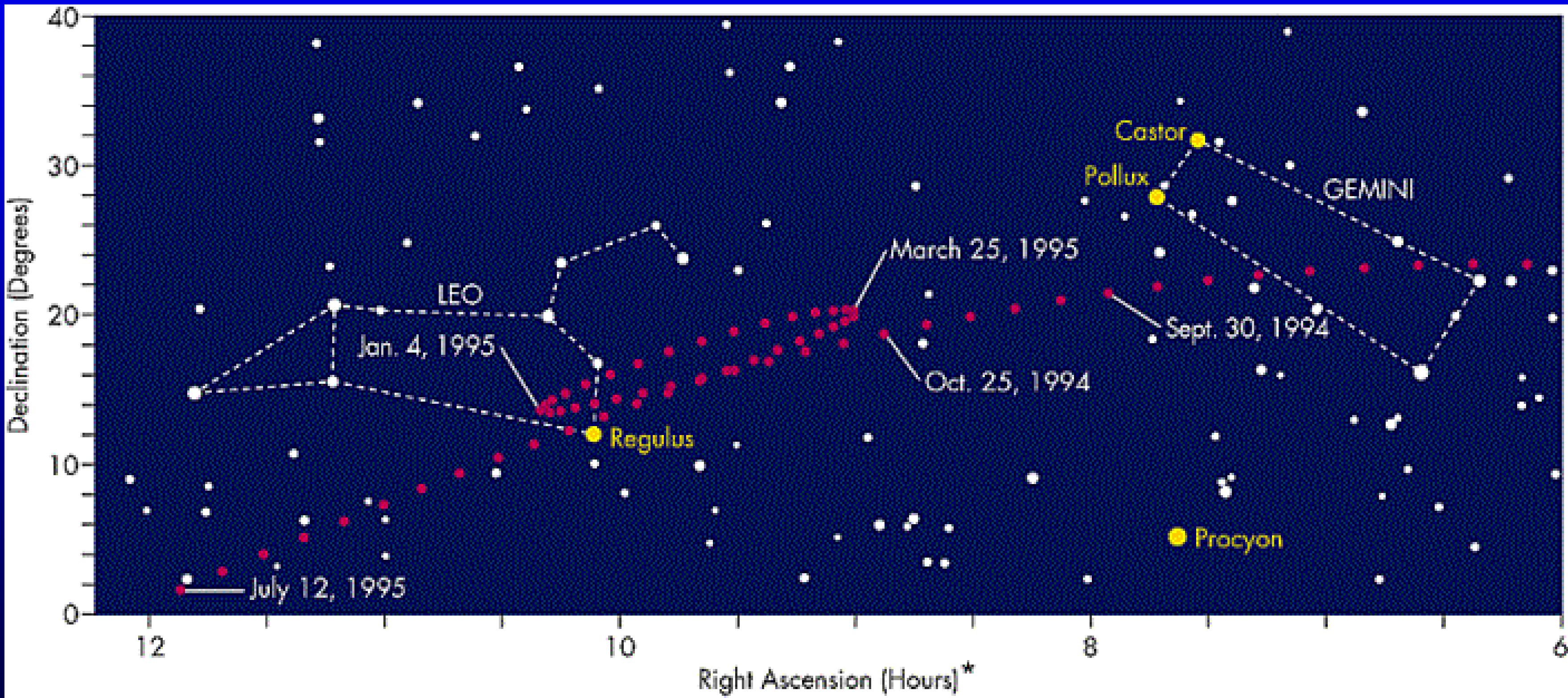
- Galaxies
  - Supermassive Black Holes
  - Radiation Mechanisms
  - Dynamics
  - Spectral Lines - Doppler Shifts
- Cosmology
  - Einstein’s theory of Gravity
  - Uncertainty Principle and Virtual Particles
  - Gravitational and Cosmological Red Shifts
- Observational Aspects
  - The wave nature of light and limitations that this imposes on optical instruments.

Models of the Solar System

- Ptolomy's Earth Centric Model
- The Copernican Heliocentric Model
- Both can explain Retrograde Motion

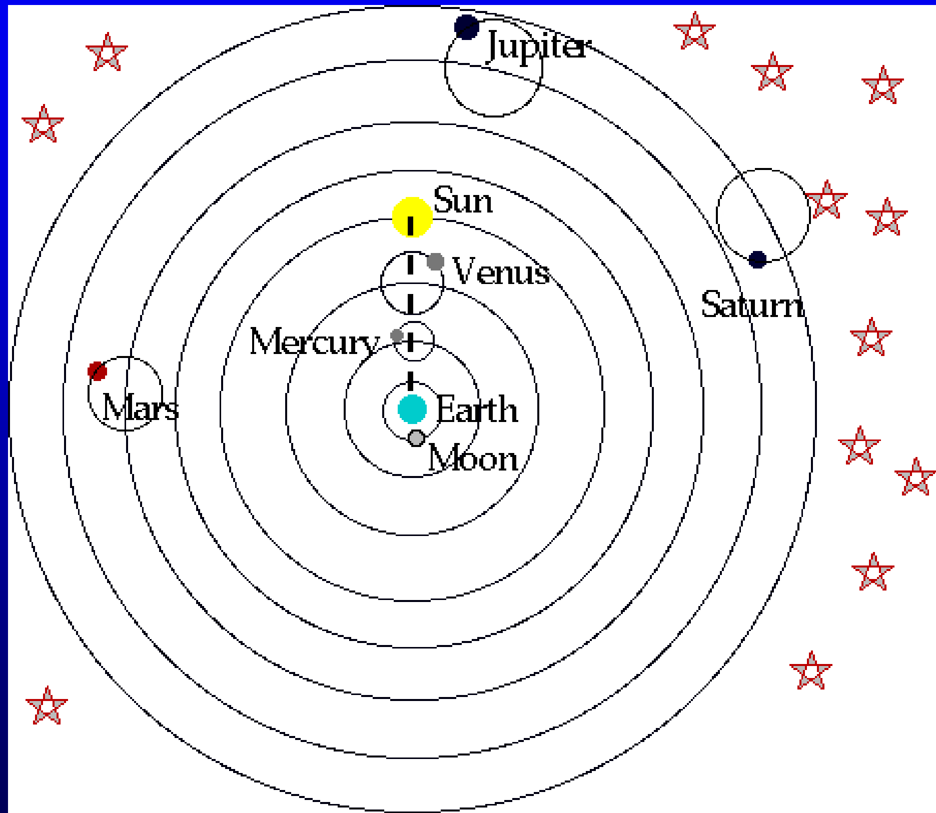
Retrograde motion of Mars

Mars 1994-5



40
30
20
10
0
Declination (Degrees)
12
10
8
6
Right Ascension (Hours)*
LEO
Jan. 4, 1995
Regulus
March 25, 1995
Oct. 25, 1994
Castor
Pollux
GEMINI
Sept. 30, 1994
Procyon
July 12, 1995

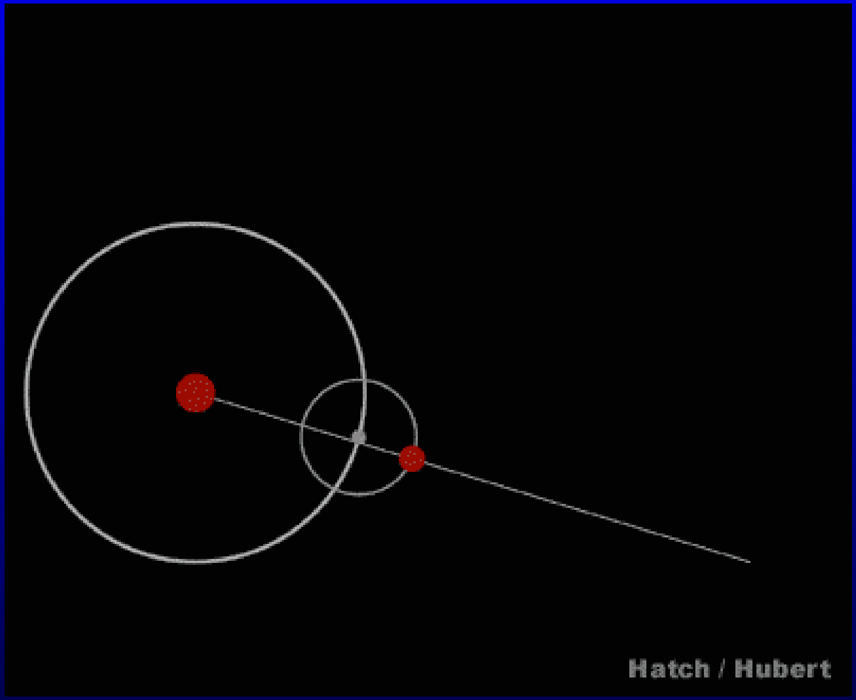
Ptolomy’s Geocentric Model



Notice Mercury nearer than Venus!

How it can explain Retrogade Motion

- As the planet moves anticlockwise around the epicycle whilst the centre-point of the epicycle also moves anticlockwise, there comes a time when the planet is moving backwards against the sky – retrograde motion.



Copernicus

Nicolas Copernicus, 1473-1543

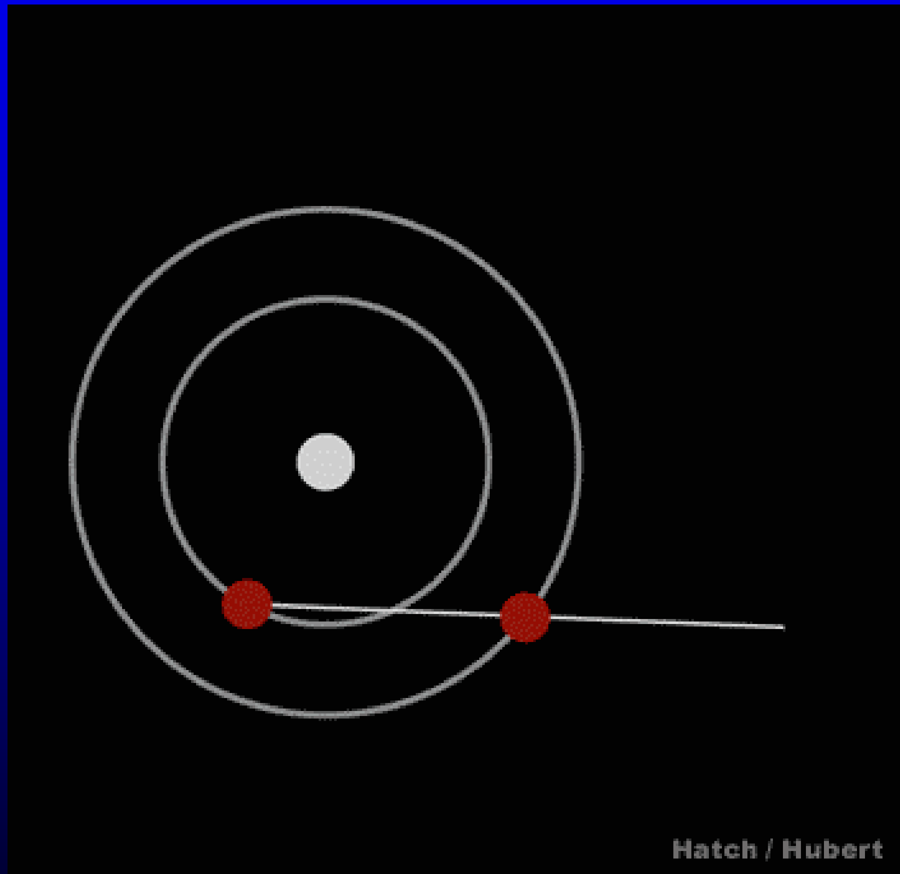
- Born in Torun, Poland.

His Theory of the Universe

- The centre of the Universe is near the Sun.
- The distance from the Earth to the Sun is imperceptible compared with the distance to the stars.
- The rotation of the Earth accounts for the apparent daily rotation of the stars.
- The apparent annual cycle of movements of the Sun is caused by the Earth revolving round it.
- The apparent retrograde motion of the planets is caused by the motion of the Earth from which one observes.

Can also explain Retrograde Motion

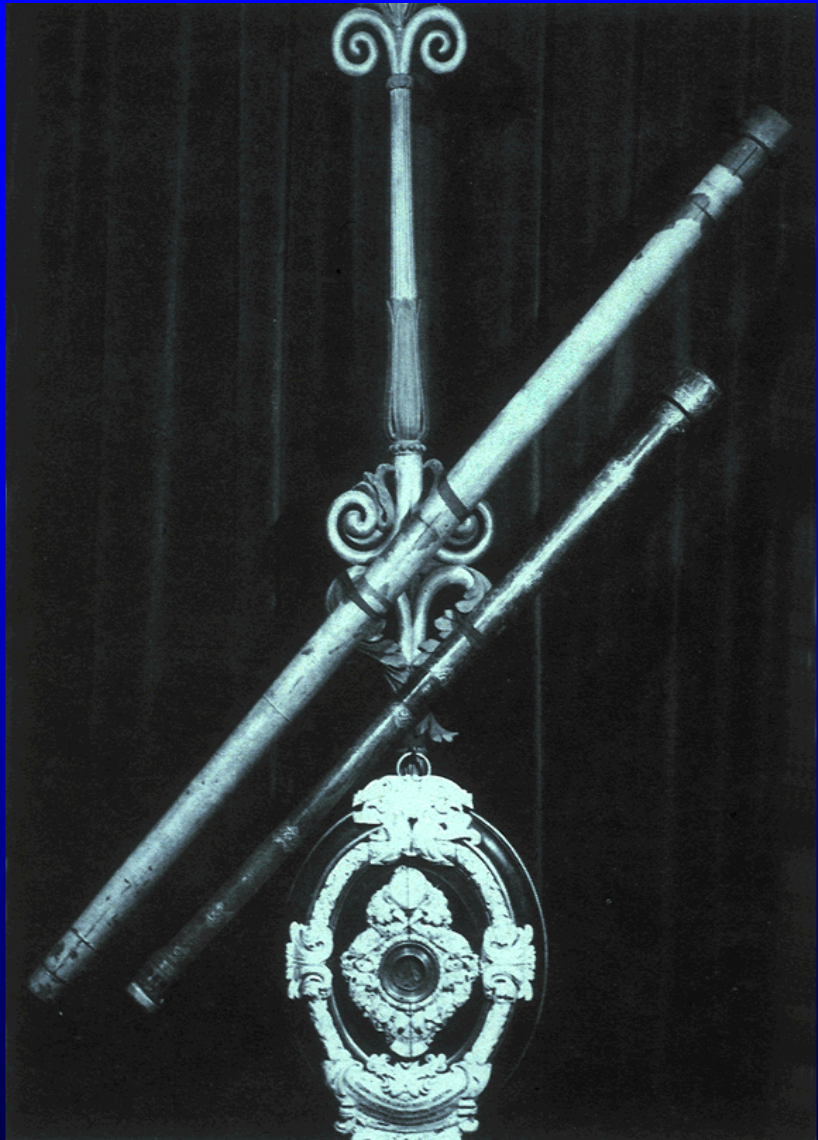
- The Earth is moving faster on the “inside track” so overtakes Mars which then appears to move backwards across the sky.

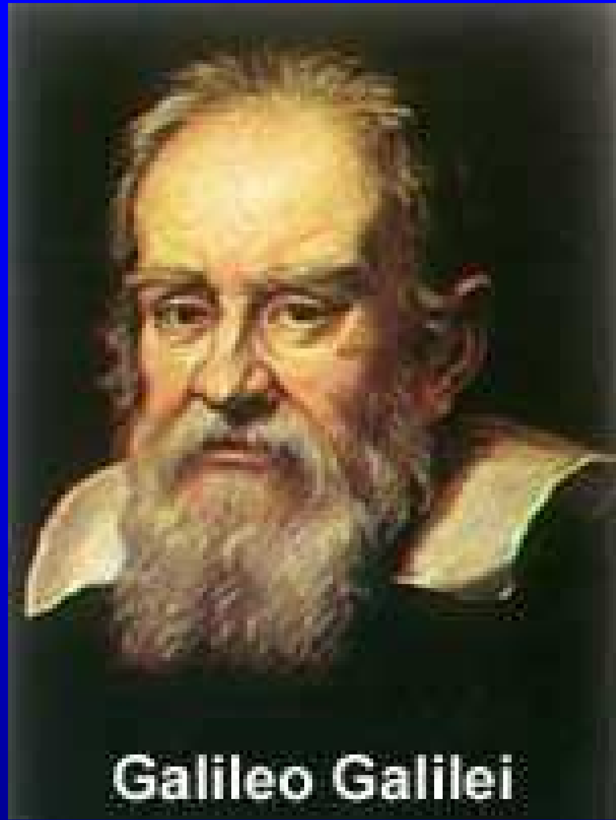


How observation proved that the Sun, not the Earth, is at the centre of the Solar System

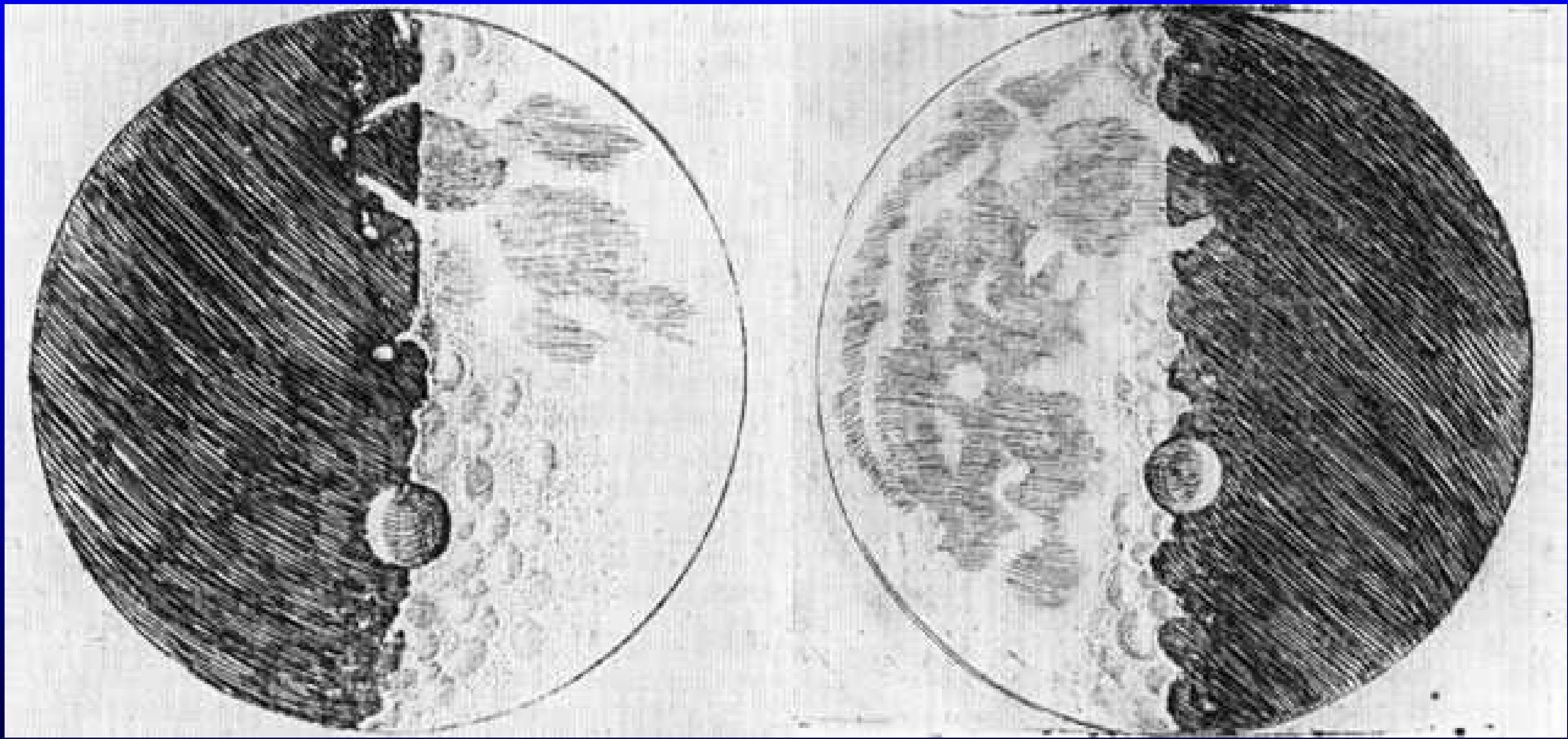
Observational Proof of the Copernican Model

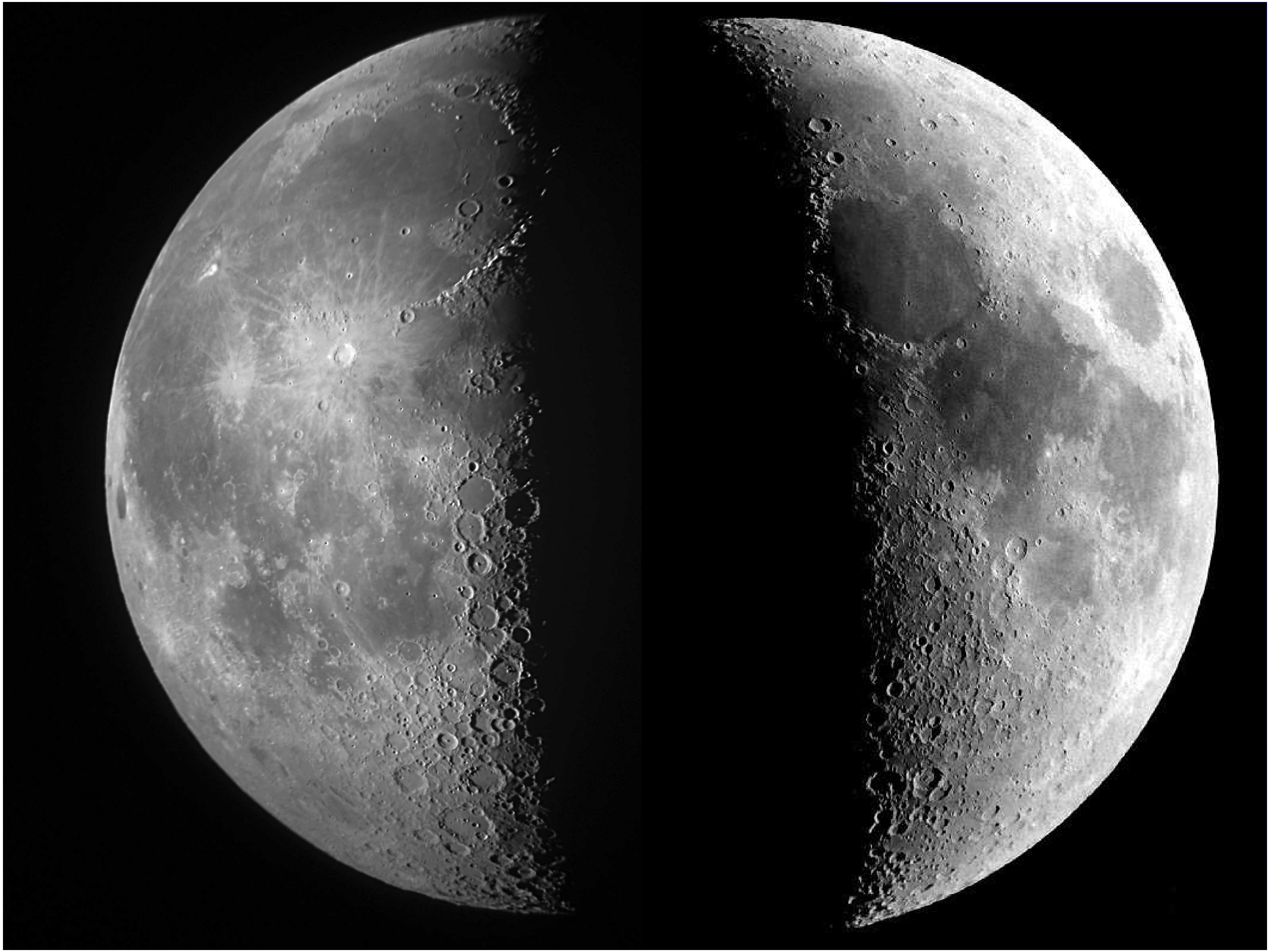
Observations of Venus by Galileo Galilei

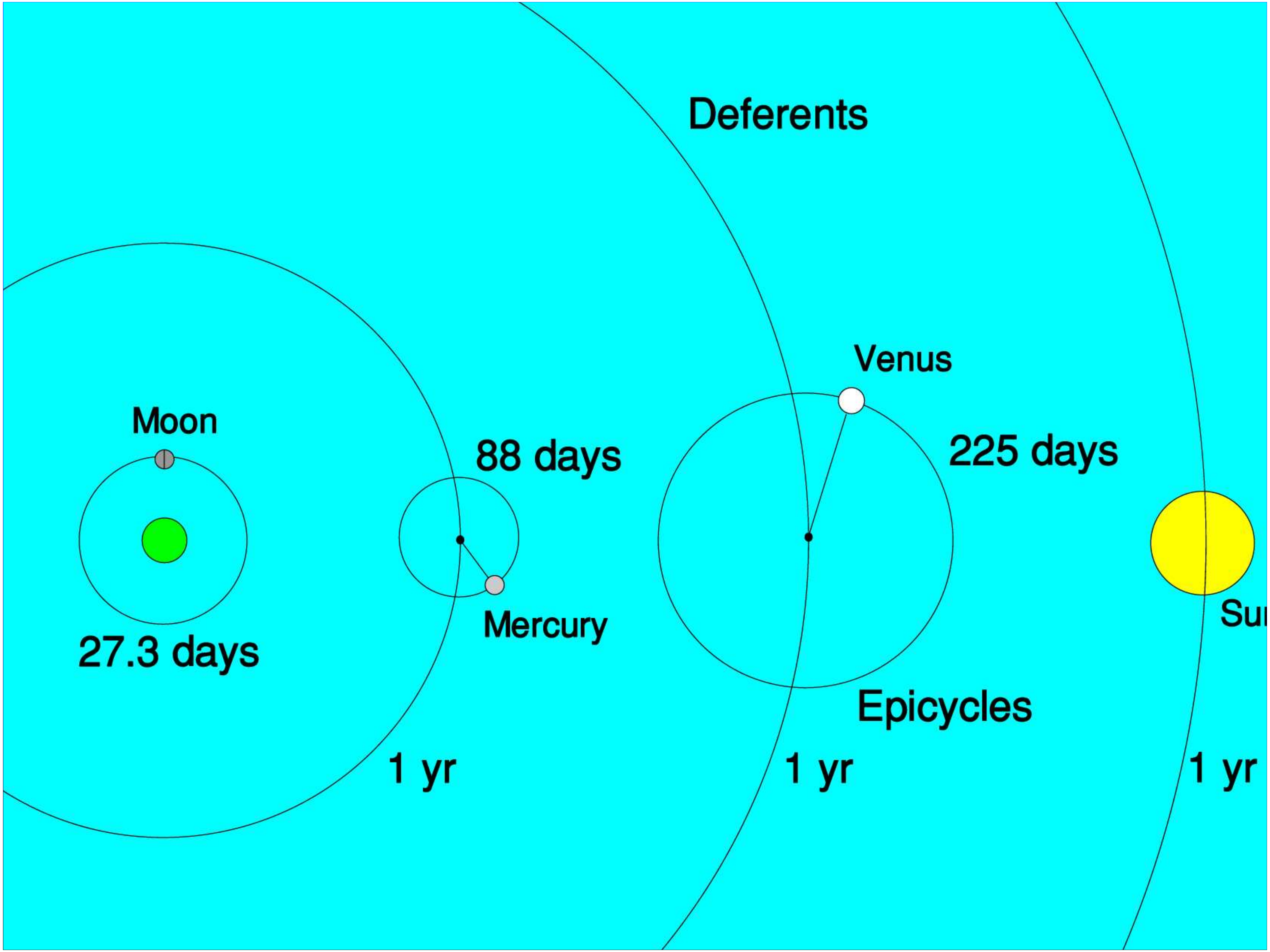



Galileo Galilei

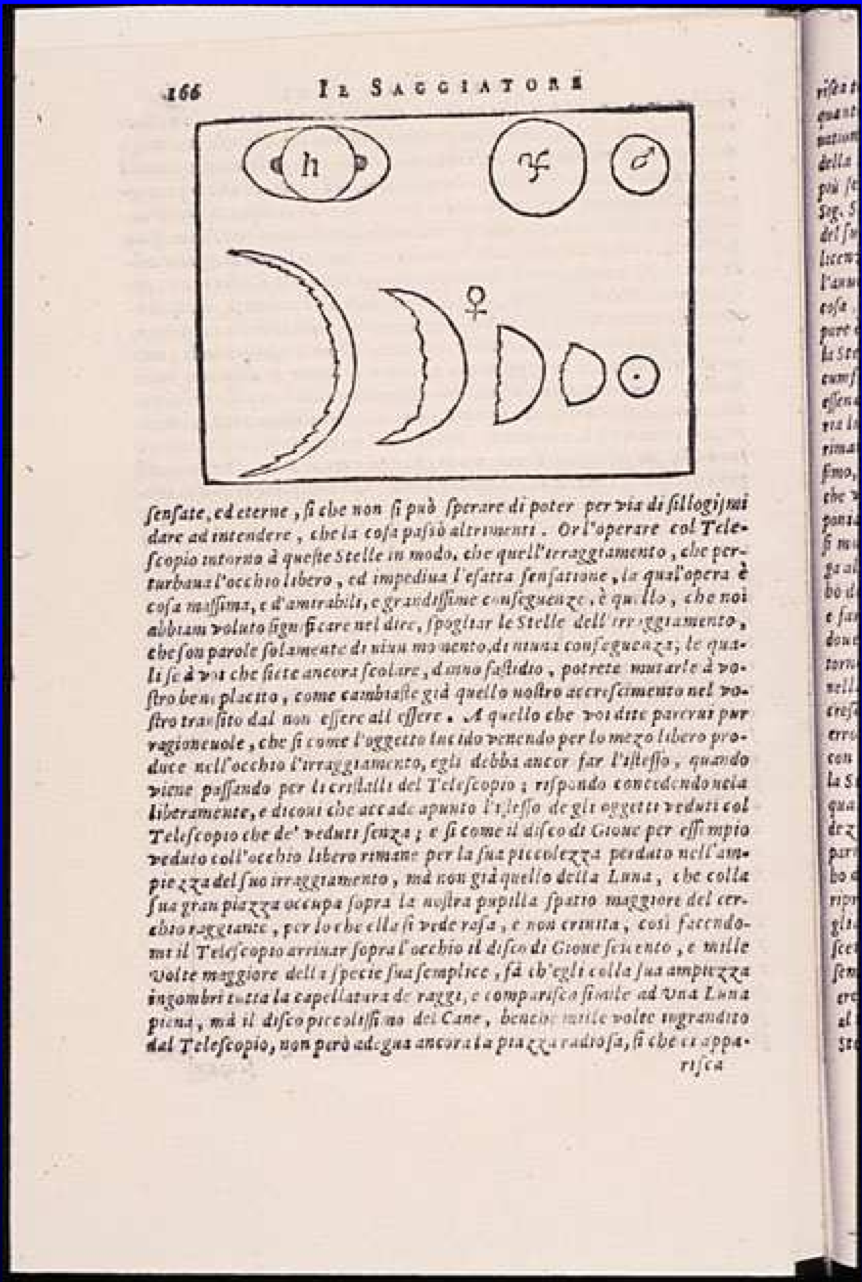
The Moon



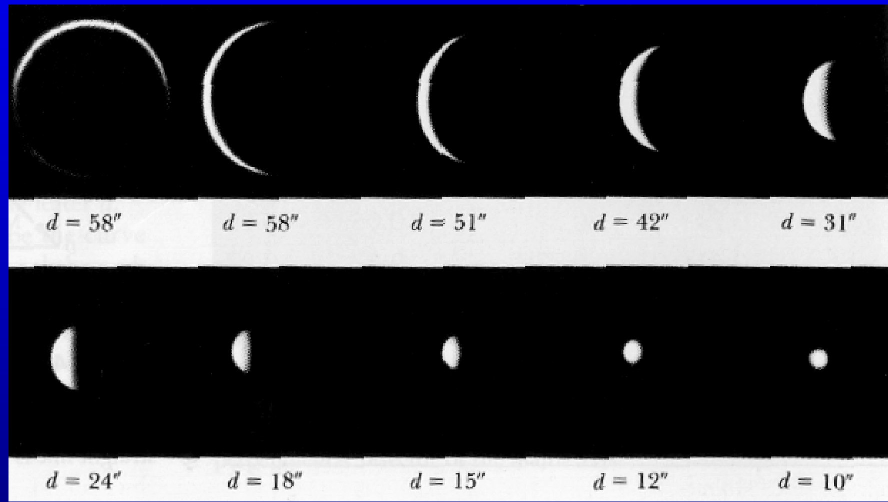


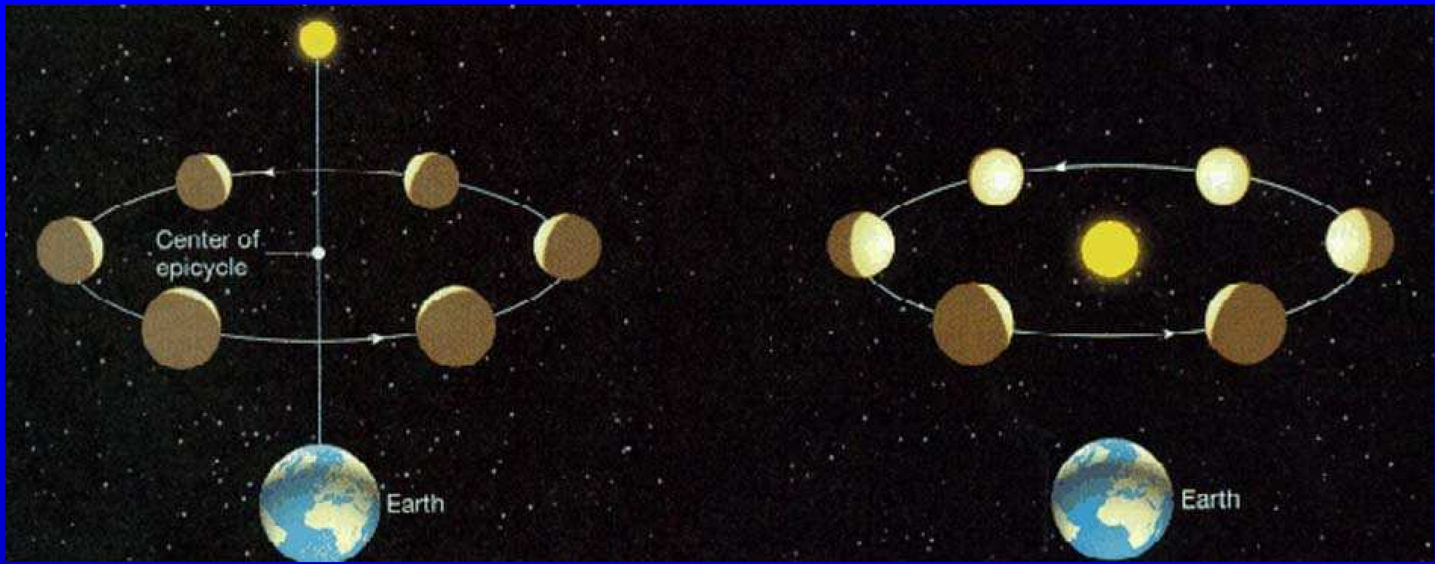

Deferents
Venus
Moon
88 days
225 days
Mercury
27.3 days
Epicycles
1 yr
1 yr
1 yr
Su

Venus



sensate, ed eterne, si che non si può sperare di poter per via di sillogismi dare ad intendere, che la cosa passò altrimenti. Or l'operare col Telescopio intorno à queste Stelle in modo, che quell'irraggiamento, che perturbava l'occhio libero, ed impediva l'esatta sensazione, la qual'opera è cosa massima, e d'ammirabili, e grandissime conseguenze, è quello, che noi abbiam voluto significare nel dire, spogliar le Stelle dell'irraggiamento, che son parole solamente di niun momento, di niuna conseguenza, le quali se à voi che siete ancora scolare, danno fastidio, potrete mutarle à vostro beneplacito, come cambiaste già quello nostro accrescimento nel vostro transito dal non essere all'essere. A quello che voi dite parervi pur ragionevole, che si come l'oggetto lucido venendo per lo mezo libero produce nell'occhio l'irraggiamento, egli debba ancor far l'istesso, quando viene passando per li cristalli del Telescopio; rispondo concedendonela liberamente, e dicovi che accade apunto l'istesso de gli oggetti veduti col Telescopio che de' veduti senza; e si come il disco di Giove per essempio veduto coll'occhio libero rimane per la sua piccolezza perduto nell'ampiezza del suo irraggiamento, mà non già quello della Luna, che colla sua gran piazza occupa sopra la nostra pupilla spatio maggiore del cerchio raggiante, per lo che ella si vede rasa, e non crinita, così facendomi il Telescopio arrivar sopra l'occhio il disco di Giove sessanta, e mille volte maggiore della specie sua semplice, fà ch'egli colla sua ampiezza ingombri tutta la capellatura de' raggi, e comparisca simile ad una Luna piena, mà il disco piccolissimo del Cane, benche mille volte ingrandito dal Telescopio, non però adegua ancora la piazza radiosa, si che ci apparisca

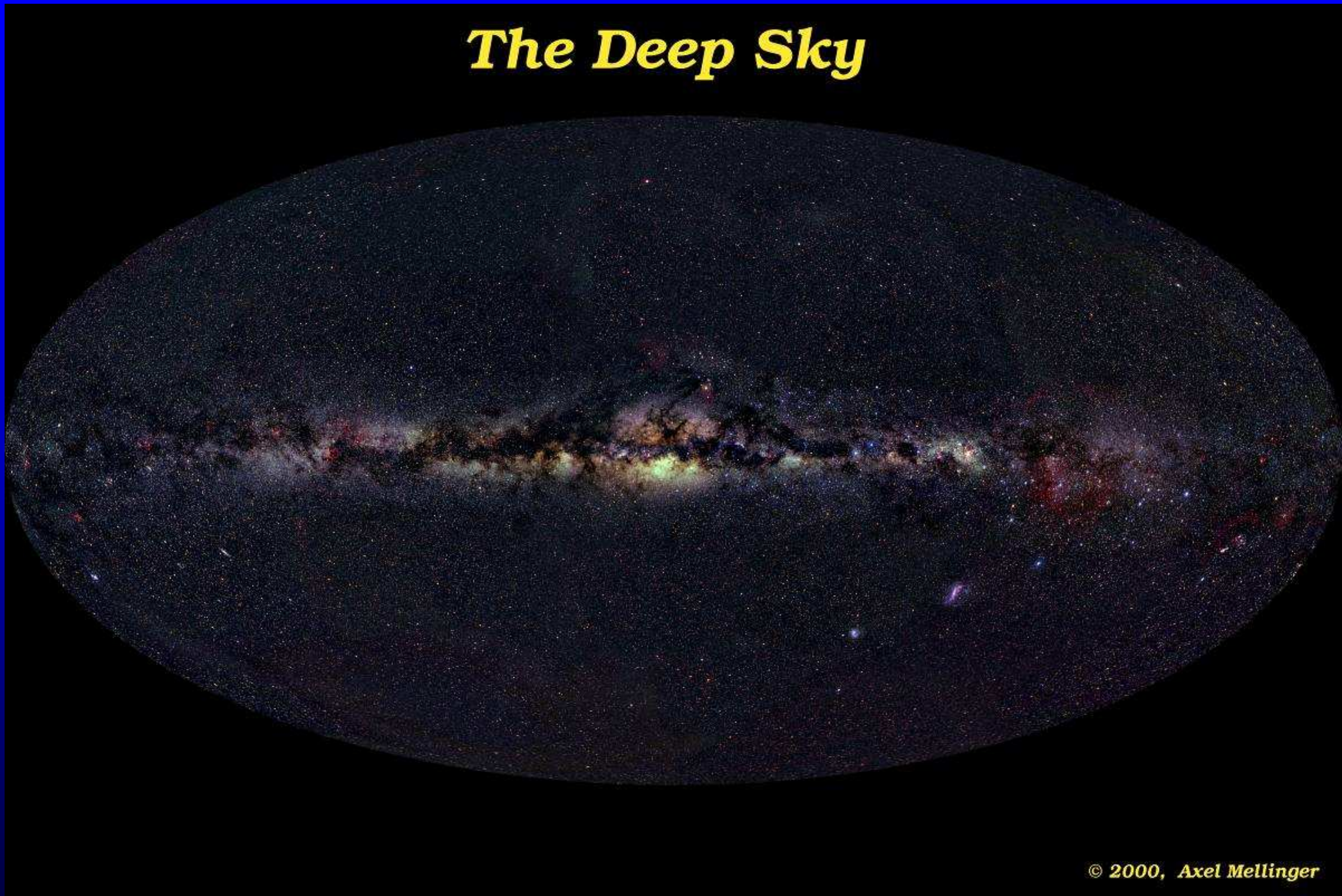




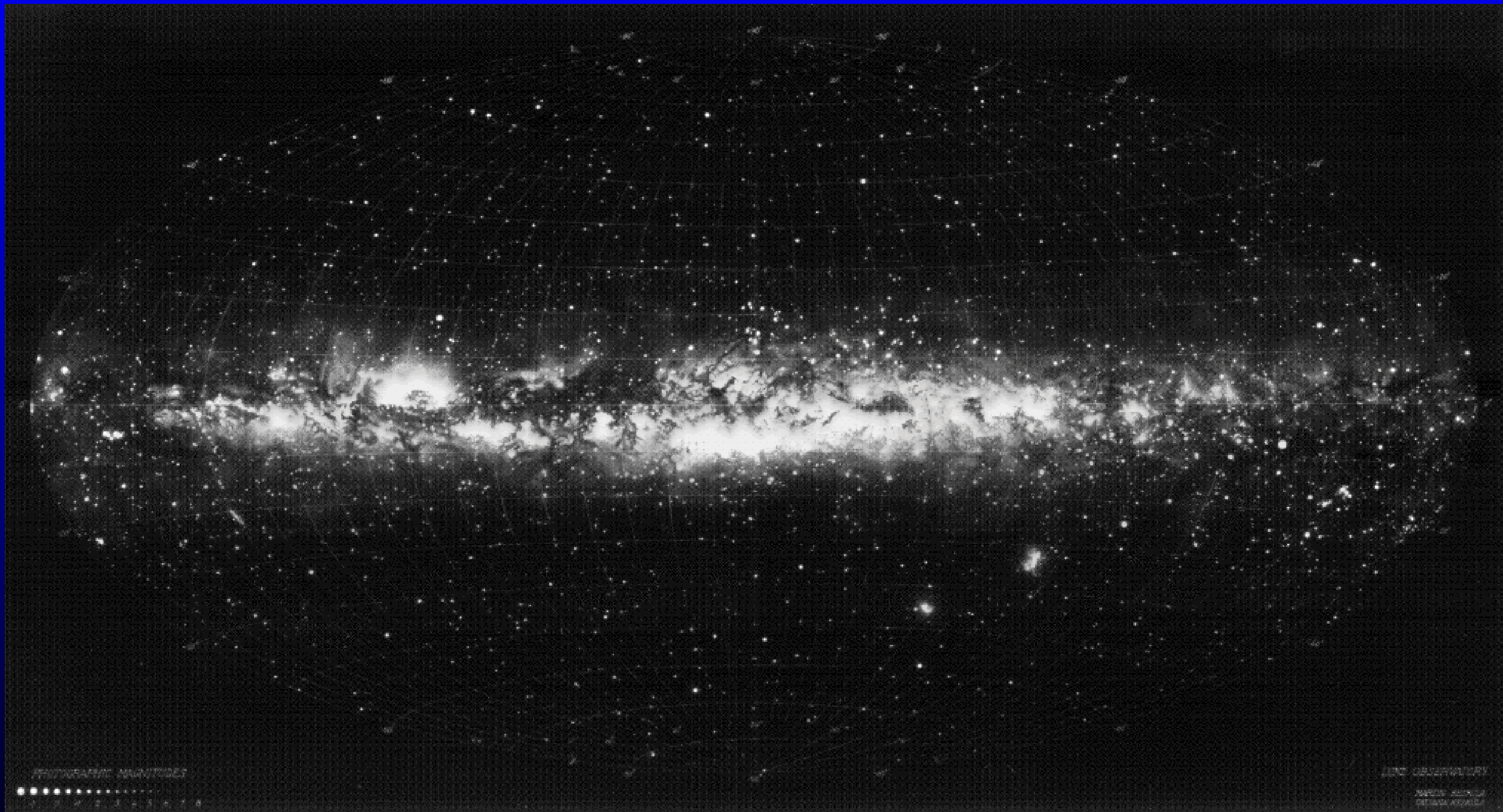
- If Venus lies between the Earth and Sun, it must always be backlight – so will show thin phases. Its angular size will not alter that much.
- If Venus orbits the Sun we will see almost full phases when it lie beyond the Sun and the angular size will change considerably as it moves around its orbit.

The Heavens

The Milky Way – our view of our own Galaxy

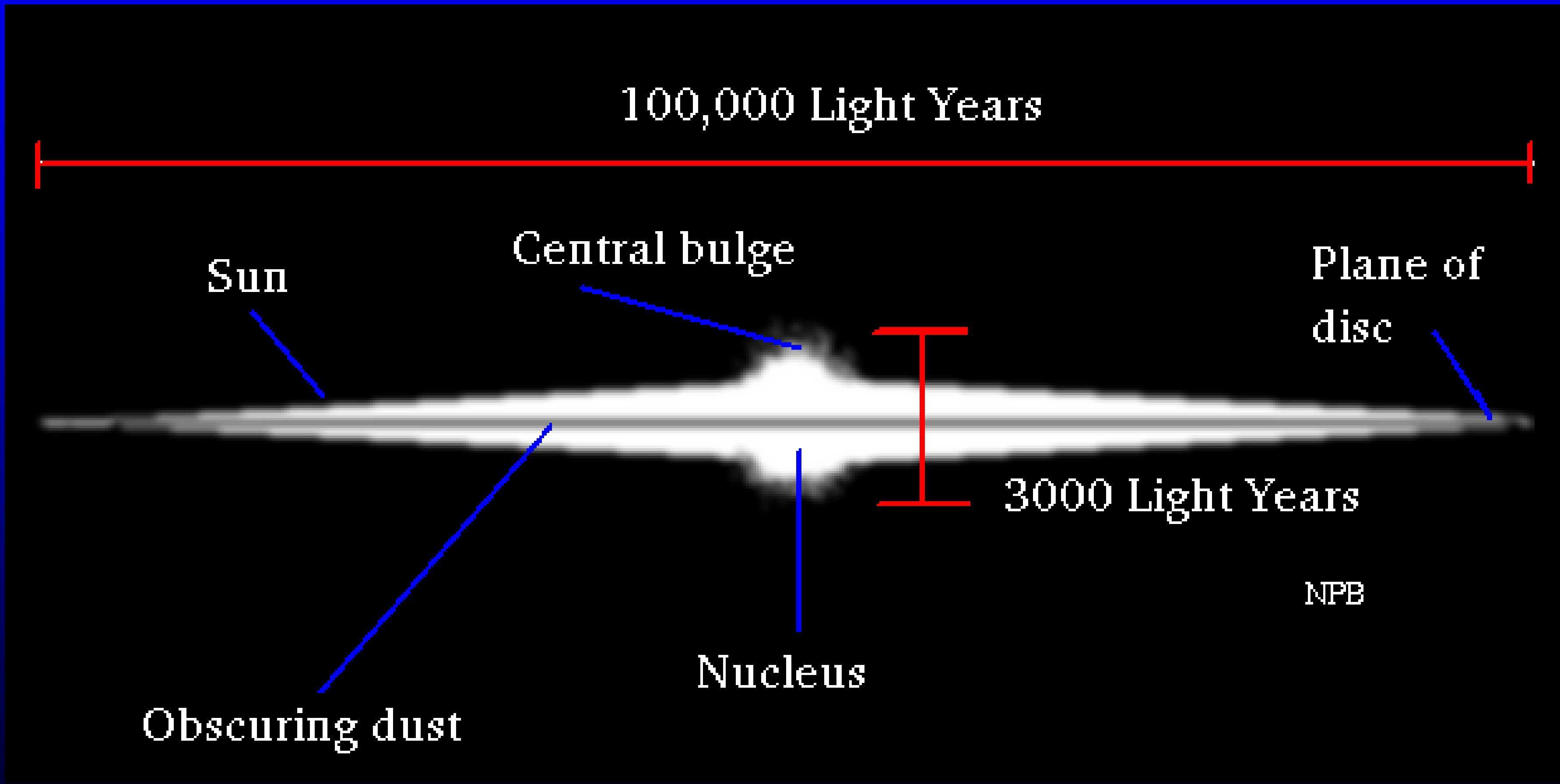

The Deep Sky
© 2000, Axel Mellinger

Our view of the Milky Way

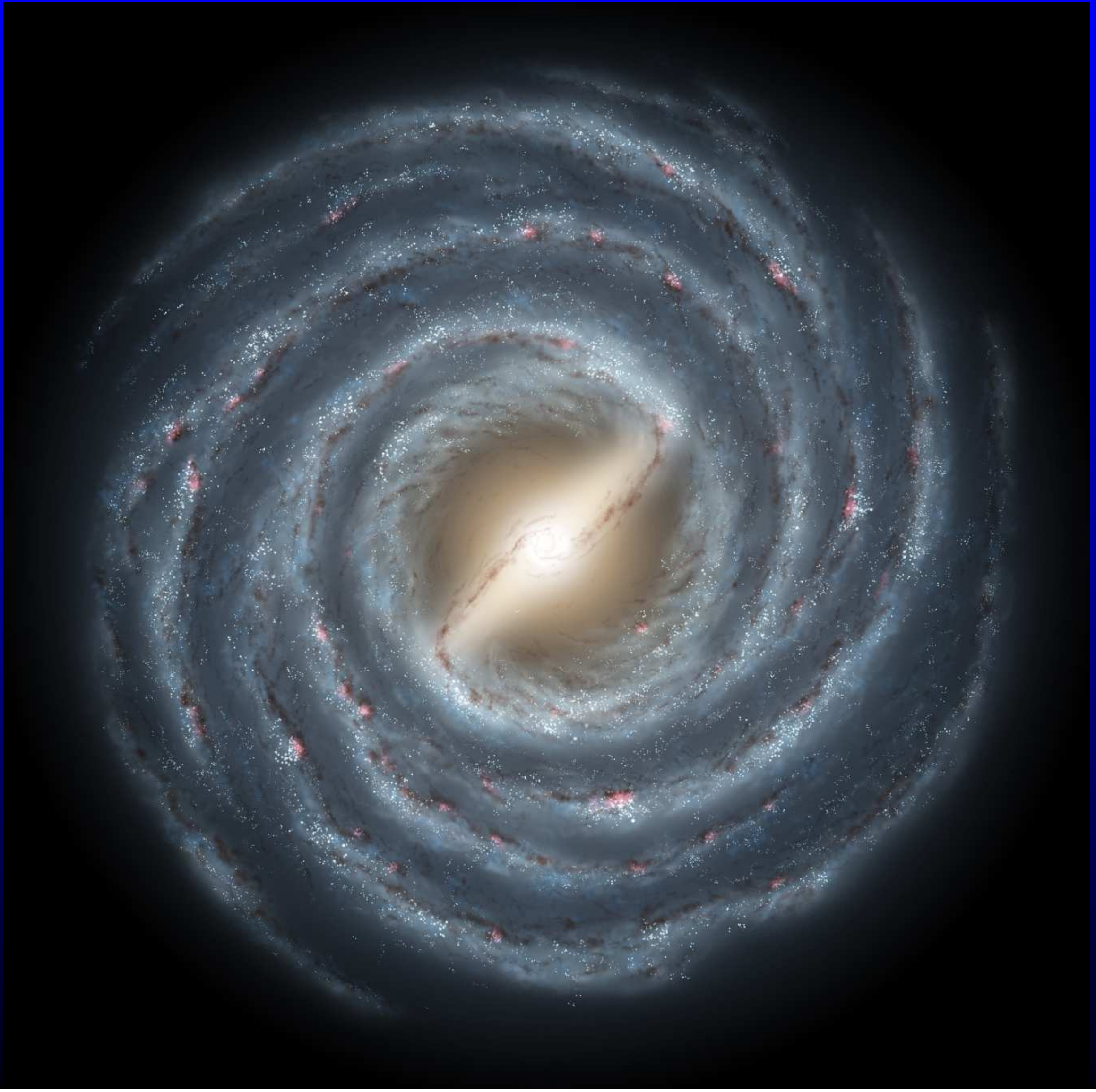


COBE Image of our Galaxy

Light takes 100,000 years to travel across the Galaxy

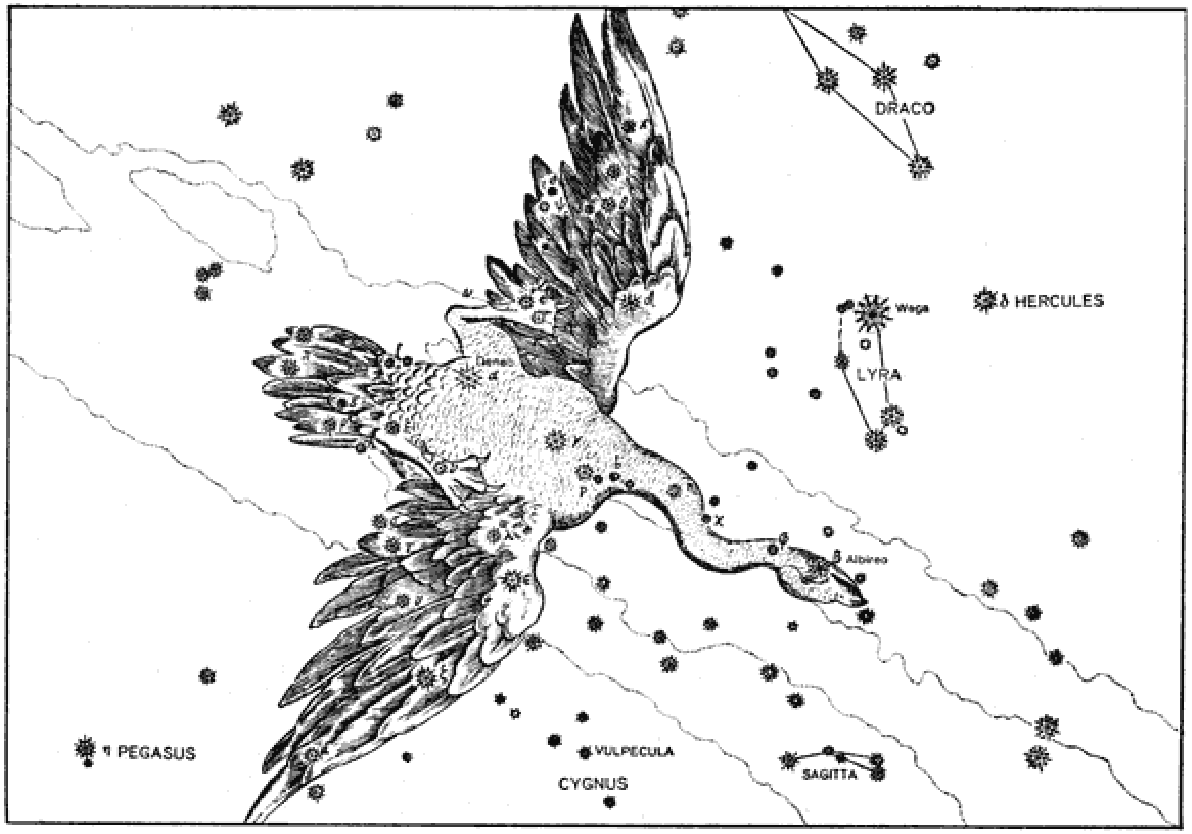


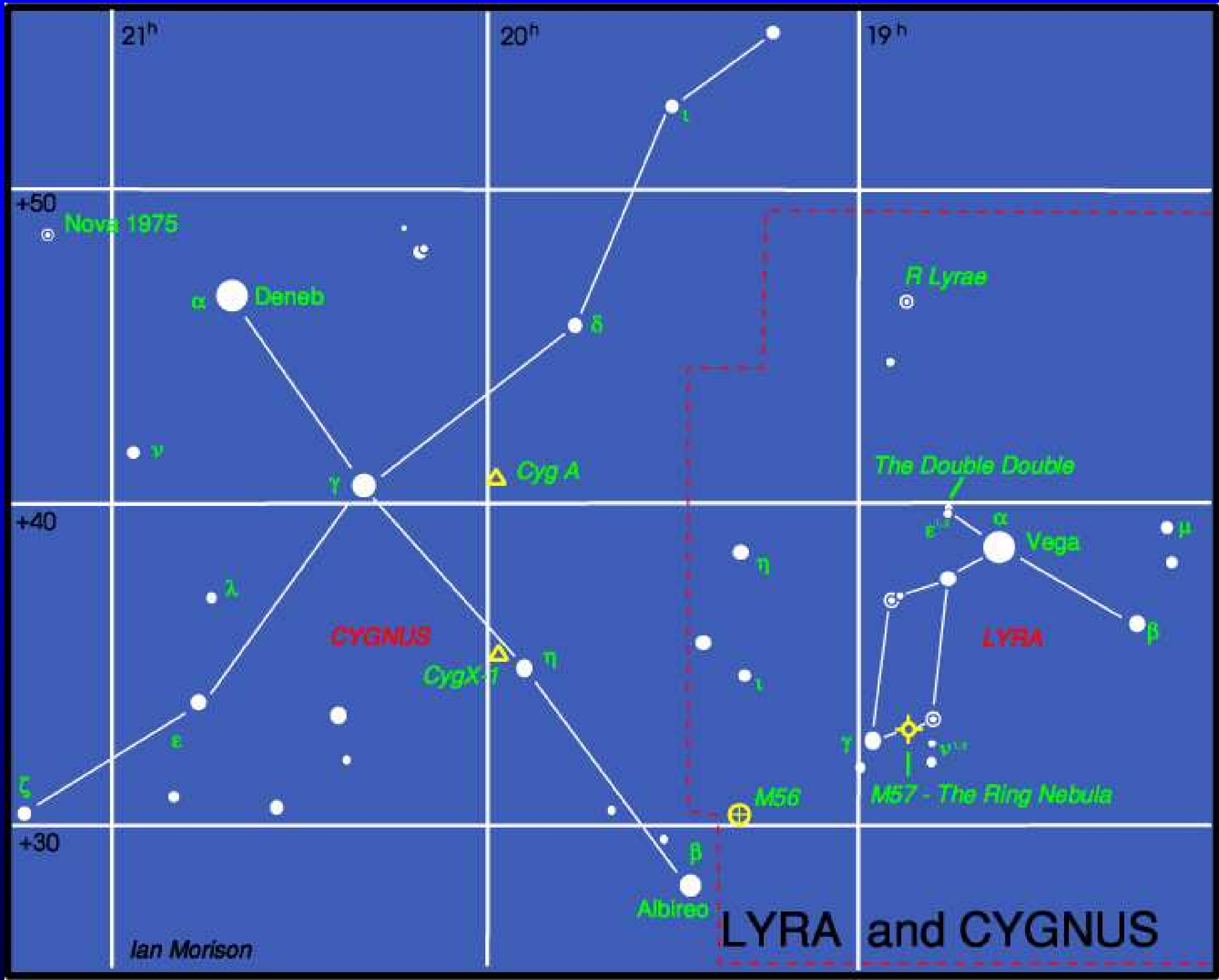
The Milky Way – a Barred Spiral



Constellations

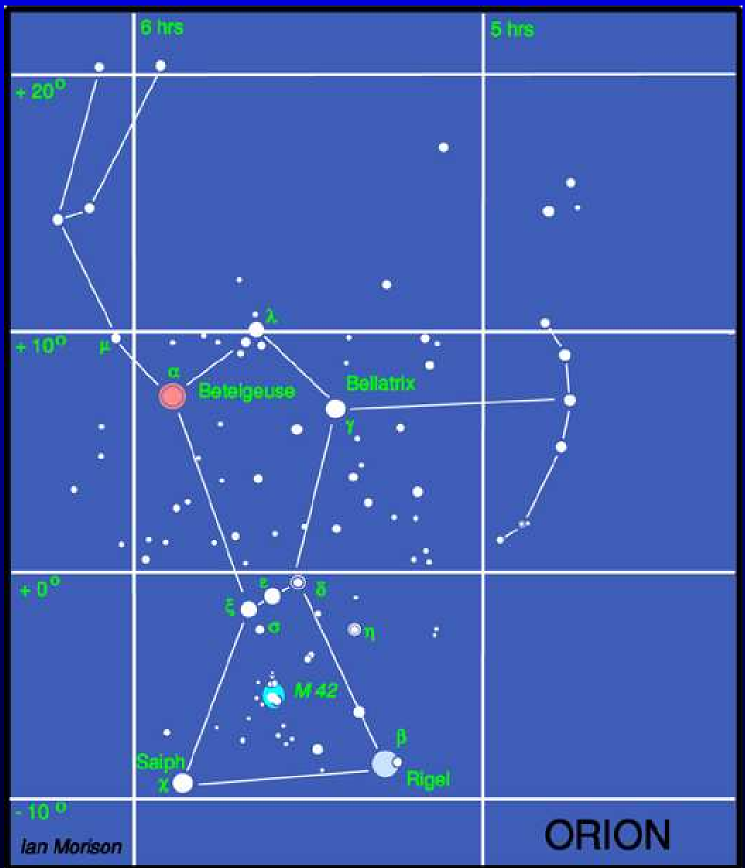
Cygnus the Swan




21h
20h
19h
+50
+40
+30
Nova 1975
Deneb
R Lyrae
Cyg A
The Double Double
Vega
CYGNUS
LYRA
CygX-1
M56
M57 - The Ring Nebula
Albireo
Ian Morison
LYRA and CYGNUS


©KAGAYA

Orion



6 hrs
5 hrs
+ 20°
+ 10°
+ 0°
- 10°
μ
λ
α
Betelgeuse
Bellatrix
γ
ε
δ
ξ
σ
η
M 42
β
Saiph
χ
Rigel
Ian Morison
ORION

Apparent Magnitudes

Classifying stars in terms of their brightness.

Hipparchus

- Lived 190 – 120 BC
- Discovered Precession
- Made catalogue of 850 stars
- Put the stars into 6 Magnitude groups, 1 to 6
- First Magnitude stars were brightest

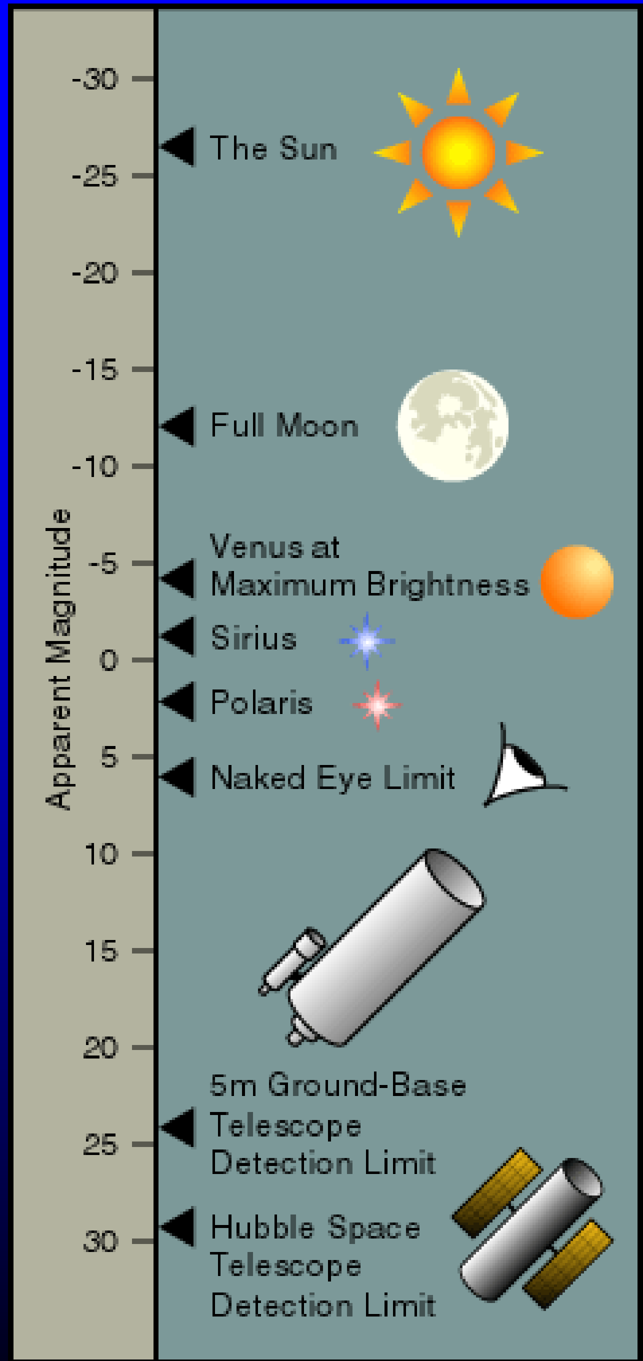
Quantitative Measurements

- In the 19th century, accurate measurements could be made of the brightness of stars.
- It was discovered that the brightest (first magnitude) were about 100 times brighter than the faintest (sixth magnitude)
- This was made a definition.
  - 5 magnitudes = a factor of 100 in brightness
  - So a star of 1st magnitude is exactly 100 times brighter than one of 6th magnitude.

- As the eye has a logarithmic response to brightness each magnitude step corresponded to an equal ratio in their brightness.
  - A first magnitude star was approximately 2.5 times brighter than a second – as was a second to a third and so on.
  - Let this factor be Z
  - Then a 5^{th} magnitude star is Z times brighter than a 6^{th}.
  - A 4^{th} magnitude star is ZxZ times brighter than a 6^{th}.
  - A 1^{st} magnitude star is ZxZxZxZxZ times brighter than a 6^{th}.
- BUT 5 magnitude steps = 100 in brightness
- So $Z = (100)^{1/5} = 2.512$

- It was found that some stars were brighter than 1st magnitude so we have some 0th magnitude star such as Vega.
- Some are brighter still so we allow negative magnitudes.
- Fractional Magnitudes are allowed too.
  - So Sirius has an apparent magnitude of –1.5.
- We can add planets and even the Sun to this magnitude scale

The range of Apparent Magnitudes



Remember

- The apparent magnitude tells us nothing about the luminosity of a star – how much radiation it is emitting into space.
- A bright star could actually be a low luminosity star close by OR a very luminous star very far away.

- From the logarithmic definition of the magnitude scale two formulae arise.
- The first gives the brightness ratio, R, of two objects whose apparent magnitude differs by a known value Δm:

$$R = 2.512^{\Delta m}$$

As an example, let us calculate how much brighter the Sun is than the Moon:

The difference in magnitudes is 26.7 – 12.6

$= 14.1$ so

$$R = 2.512^{(14.1)}$$

$$= 436{,}800.$$

The Sun is ~440,000 times brighter than the full Moon.

The second gives the magnitude difference between two objects whose brightness ratio is known. We can derive this from the first:

Taking logs to the base 10 of both sides of

$$R = 2.512^{\Delta m}$$

gives:

$$\mathrm{Log}_{10} R = \mathrm{Log}_{10}(2.512) \times \Delta m$$

$$\mathrm{Log}_{10} R = 0.4 \times \Delta m$$

$$\Delta m = \mathrm{Log}_{10} R / 0.4$$

$$\Delta m = 2.5 \times \mathrm{Log}_{10} R$$

A star has a brightness which is 1,000 times less than Vega (magnitude 0). What is its magnitude?

Using the formula:

$$\begin{aligned}\Delta m &= 2.5 \text{ x } \mathrm{Log}_{10}(1{,}000)\\ &= 2.5 \text{ x } 3\\ &= 7.5\end{aligned}$$

So the star will have a magnitude of (0+7.5)

$$= 7.5$$

Seeing Fainter Objects

- Instruments such as binoculars and telescopes collect more light that our eyes so enable us to see fainter objects.
- How can we calculate by how much?

Binoculars

- Specified as for example 8 x 40
- First number is the magnification
- Second number is the diameter of the objective lens in mm
- Assuming a eye pupil of 5 mm, a 40mm objective will collect $(40/5)^2$ more light.
  - = 64 times
  - This will allow you to see stars about 4.5 magnitudes greater.
  - Why?

- 1 magnitude = ~2.5
- 2 magnitudes = ~6.3 (2.5 x 2.5)
- 3 magnitudes = ~16 (2.5 x 2.5 x 2.5)
- 4 magnitudes = ~40
- 5 magnitudes = 100

64 lies between 40 and 100

Finding the accurate value

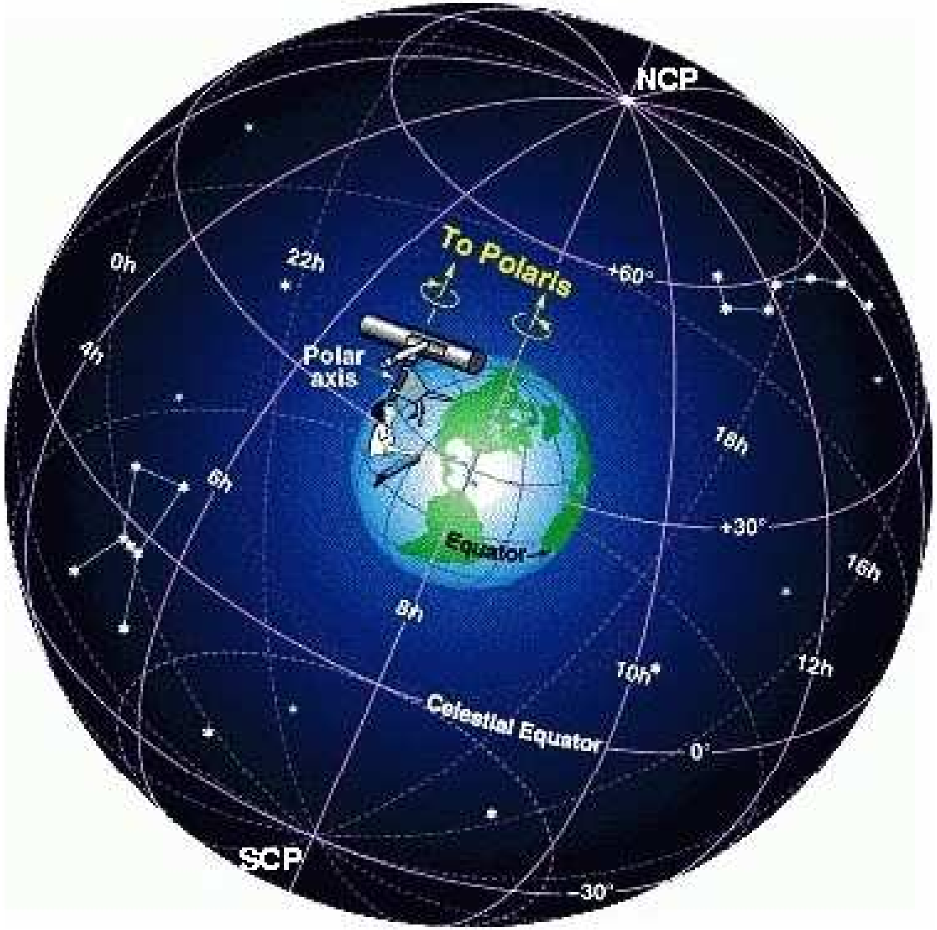
1) Find the brightness ratio R
2) Find $\log_{10}(R)$
3) Multiply by 2.5

For these binoculars R = 64

$\log_{10}(R) = 1.8$

$M = 2.5 \times 1.8 = \mathbf{4.51}$

Celestial Co-ordinate System


NCP
To Polaris
Polar
axis
0h
22h
+60°
4h
18h
6h
+30°
Equator
16h
8h
12h
10h
Celestial Equator
0°
SCP
-30°

The Celestial Co-ordinate System

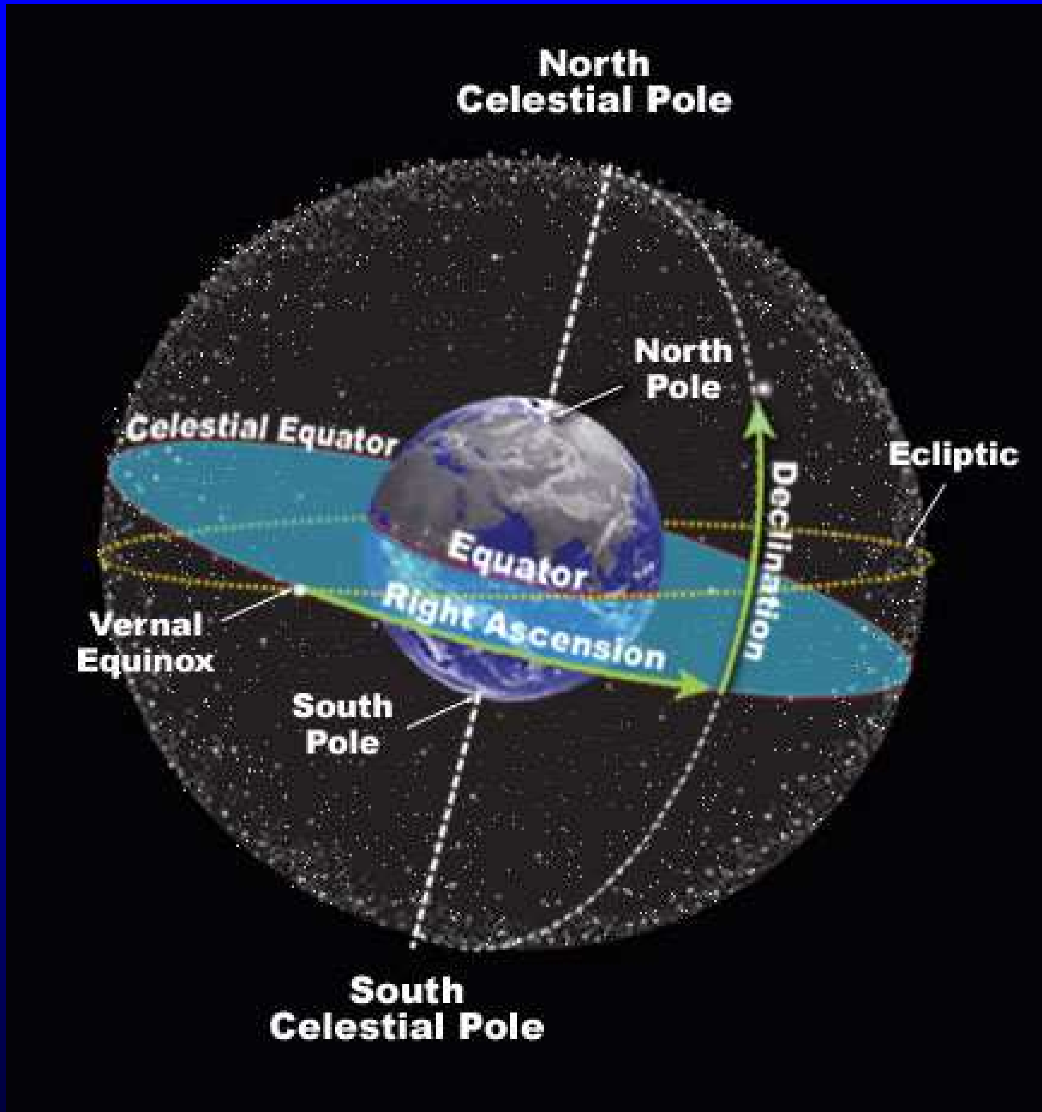
- Uses the Earth's poles and equator as its basis.
- Stars are positioned on the Celestial Sphere.
- The North and South Celestial Poles are where the Earth's rotation axis meets this sphere.
  - North Celestial Pole (Near the Pole Star)
  - South Celestial Pole (no bright star is close)

Celestial Equator

- The Celestial Equator is the projection of the Earth’s Equator onto the Celestial Sphere.
- The coordinate system used for stellar (and planetary) positions is similar to the use of Latitude and Longitude on Earth.

The Ecliptic

- The path of the Sun across the sky is called the Ecliptic.
- It defines the plane of the Solar System.
- So the planets will be found close to the ecliptic.


North
Celestial Pole
North
Pole
Celestial Equator
Ecliptic
Declination
Equator
Right Ascension
Vernal
Equinox
South
Pole
South
Celestial Pole

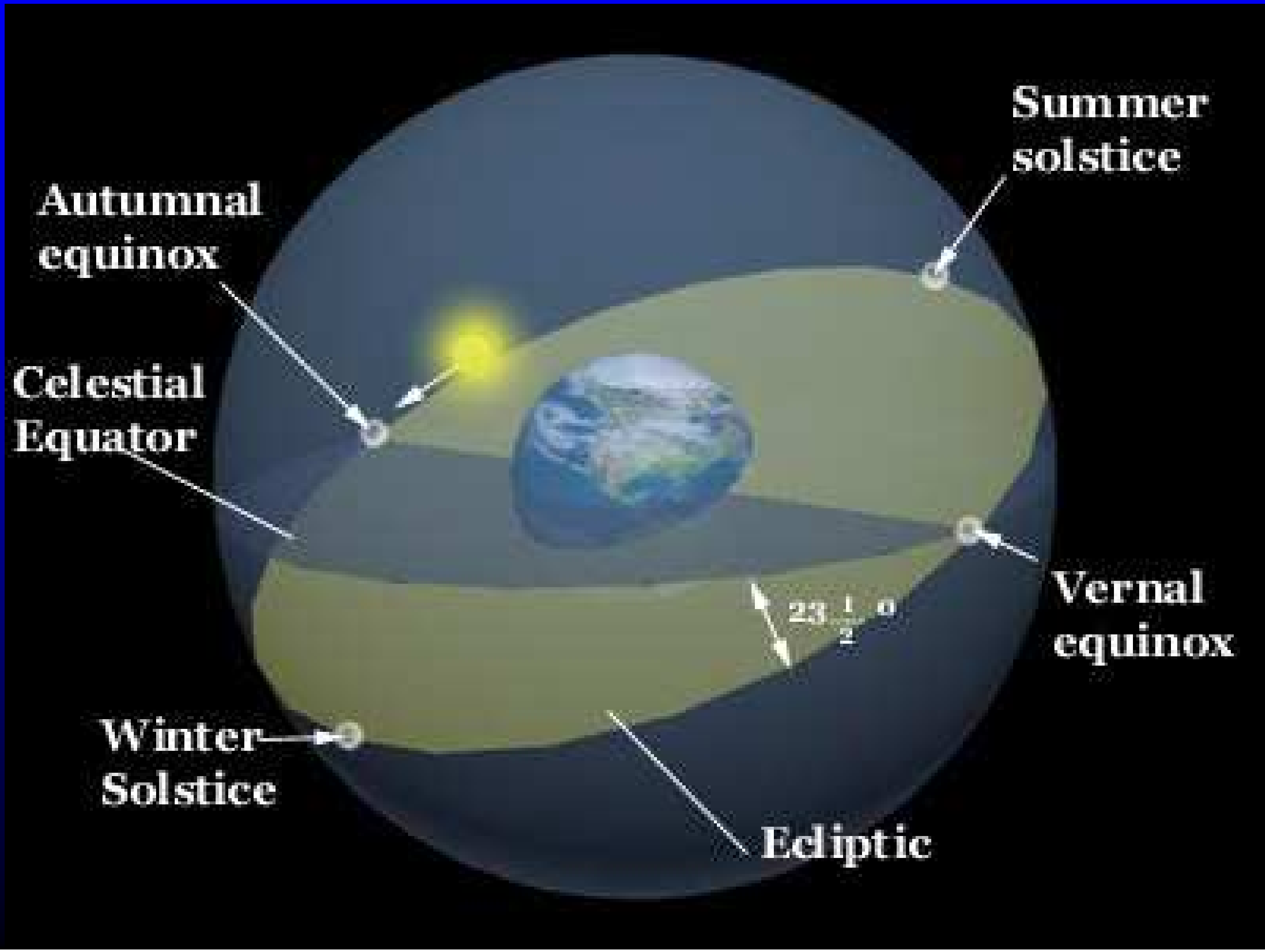
Declination

- Declination (dec) is used to define the position of the star above or below the celestial equator. (similar to latitude).
  - A star on the celestial equator has zero declination
  - Towards the north celestial pole it has positive declination
  - Towards the south celestial pole is has negative declination
  - The north celestial pole is at dec +90.

Right Ascension

- The position around the celestial sphere is defined by the Right Ascension (RA) of the Star.
- It is usually defined in hours, minutes and seconds with 24 hrs = 360 degrees.

  1 Hour = 15 degrees
- The zero of RA is arbitrary (like the zero of longitude) and is defined as the point where the Sun crosses the celestial equator at the Vernal Equinox. (The first day of Spring.)
  - This point is called the First Point of Aries


Summer solstice
Autumnal equinox
Celestial Equator
Vernal equinox
$23\frac{1}{2}°$
Winter Solstice
Ecliptic

- Looking at this point due south, RA increases to the East (leftwards)
  - A star with a RA of 1 hour will cross the Meridian (the line defining due south) ~1 hour later that one with an RA of 0 hours.
  - To be able to specify the RA we need to know how we define time so we have to take a look how this has developed over the years.

TIME

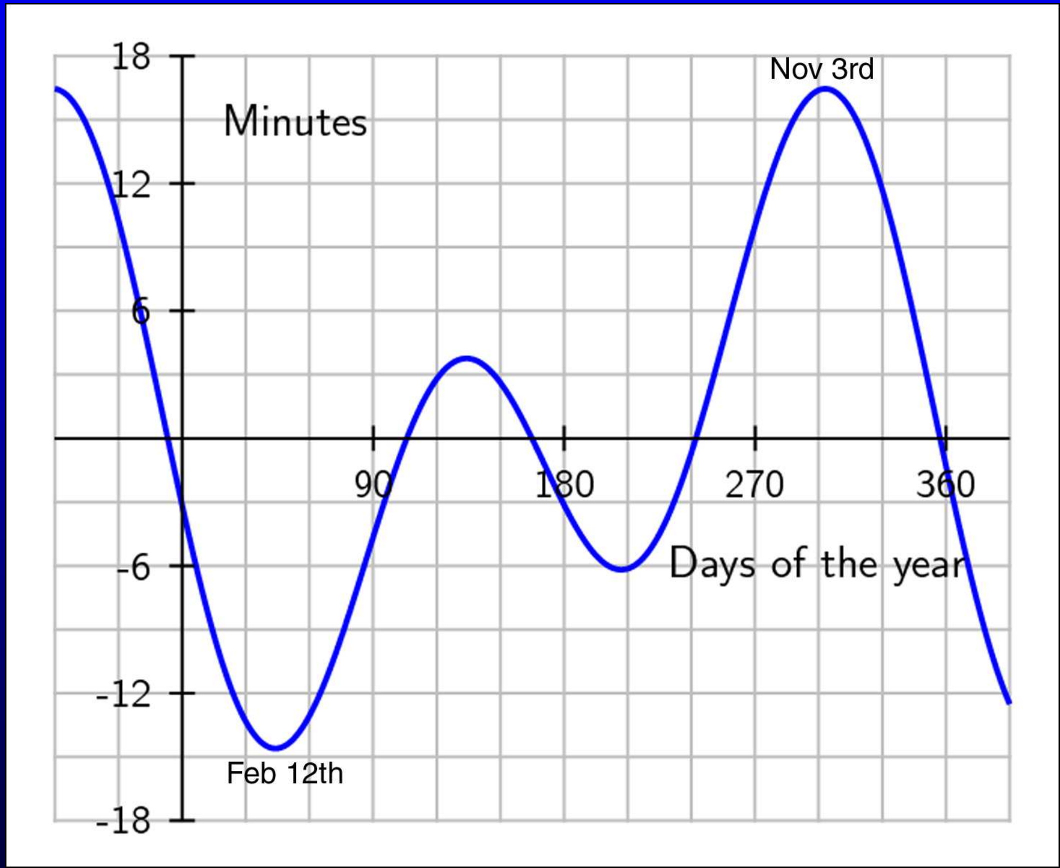
Local Solar Time

- 24 hours per day
- Sun is due south at Noon (midday)
- Varies by ~ 36.8 minutes from the East to the West of the UK!
- Problem when trains came into use.
- So use one time for the whole of the UK ~ Solar time for London (Greenwich) – but there is a another problem.

Greenwich Mean Time

- As the Earth's orbit is elliptical, the length of the day varies slightly.
- So we use a "mean time" and 24 hours is the average length of the day.
- One result is that the Sun is not always due south at midday (in London).
  - Up to 17 minutes difference.
  - Sunrise and sunset are not symmetrically spaced about 12 noon.

Equation of Time



Universal Time

- GMT was formally replaced by Universal Time (UT) in 1928.
- In 1967 the definition of the second was changed.
- The problem was that due to the tidal forces of the Moon, the Earth's rotations rate is gradually slowing - this means that the length of time defined by the second was increasing!

Atomic Time

- In 1967 the definition of the second was changed to one based on a Caesium Beam Atomic Frequency Standard:

The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

Leap Seconds

- This has not stopped the Earth slowing down so very gradually the synchronization between the Sun's position in the sky and our clocks would be lost. To overcome this, when the difference between the time measured by the atomic clocks and the Sun differs by around a second, a leap second is inserted to bring solar and atomic time back in step.

- This is usually done at midnight on New Year’s Eve or the 30th June. Since the time definition was changed, 22 leap seconds have had to be added, about one every 18 months, but there were none between 1998 and 2005 showing the slowdown is not particularly regular. Leap seconds are somewhat of a nuisance for systems such as the Global Positioning System (GPS) Network and there is pressure to do away with them which is, not surprisingly, opposed by astronomers! If no correction were made and the average slow down over the last 39 years of 0.56 of a second per year continues, then in 1000 years UT and solar time would have drifted apart by ~ 9 minutes.

Now back to where we were

- Looking at this point due south, RA increases to the East (leftwards)
  - A star with a RA of 1 hour will cross the Meridian (the line defining due south) ~1 hour later that one with an RA of 0 hours.

Sidereal Day

- Why approximately 1 hour, not exactly 1 hour?
- The stars appear to rotate around the Earth in just less than 24 hours
  - 23 hours 56 minutes and 4 seconds.
- Why?
  - The apparent motion of the stars is caused by a combination of BOTH the rotation of the Earth
    - ~365 times per year
  - AND the rotation of the Earth in its orbit around the Sun
    - Once per year.

- The stars thus appear to rotate around the Earth 366 times per year.
- Thus the sidereal day is
  - 365/366 x 24 hours.
  - Difference is 1/366 x 24 hours

    = ~ 24 x 60 / 366

    = ~ 3.93 minutes

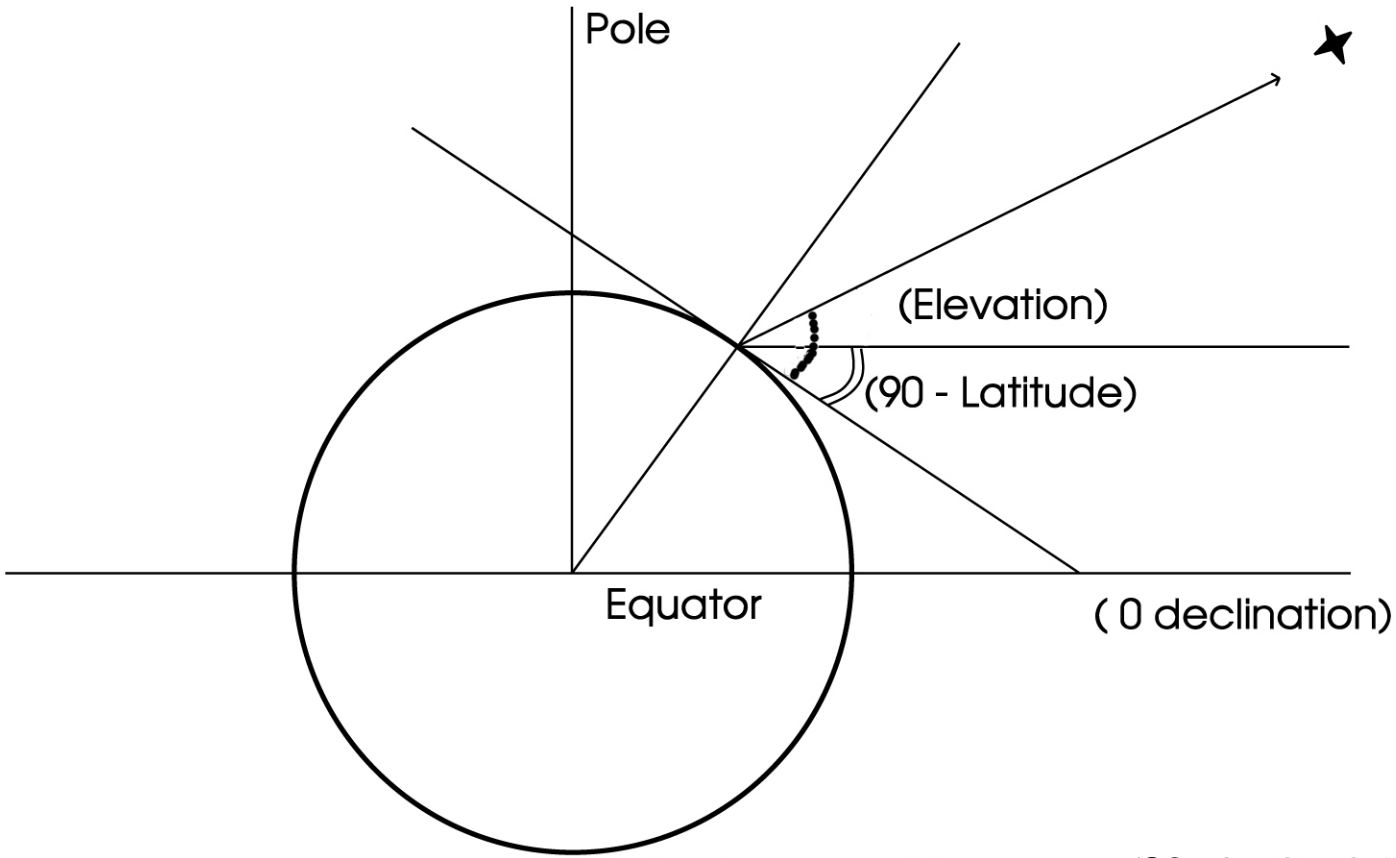
The period of 23 hours 56 minutes and 4 seconds is called the Sidereal Day.

- A star will thus be seen to cross the meridian ~ 4 minutes earlier each night.
- This means that the star patterns, called constellations, that we see in the sky each night vary throughout the year.

Finding Stellar Co-ordinates

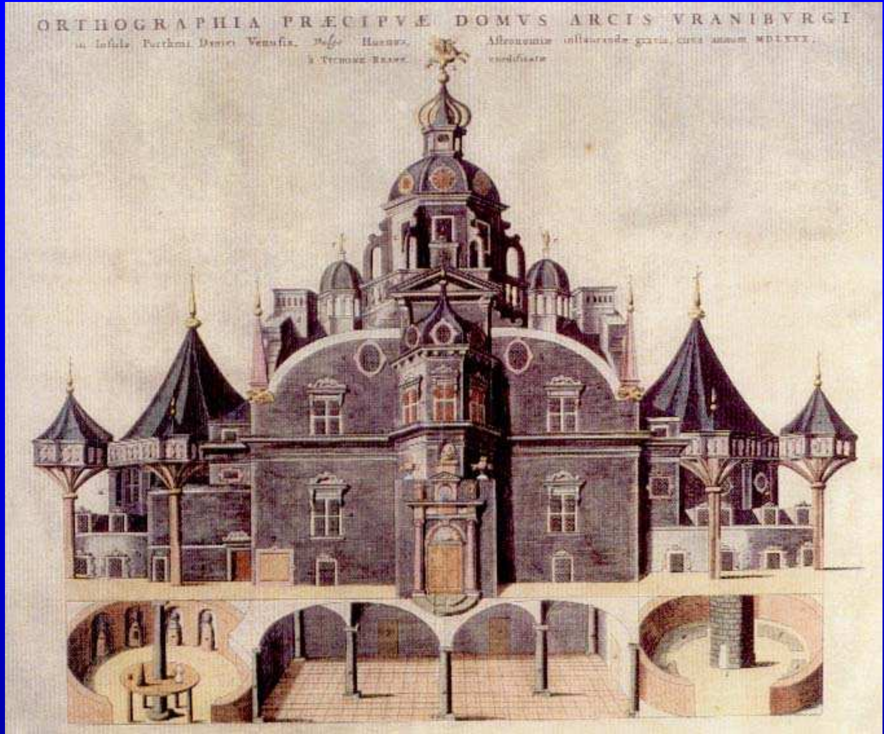
- Have a clock running on Sidereal Time – so the first point in Aries is on the meridian at 0 hrs.
- Use a transit telescope
  - Which observes on the meridian and can only move in elevation.
- Measure the time at which a star crosses the Meridian – this directly give the Right Ascension
- Measure the Elevation of the star.

$\text{Dec} = \text{Elevation}_{\text{star}} - (90 - \text{Latitude})$

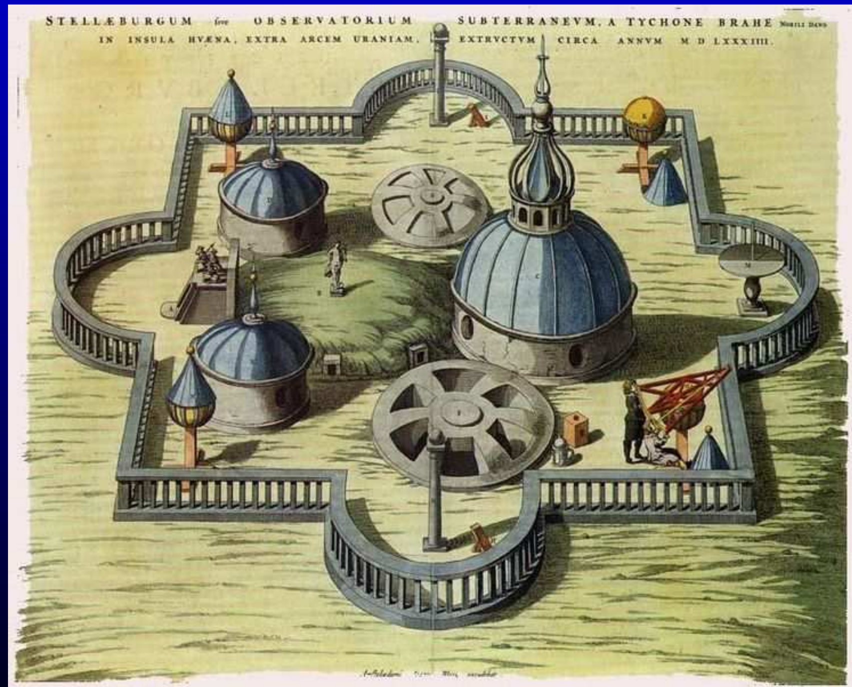


Declination = Elevation - (90 - Latitude)

1572: Tycho's Supernova



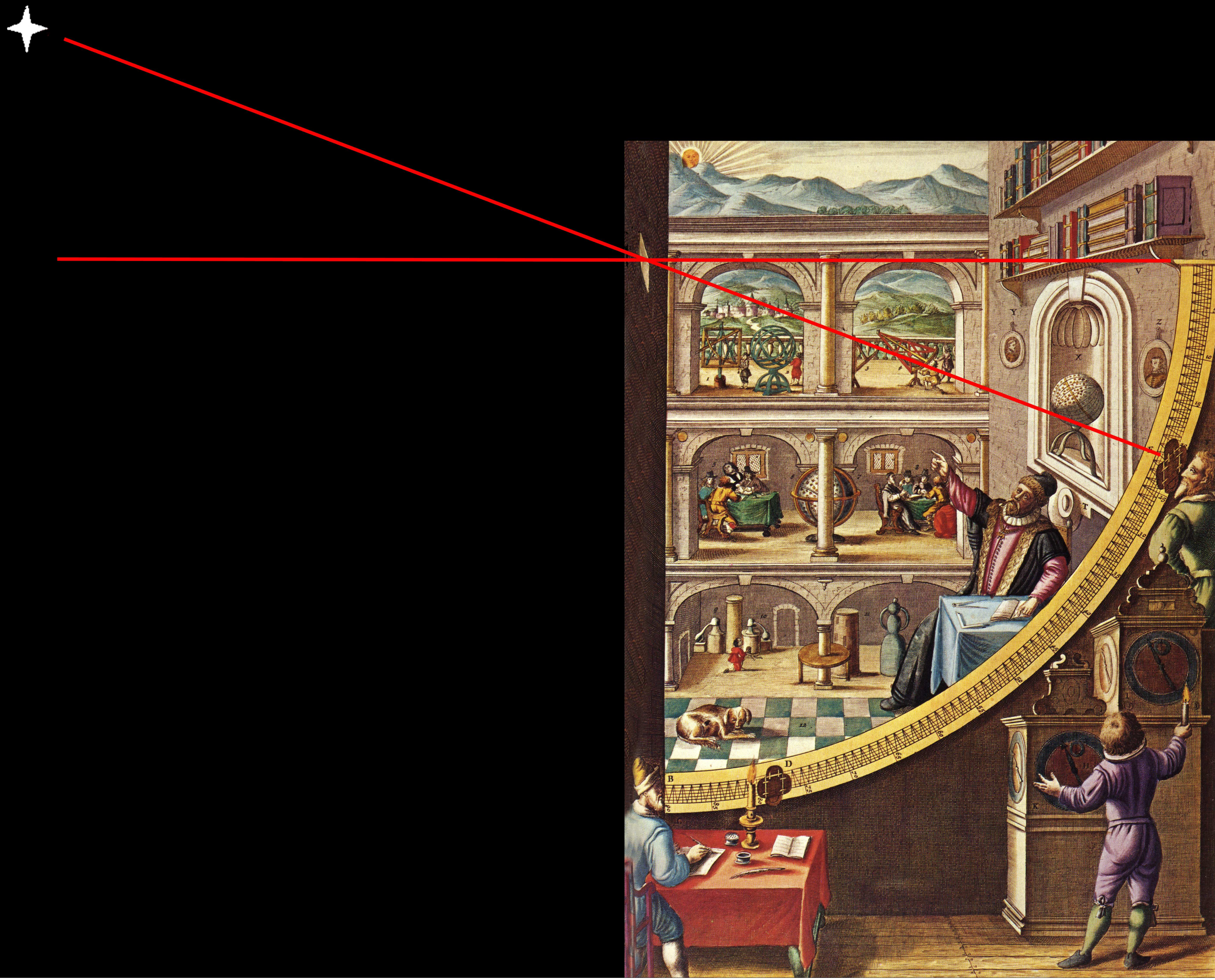
Tycho Brahe at Uraniborg



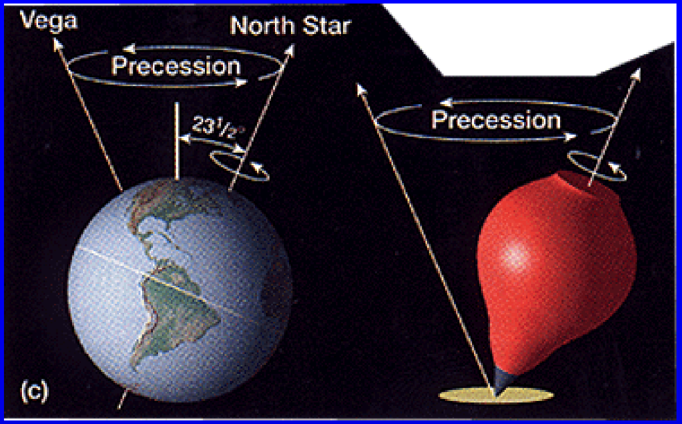
Tycho’s Quadrant

- Tycho Brahe built a large quadrant (with vernier scales) to measure the elevation of a star as it crossed the meridian – so enabling the declination of a star to be measured. By using a clock (lower right in the images to follow) to measure the Sidereal Time when the star crossed the meridian the Right Ascension of the star could be measured.

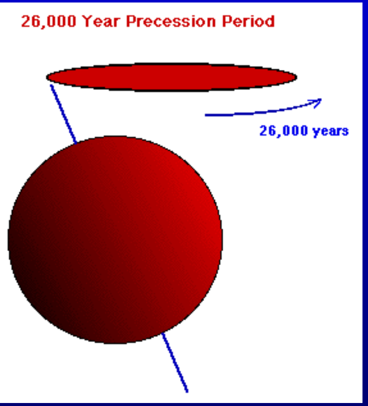
Tycho's Quadrant



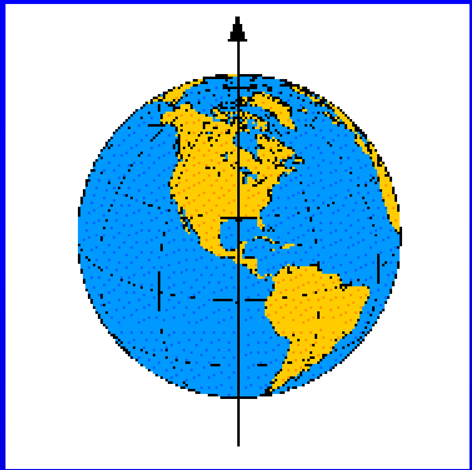
Precession

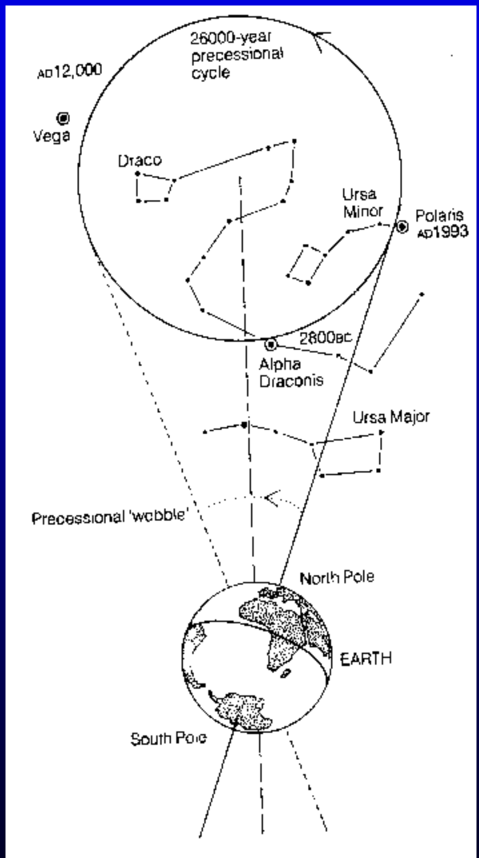


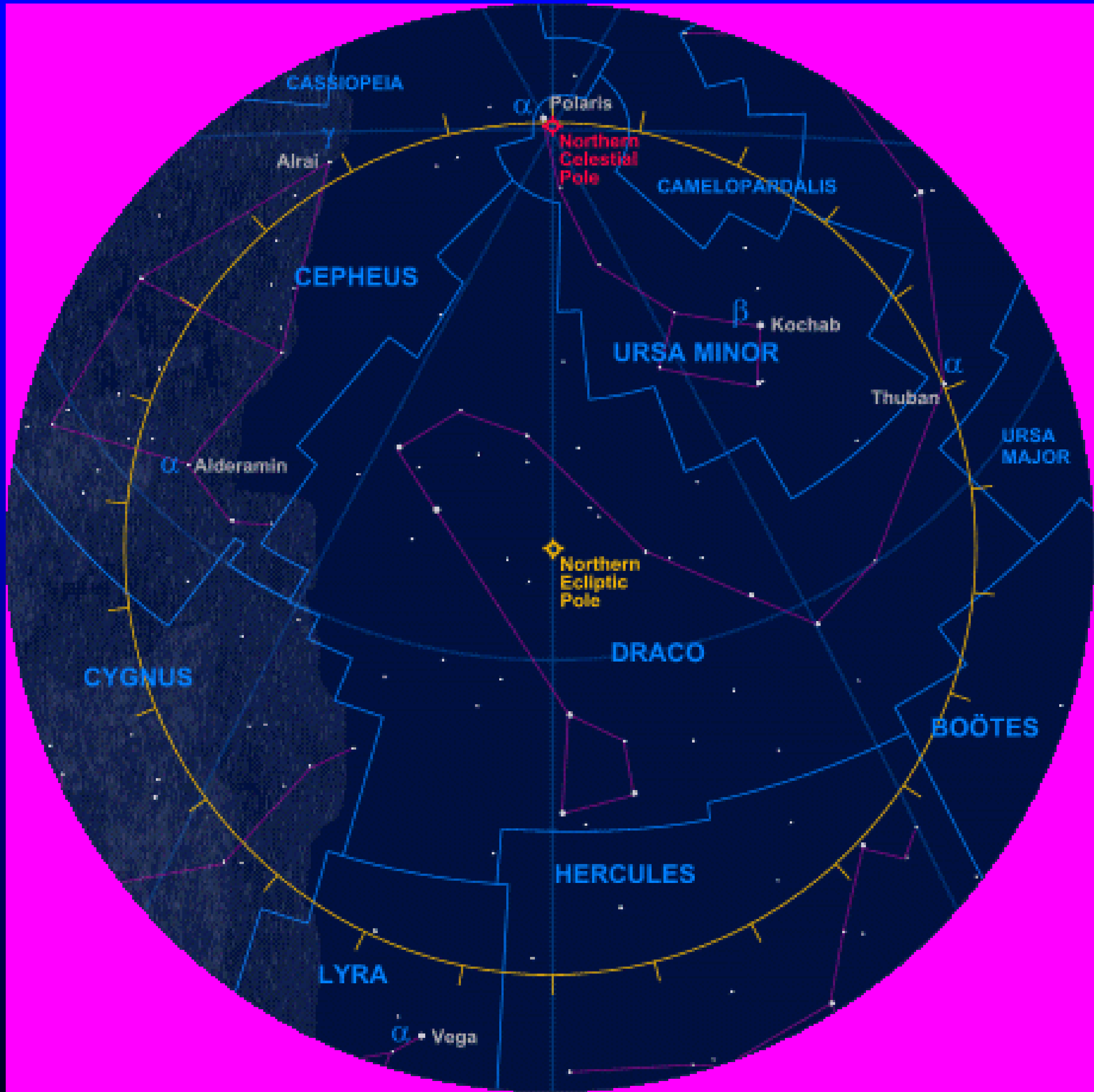
- The First Point of Aries is now in Pisces. Why?
- The Earth's rotation axis is precessing, like a top, once every ~26,000 years.
  - Thus the North Celestial Pole will move in a circle of angular radius 23.5 degrees * around the Celestial Sphere.
    - The "pole star" is only that for a while
    - In ~ 13,000 years Vega will be the pole star.
    - In 26,000 years the "pole star" will again help scouts and guides to find north.



* This is because the Earth rotation axis is inclined at 23.5 degrees to the plane of the Earth's orbit.




26000-year
precessional
cycle
AD12,000
Vega
Draco
Ursa
Minor
Polaris
AD1993
2800BC
Alpha
Draconis
Ursa Major
Precessional 'wobble'
North Pole
EARTH
South Pole


CASSIOPEIA
Polaris
Northern
Celestial
Pole
Alrai
CAMELOPARDALIS
CEPHEUS
Kochab
URSA MINOR
Thuban
URSA
MAJOR
Alderamin
Northern
Ecliptic
Pole
DRACO
CYGNUS
BOÖTES
HERCULES
LYRA
Vega

A problem for star charts

- The celestial co-ordinates will slowly vary over time.
- A star chart is only valid for strictly one date – actually no great change over ~ 50 years.
- So star charts and catalogues are given an “Epoch”
- We were using epoch 1950.
- Now use epoch 2000.
- Use computers to calculate the gradual change from epoch to current date.

- In Astrology the Ecliptic is divided up into 12 “houses” so the First Point of Aries will spend 26,000/12 years in each house.
  - = 2166 years
  - This is an astrological “age”
  - The first point of aries is moving into the
  - “house” of Aquarius.
  - Hence in the song the words “the dawning of the age of Aquarius”