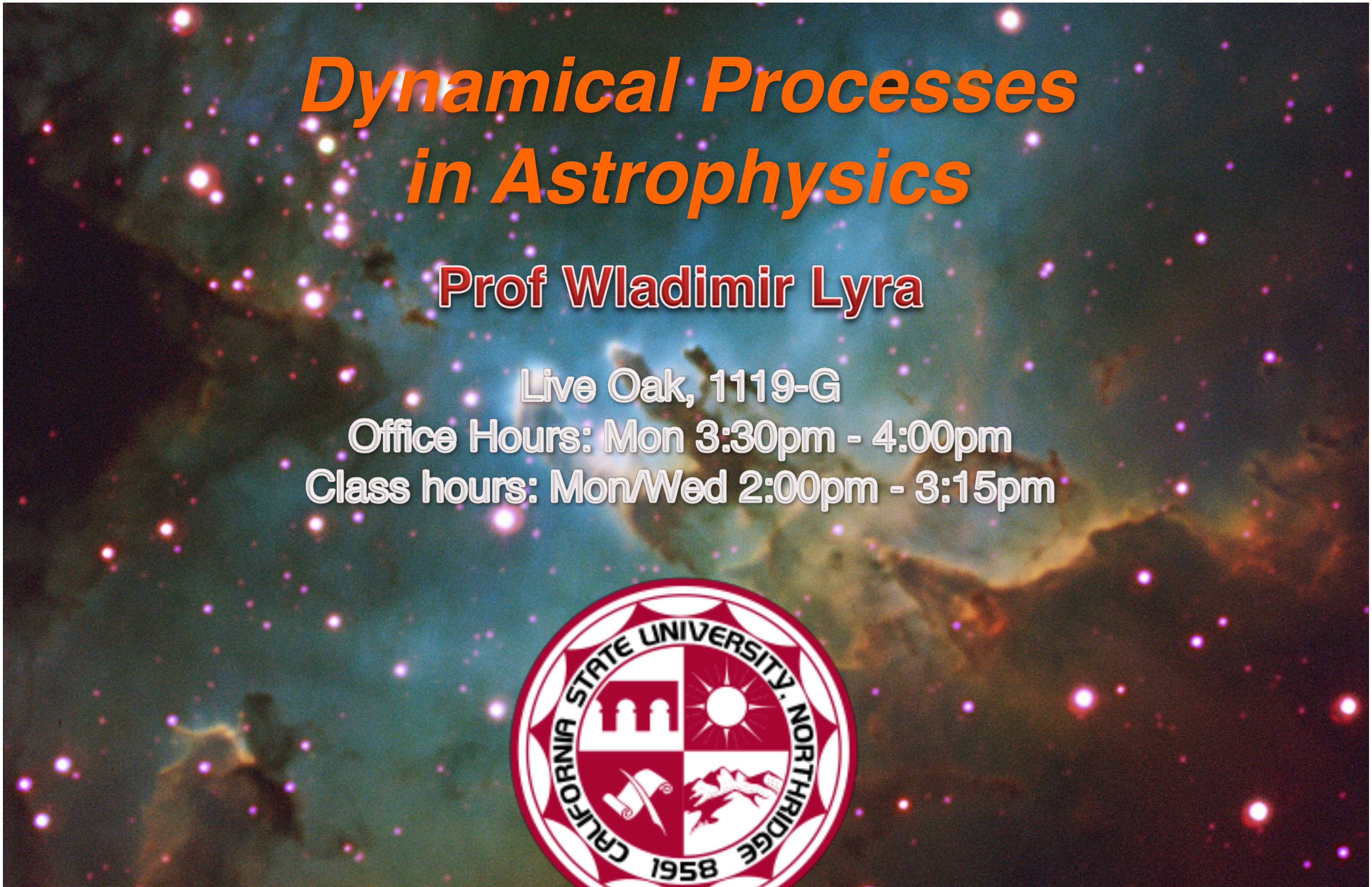


Dynamical Processes in Astrophysics

Prof Wladimir Lyra

Live Oak, 1119-G
Office Hours: Mon 3:30pm - 4:00pm
Class hours: Mon/Wed 2:00pm - 3:15pm

Quick Bio

Wladimir Lyra

B.Sc. in Astronomy, Federal University of Rio de Janeiro (UFRJ, **Brazil**), 1999-2003.

Research Assistant 2003-2004

Space Telescope Science Institute (*STScI*, Baltimore **MD**)
Cerro Tololo Interamerican Observatory (*CTIO*, La Serena – **Chile**)
European Southern Observatory (*ESO*, Munich – **Germany**)
Lisbon Observatory, **Portugal**.

Ph.D. in Astronomy, Uppsala University (Uppsala, **Sweden**), 2004-2009.

Nordic Institute for Theoretical Physics (*NORDITA*, Stockholm, **Sweden**)
Max-Planck Institute for Astronomy (*MPIA*, Heidelberg, **Germany**)

Postdoctoral Researcher

American Museum of Natural History (*AMNH*, New York **NY**), 2009-2011.
Jet Propulsion Laboratory (NASA-JPL/Caltech, Pasadena **CA**), 2011-2015.

Stellar Astrophysics, Planetary Sciences

Solar-type stars, extrasolar planets, star formation, *circumstellar disks and planet formation*.
Hydrodynamics, plasma physics, turbulence, life in the universe, *icy moons and Europa*.

Grading

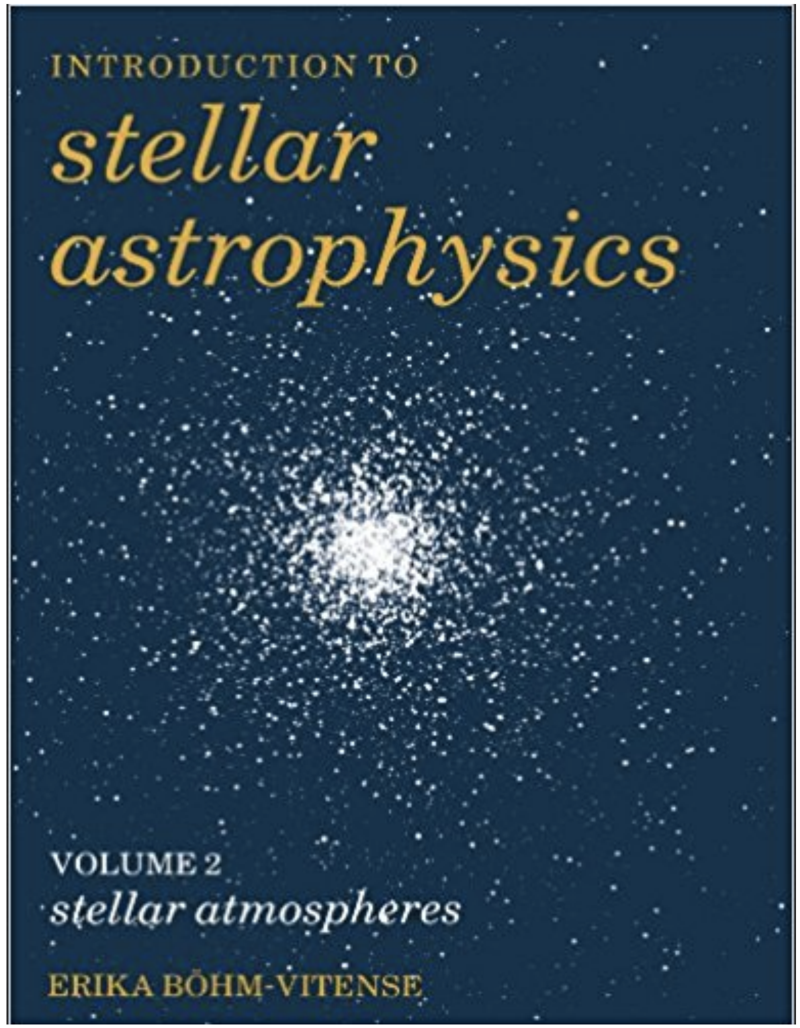
Homework	*(30%)*
Exams	*(70%)*
Checkpoint	
Midterm	
Exam	

Topics

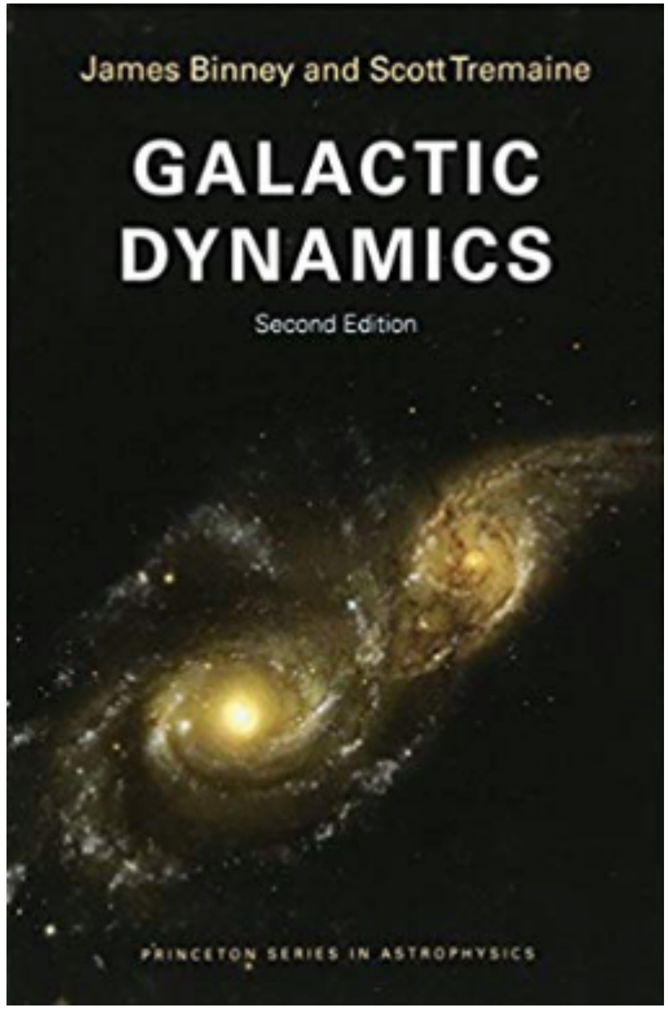
- Coordinate Systems
- Photometric Systems
- Stellar and Galactic Dynamics
- Relativistic Astronomy
- Cosmology

Class #	Date	Topics
1	8/27	Syllabus and overall overview.
2	8/29	Celestial Sphere - Definitions
3	9/5	Celestial Sphere – Planetary motion
4	9/10	Coordinate Systems - Equatorial
5	9/12	Coordinate Systems – Other systems
6	9/17	Spherical Trigonometry - Fundamentals
7	9/19	Spherical Trigonometry - Conversions
	9/24	**Checkpoint**
8	9/26	Distances of nearby stars - Parallax
9	10/01	The brightness of the stars: Stellar Magnitudes
10	10/03	The colors of the stars
11	10/08	Color-magnitude diagrams
12	10/10	Photometric systems
13	10/15	Angular radii of stars
14	10/17	Masses and radii of stars
	10/22	**Midterm**
15	10/24	Dynamics of planetary and satellite systems
16	10/29	Dynamics of planetary rings
17	10/31	Stellar dynamics – collisionless systems
18	11/5	Stellar dynamics - clusters
19	11/7	Galactic Dynamics
20	11/14	Dark Matter
21	11/19	Relativistic orbits – Mercury's orbit
22	11/21	Relativistic orbits – Binary pulsars
23	11/26	Black holes – Formation and structure
24	11/28	Black holes - Dynamics
25	12/3	Cosmology: Fundamentals
26	12/5	Hubble law and Friedmann equation
27	12/10	Evolution of the Universe
	12/17	**Final exam.**

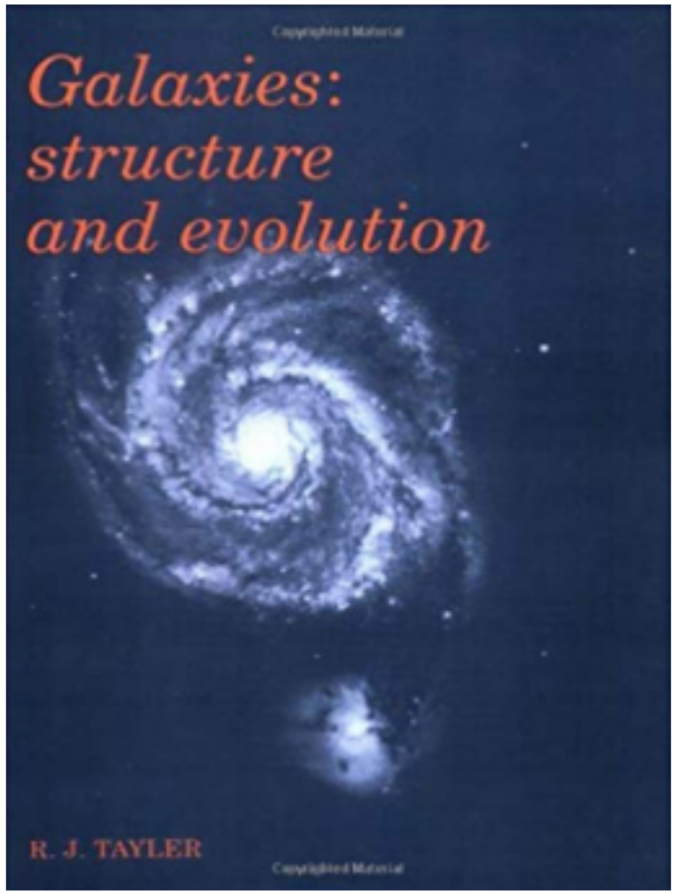
Books (or lack thereof)



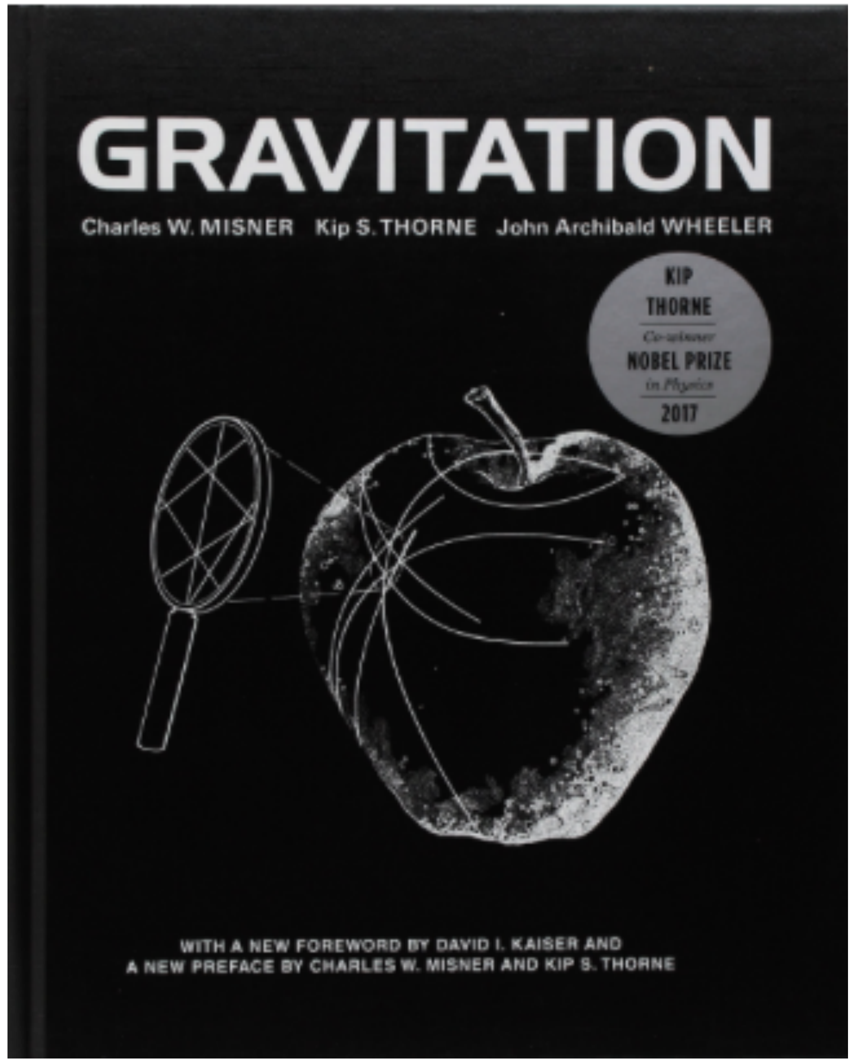
Books (or lack thereof)



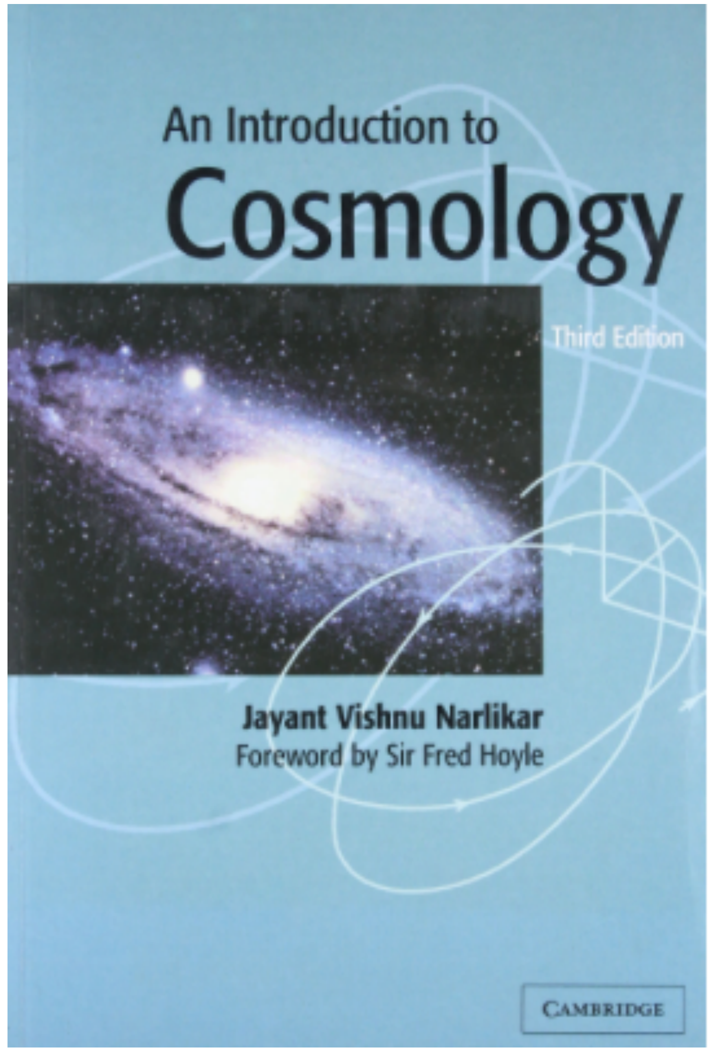
Books (or lack thereof)



Books (or lack thereof)



Books (or lack thereof)




AllPosters

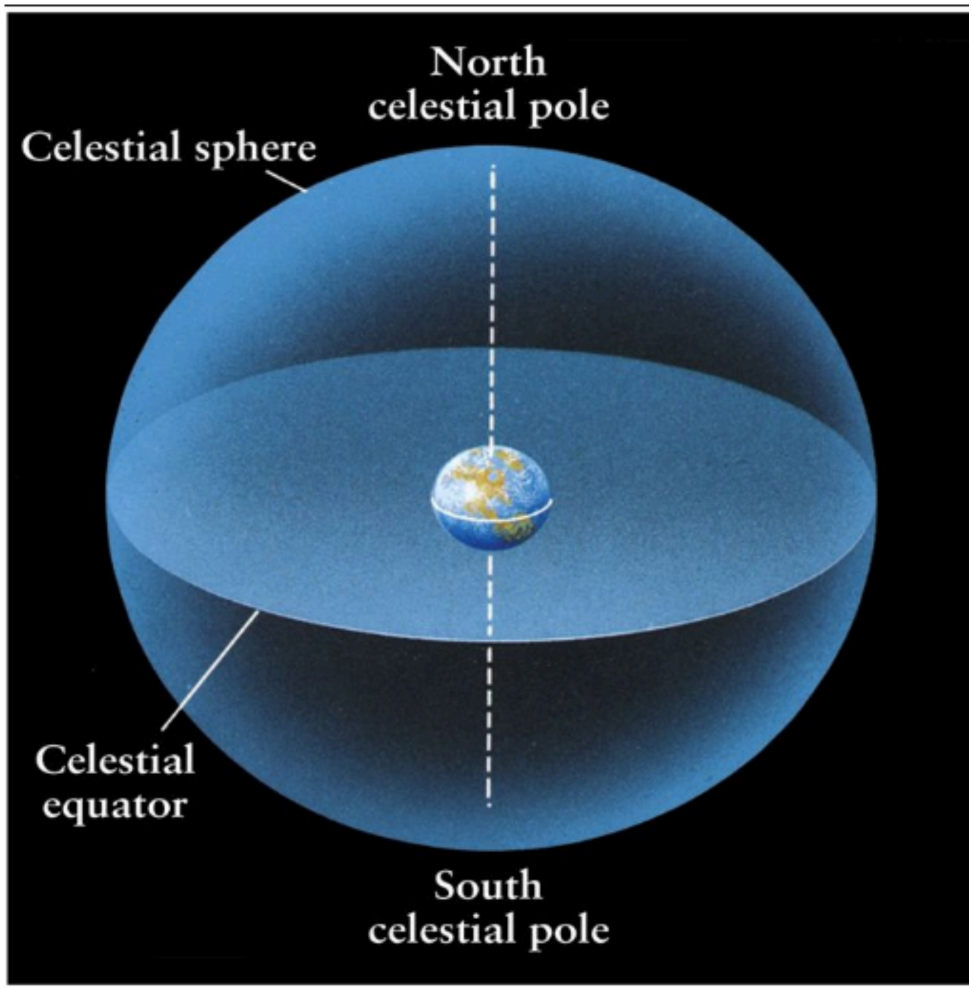
Positional Astronomy

- Spherical Astronomy
- Coordinate Systems
- Time

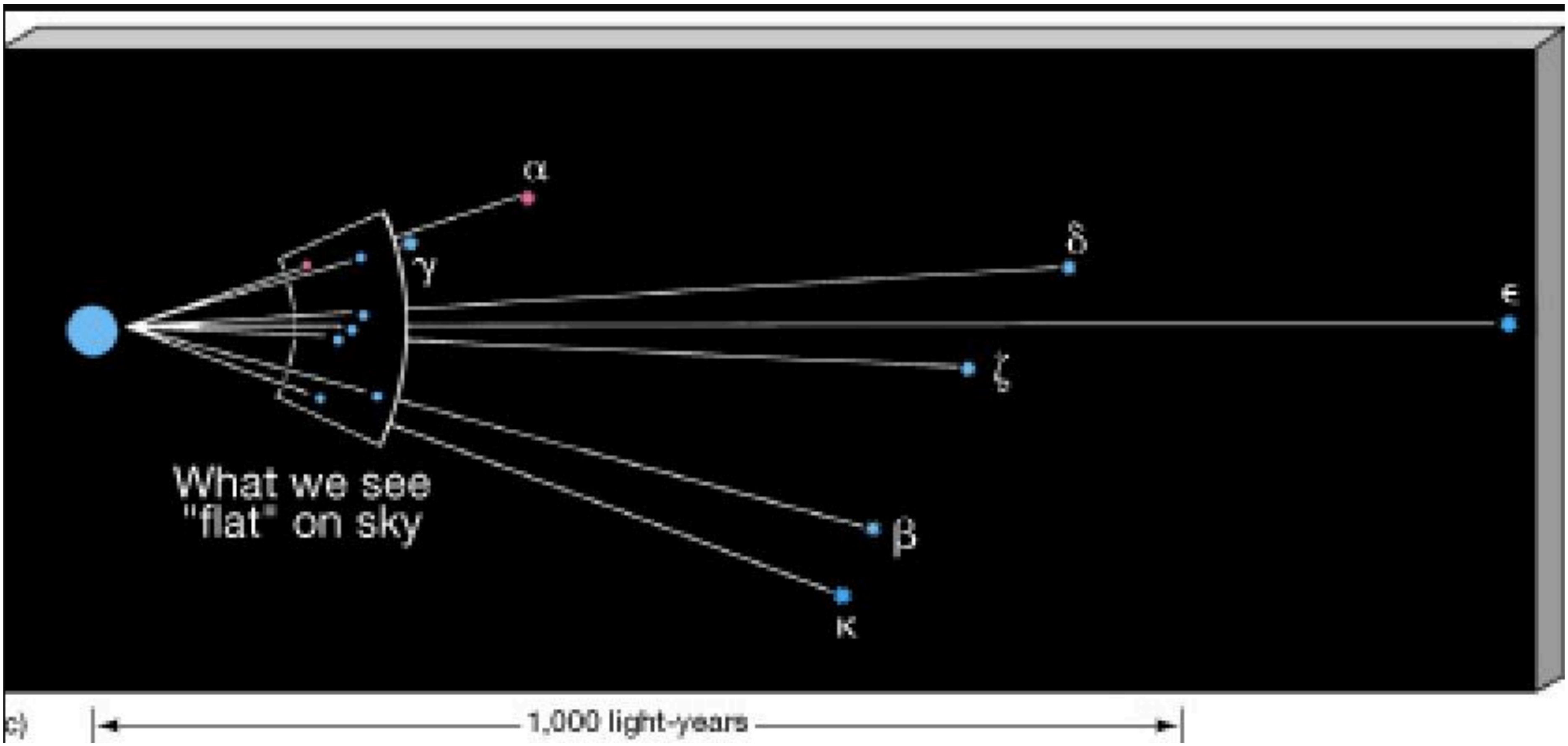

Richard Wainscoat

Diurnal motion

Celestial Sphere

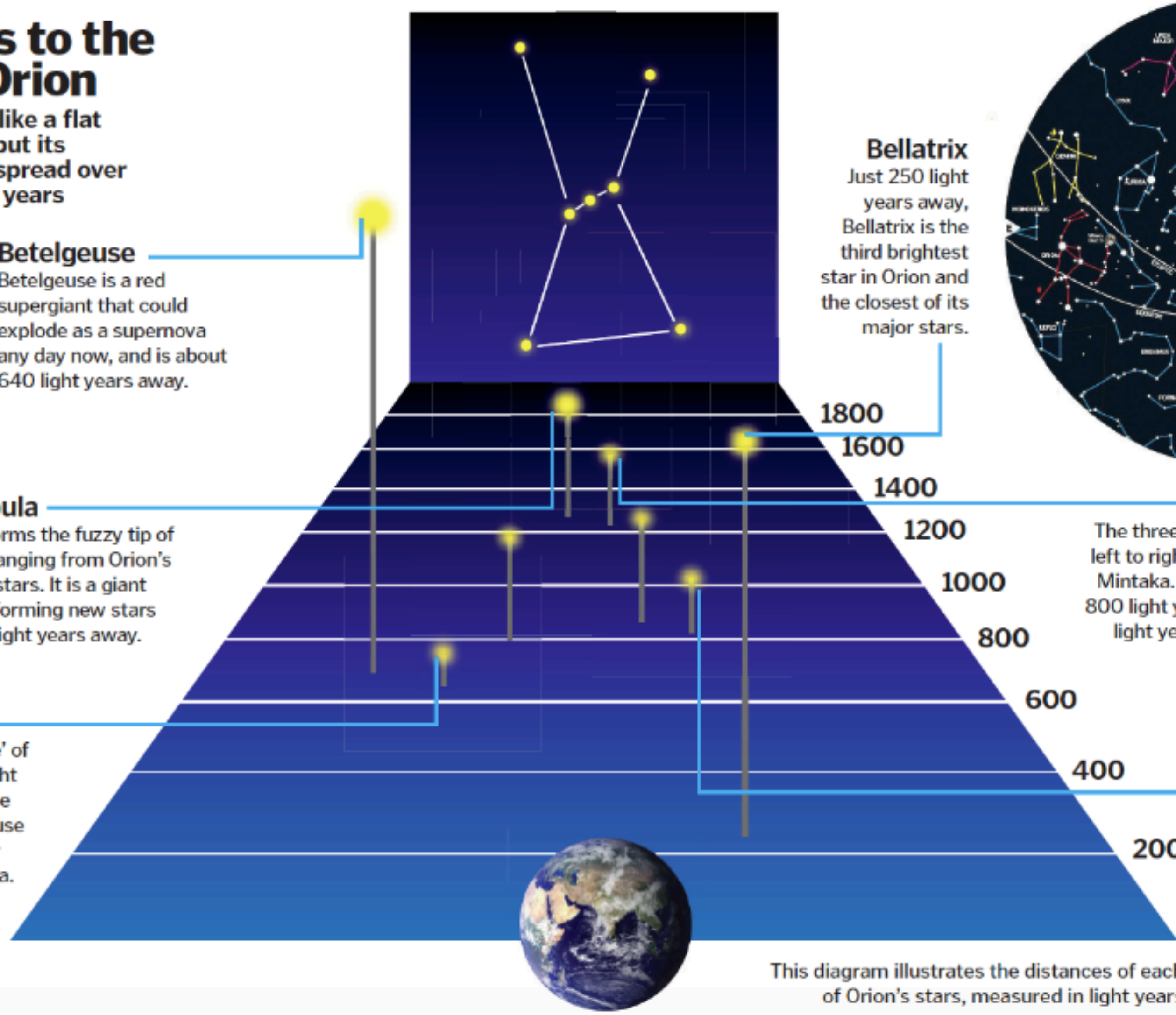



© Christopher J. Picking
www.southernskyphoto.com


α
δ
γ
ϵ
ζ
What we see
"flat" on sky
β
κ
c)
1,000 light-years

Distances to the stars of Orion

Orion might look like a flat blanket of stars, but its components are spread over hundreds of light years



Betelgeuse
Betelgeuse is a red supergiant that could explode as a supernova any day now, and is about 640 light years away.

Orion nebula
The nebula forms the fuzzy tip of the 'sword' hanging from Orion's belt of three stars. It is a giant cloud of gas forming new stars and is 1,344 light years away.

Saiph
At the lower-left 'knee' of Orion, Saiph is 650 light years away. It is a large star that, like Betelgeuse and Rigel, will one day blow up in a supernova.

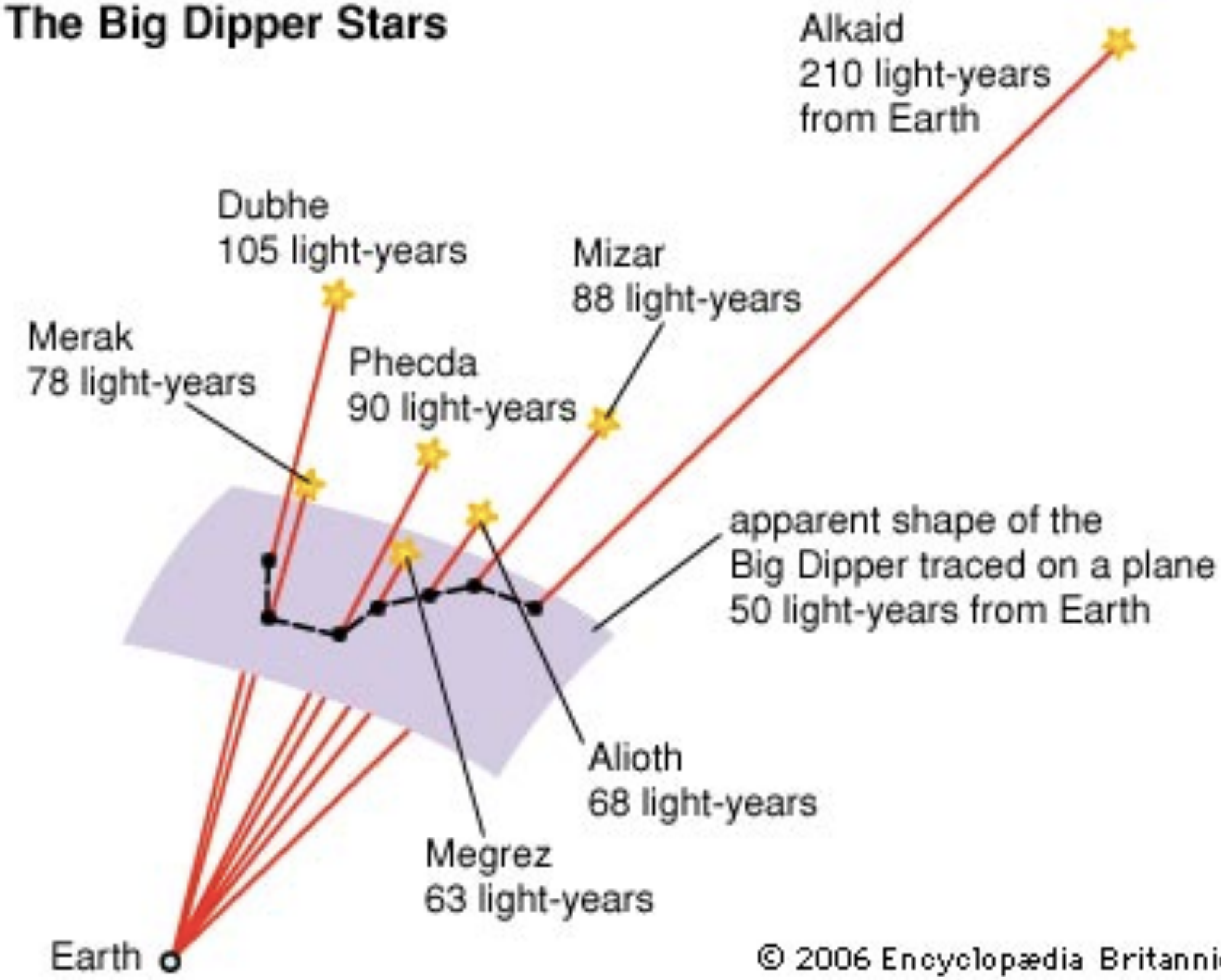
Bellatrix
Just 250 light years away, Bellatrix is the third brightest star in Orion and the closest of its major stars.

Orion's Belt
The three stars in Orion's Belt, from left to right, are Alnitak, Alnilam and Mintaka. Estimates place Alnitak at 800 light years away, Mintaka 1,300 light years away and Alnilam 900 light years away.

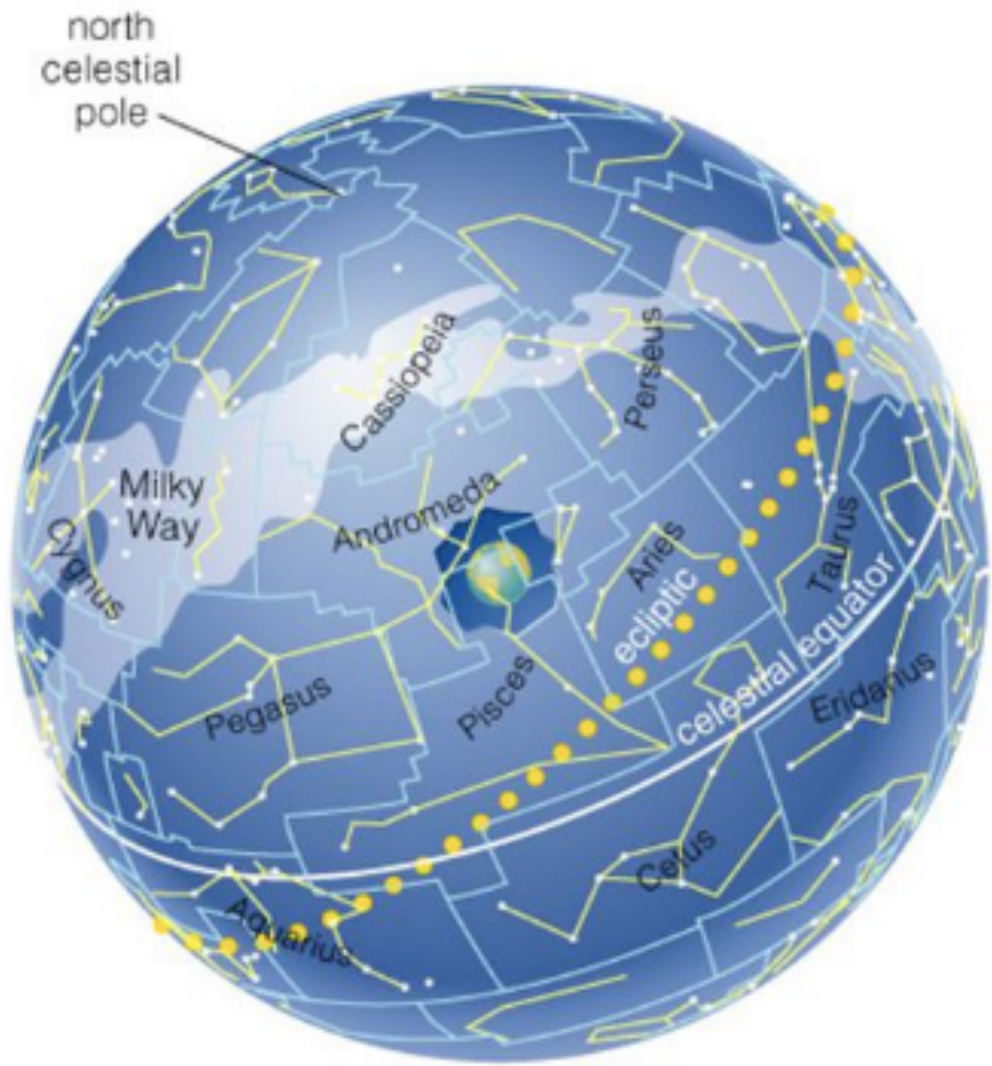
Rigel
The brightest star in Orion is Rigel, a white supergiant, about 860 light years away.

This diagram illustrates the distances of each of Orion's stars, measured in light years

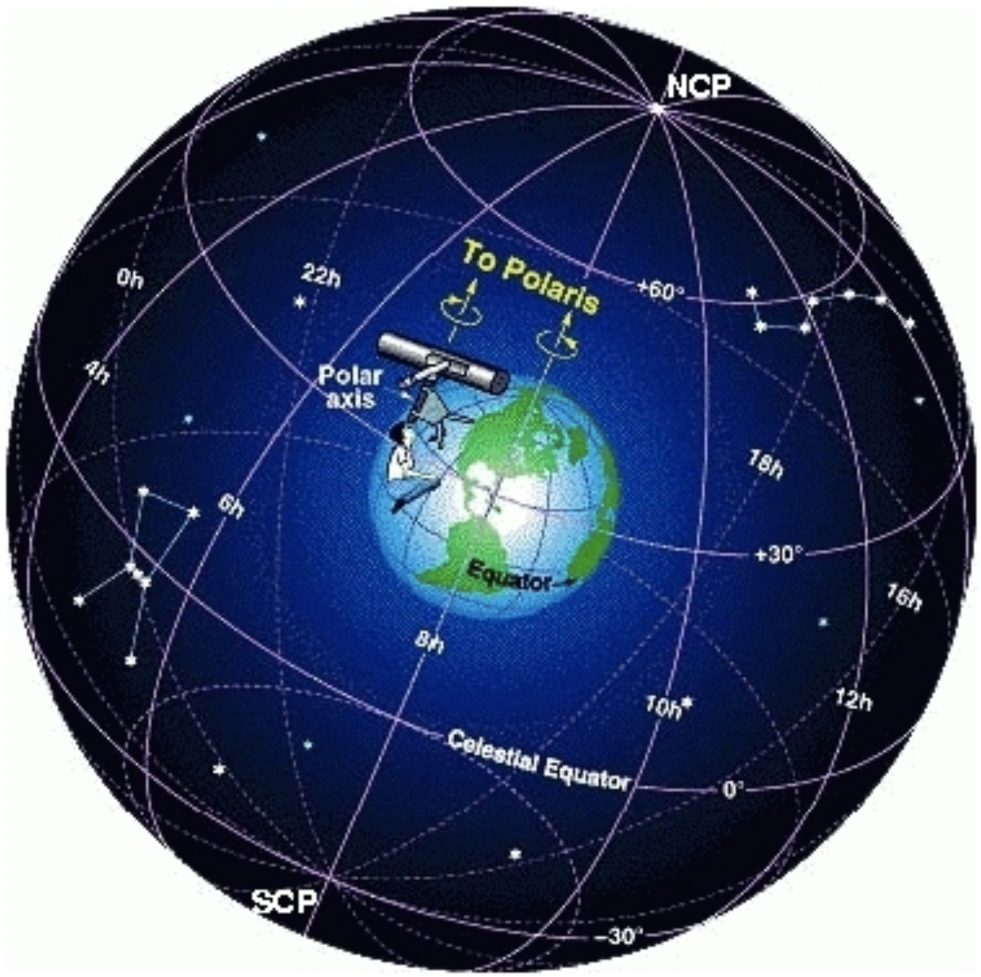
The Big Dipper Stars



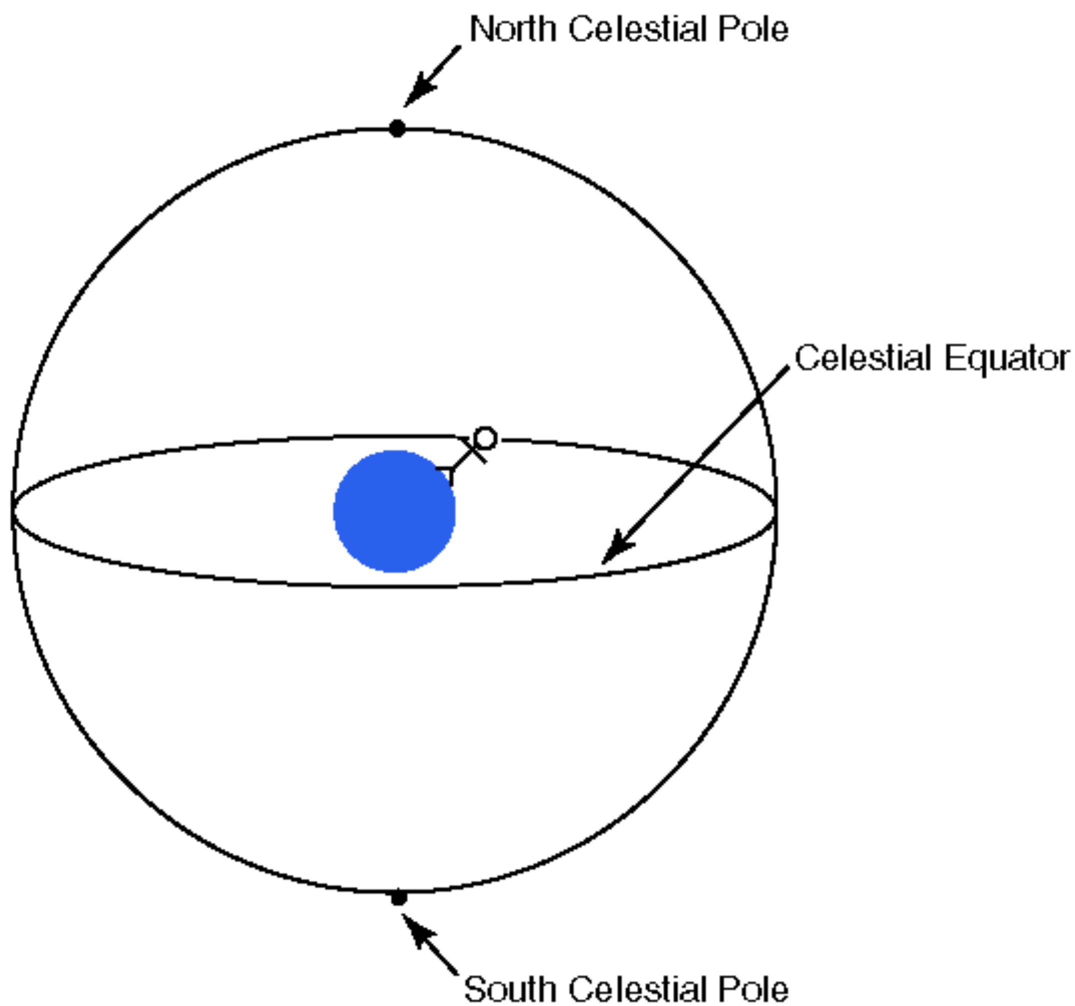
Celestial Sphere

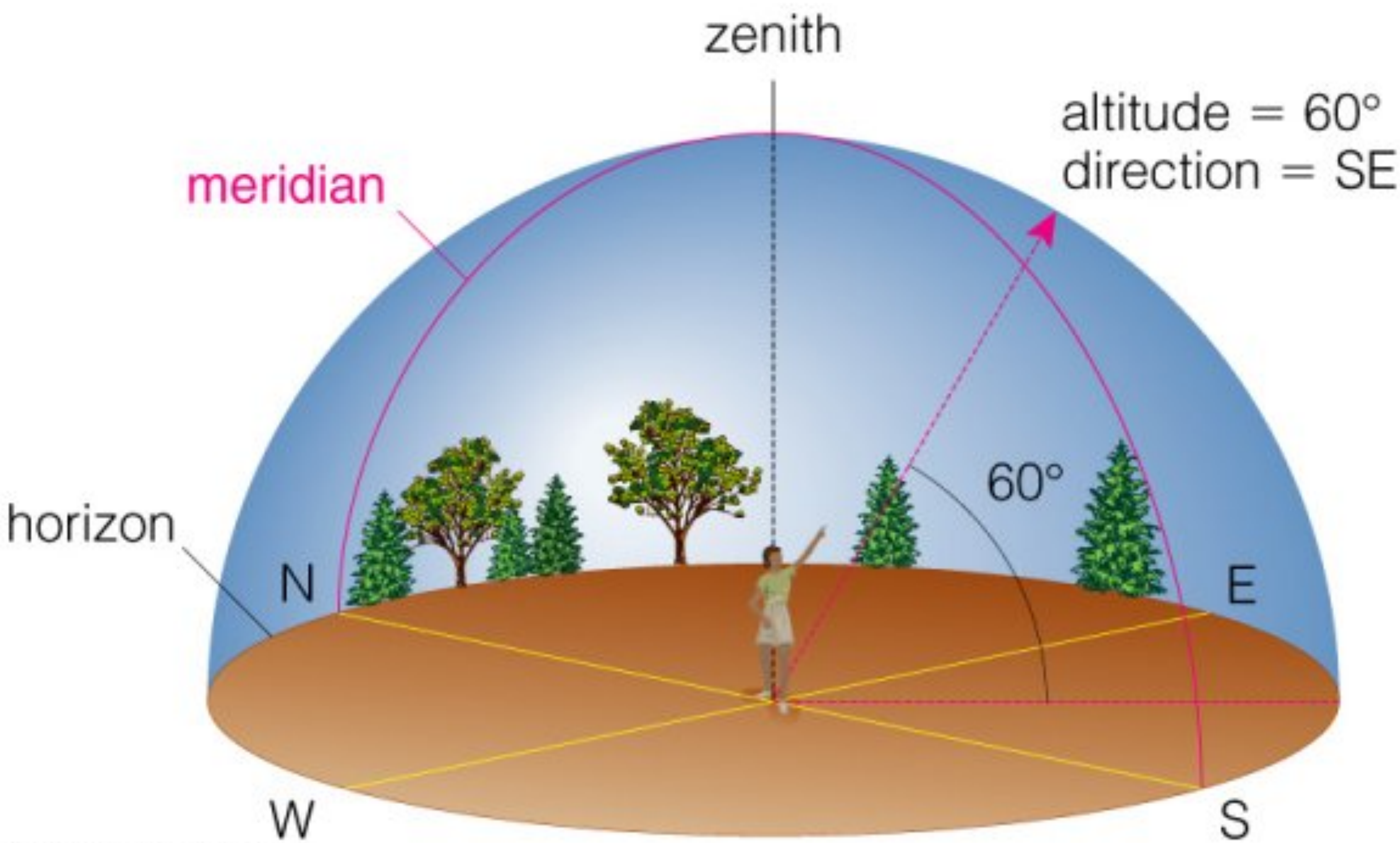


Celestial Sphere

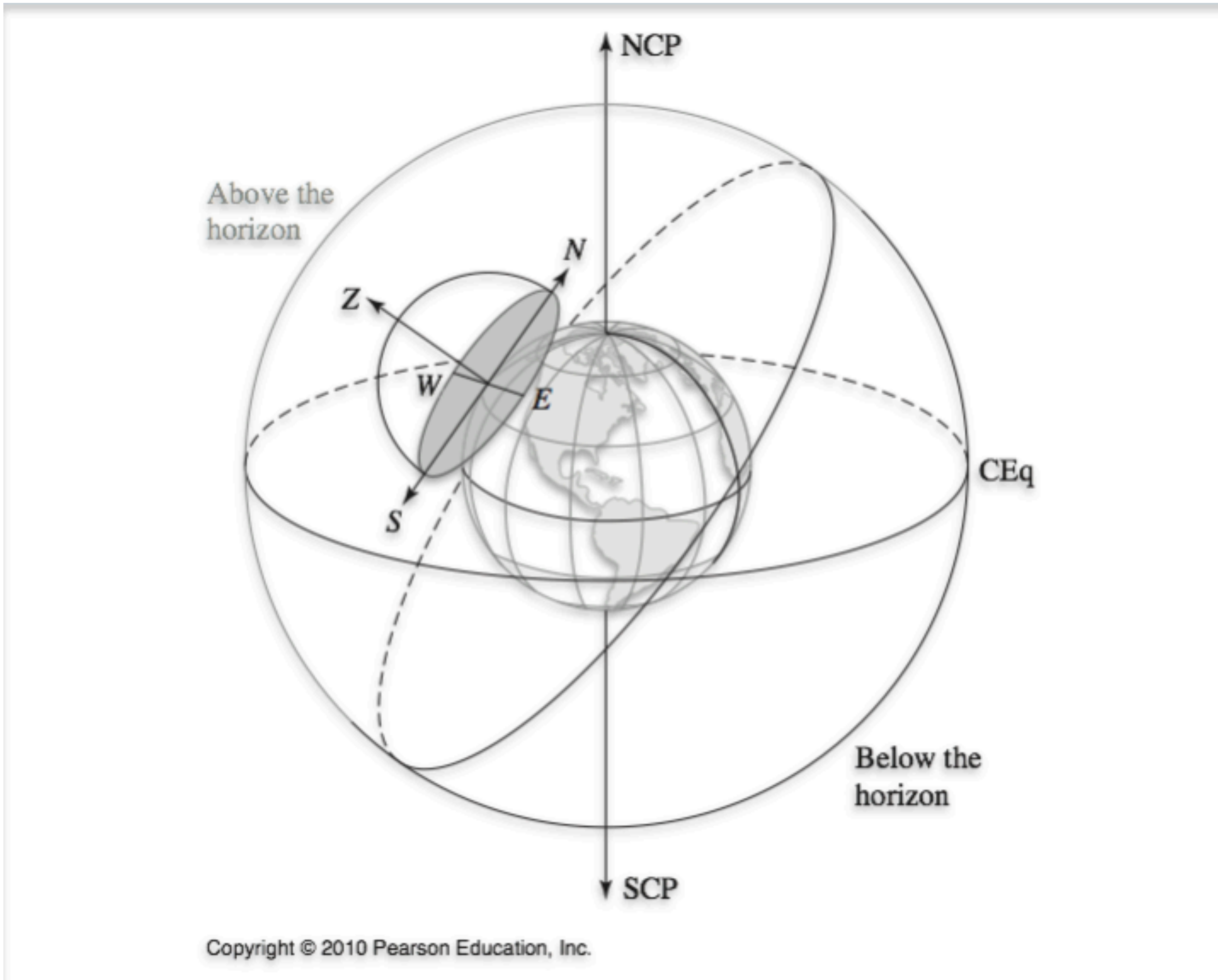


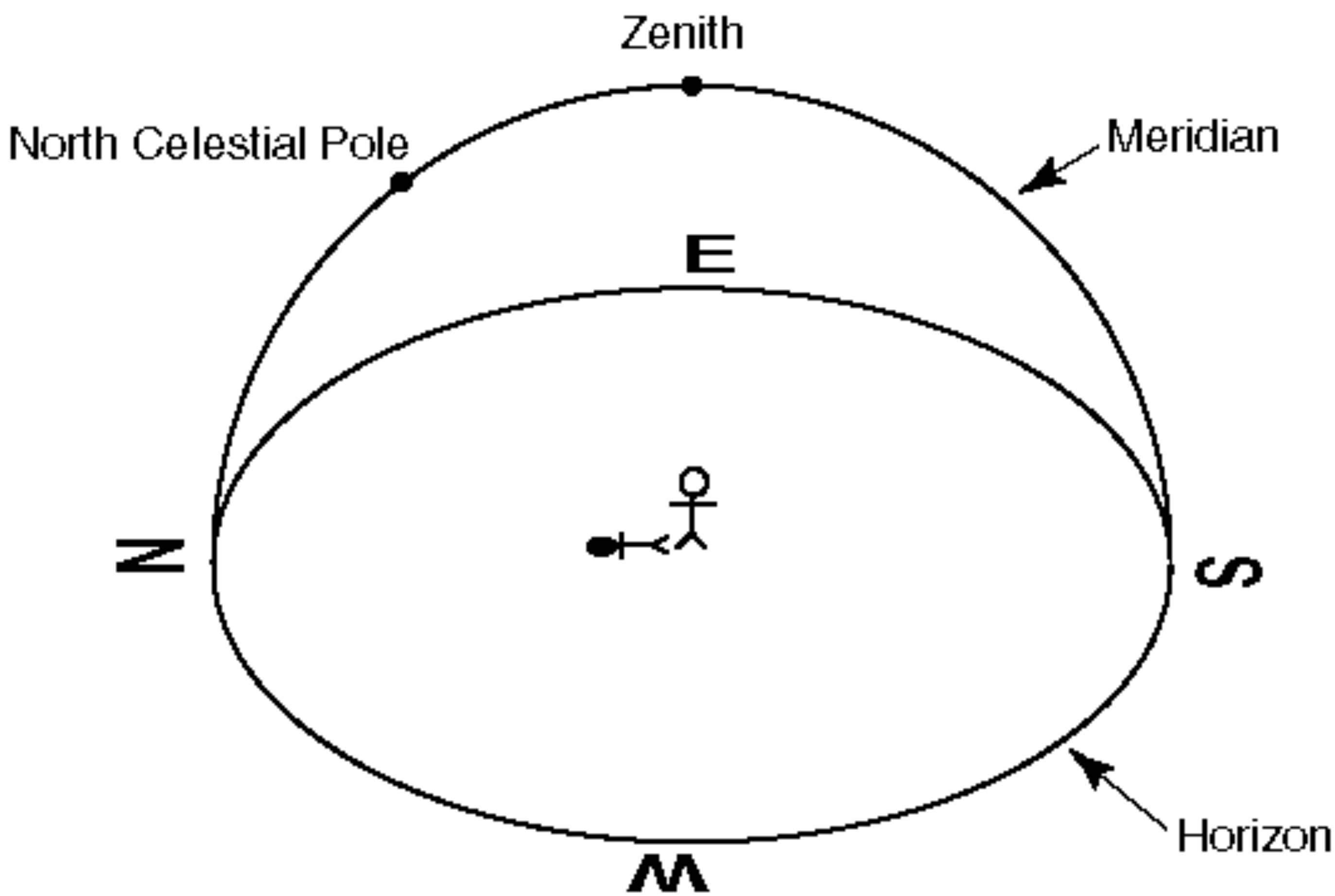
The celestial sphere



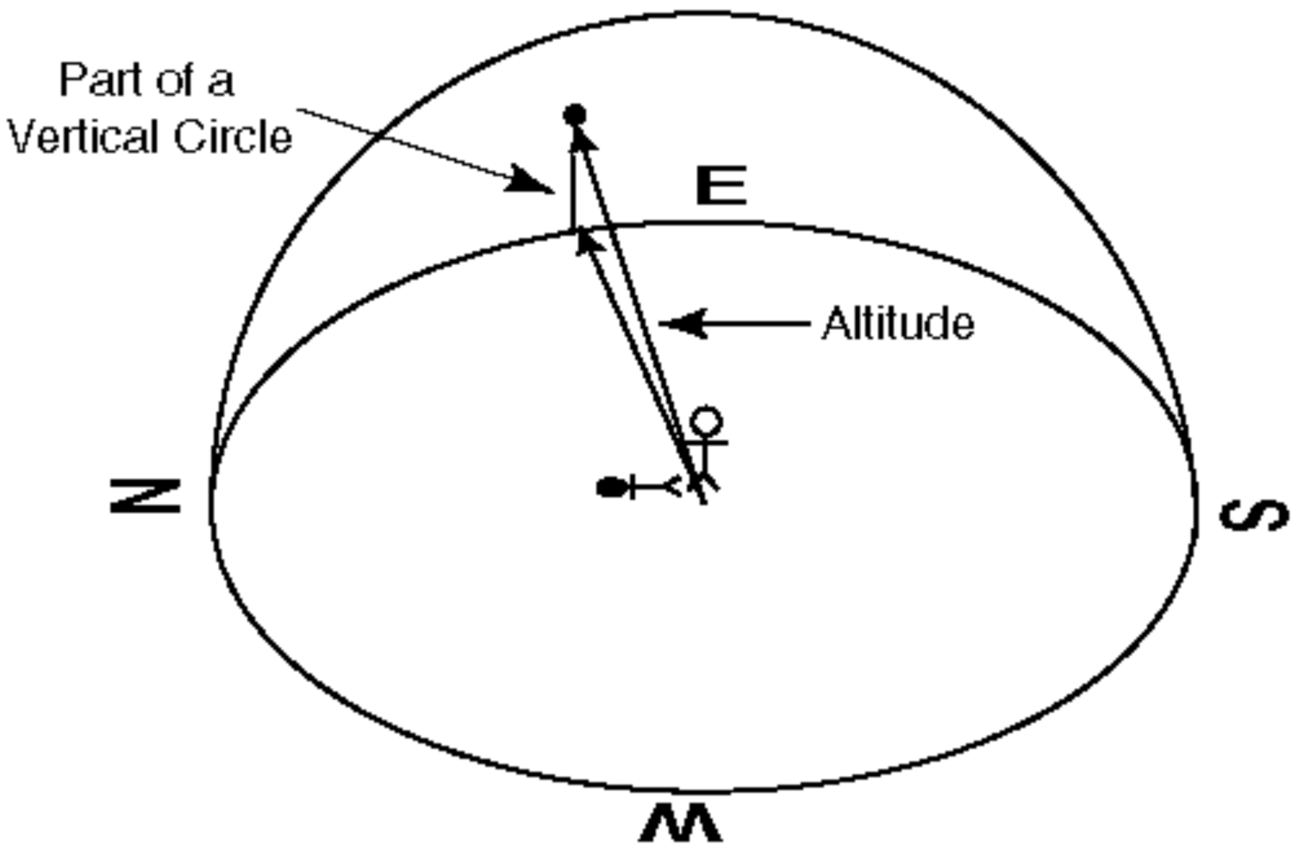

zenith
altitude = 60°
direction = SE
meridian
60°
horizon
N
E
W
S

Our perception of the sky

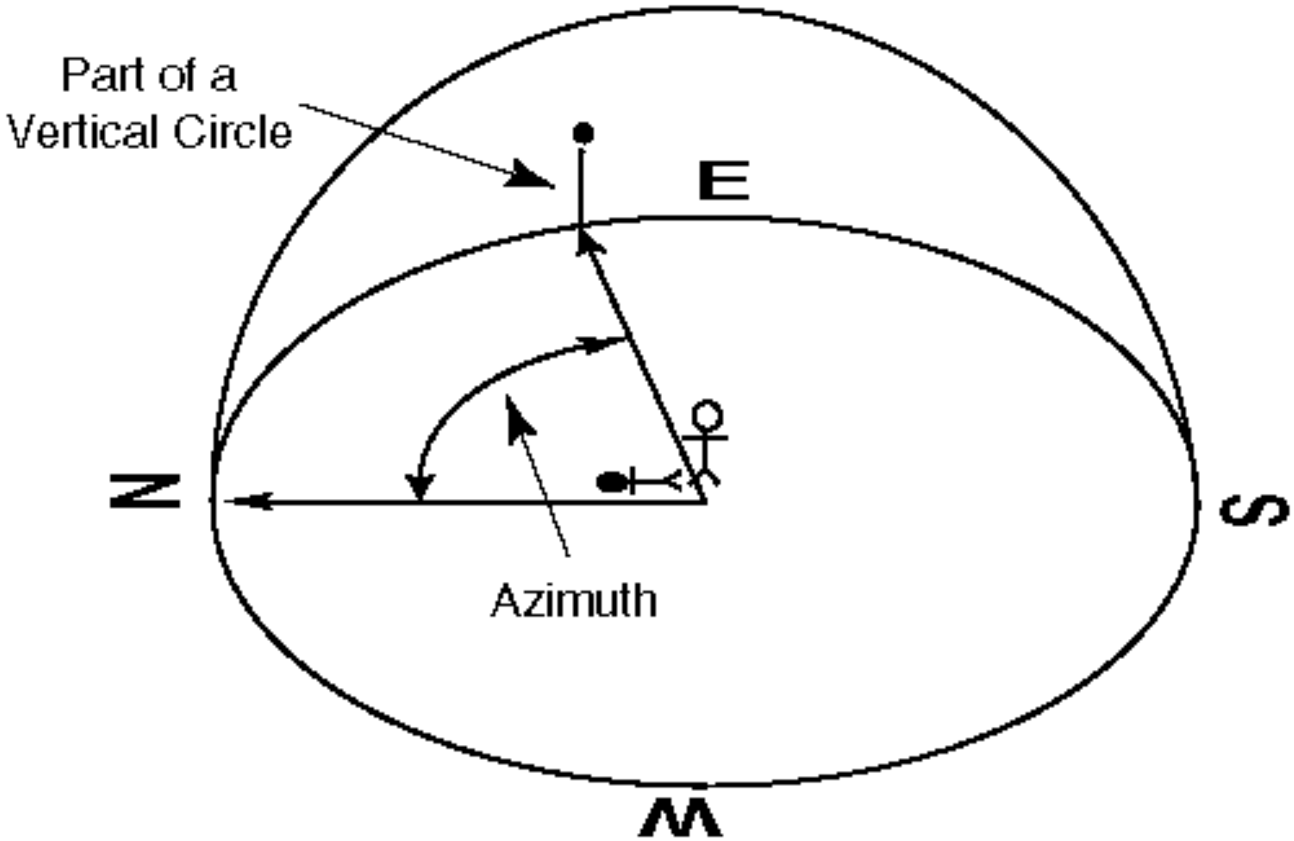



Zenith
North Celestial Pole
Meridian
E
N
S
W
Horizon

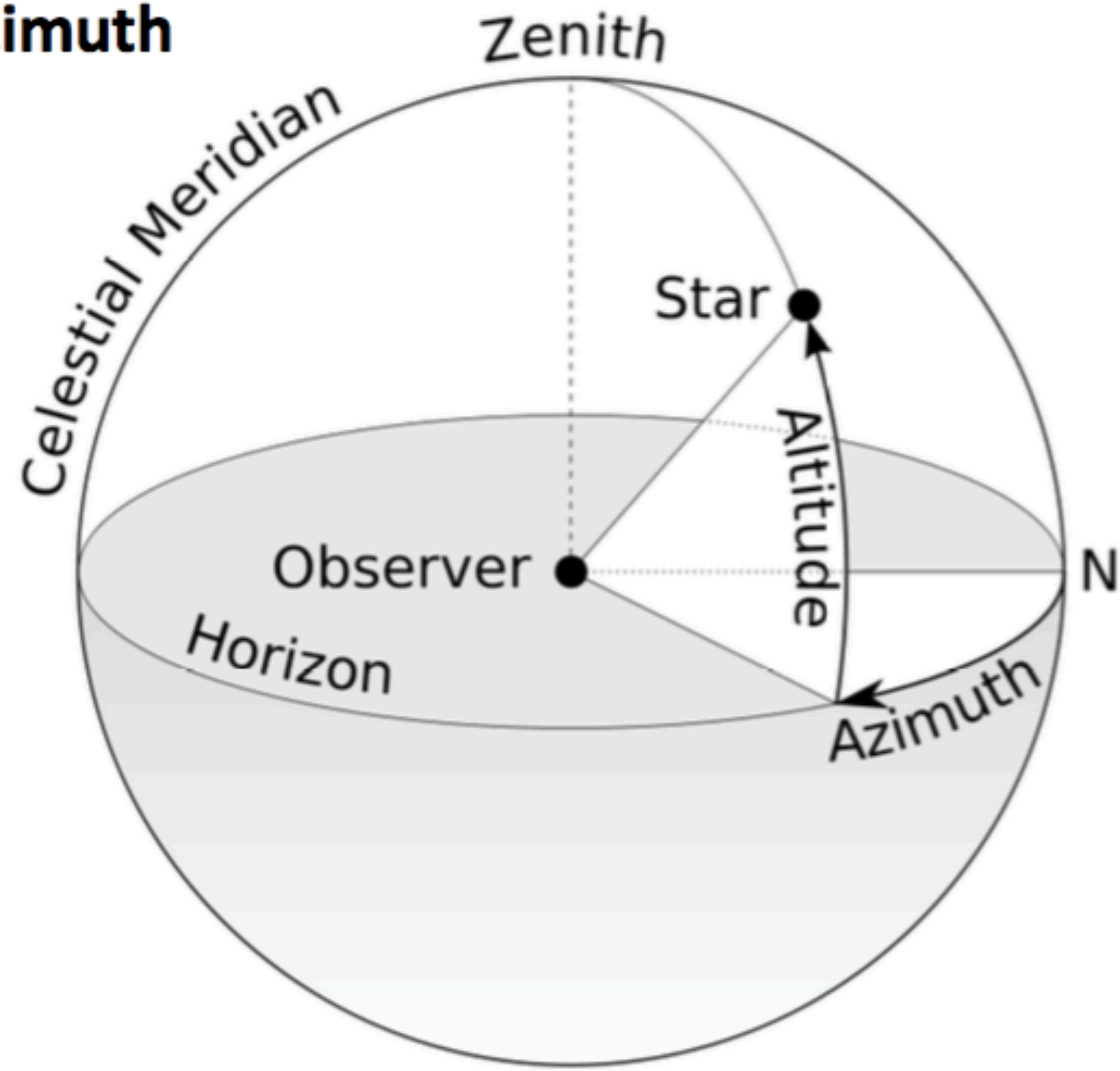
Altitude = 10°



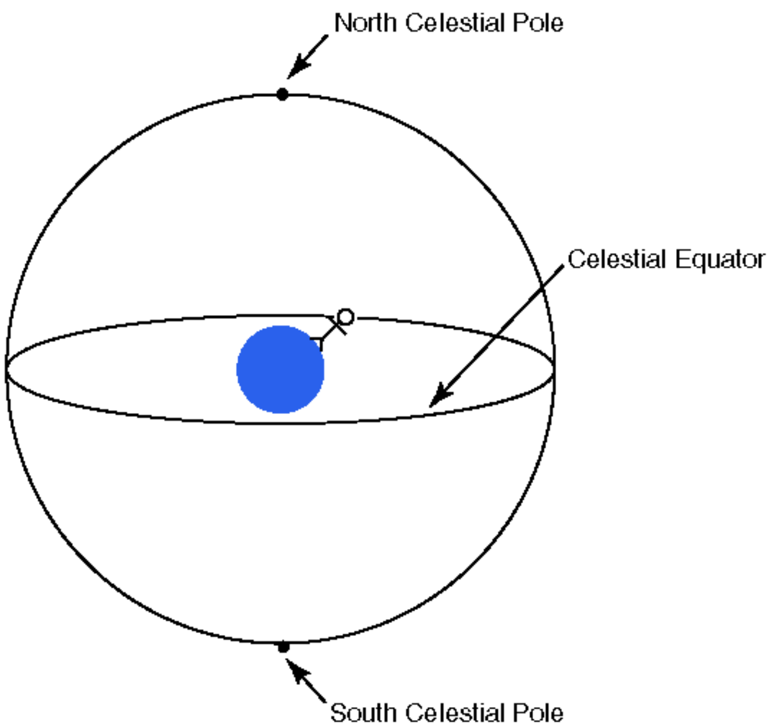
Azimuth = 80°

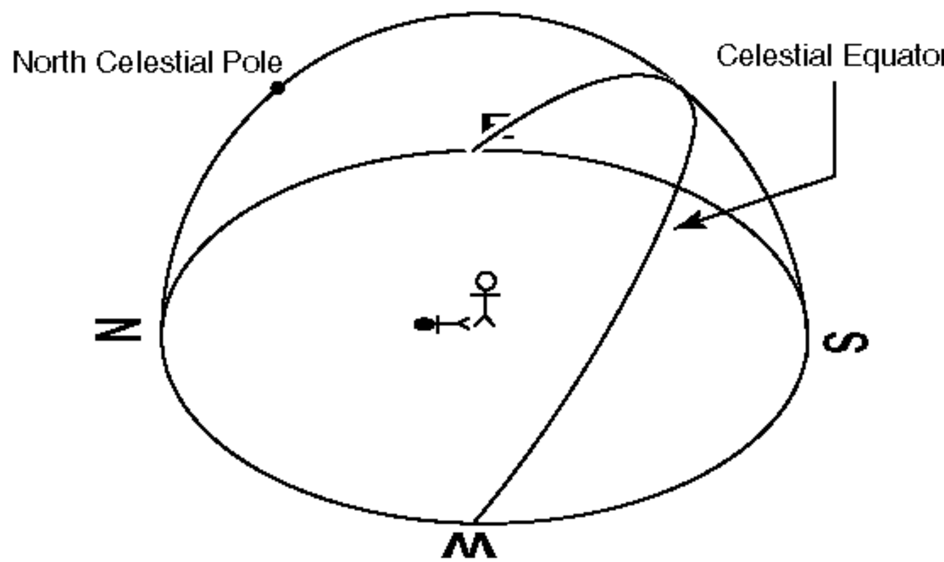


Alt-azimuth

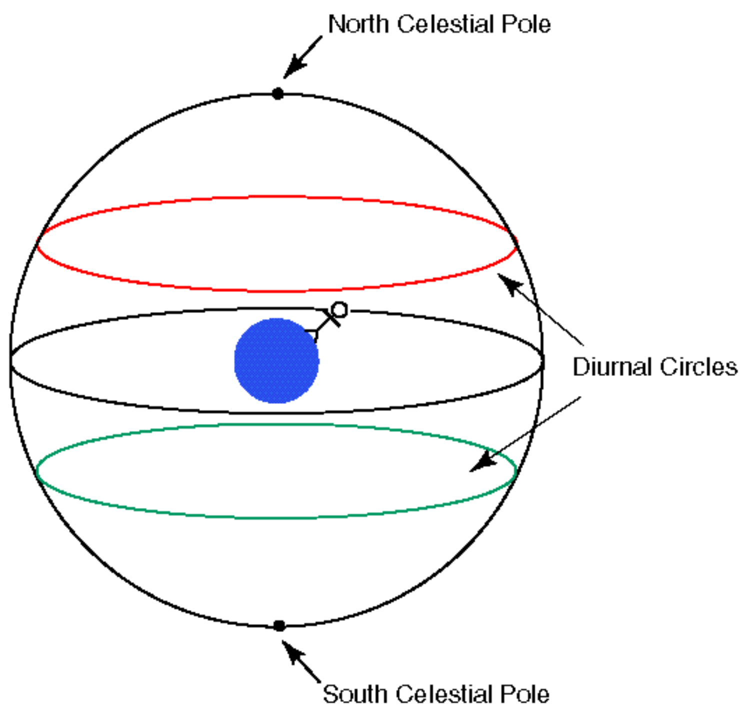

Zenith
Celestial Meridian
Star
Altitude
Observer
N
Horizon
Azimuth

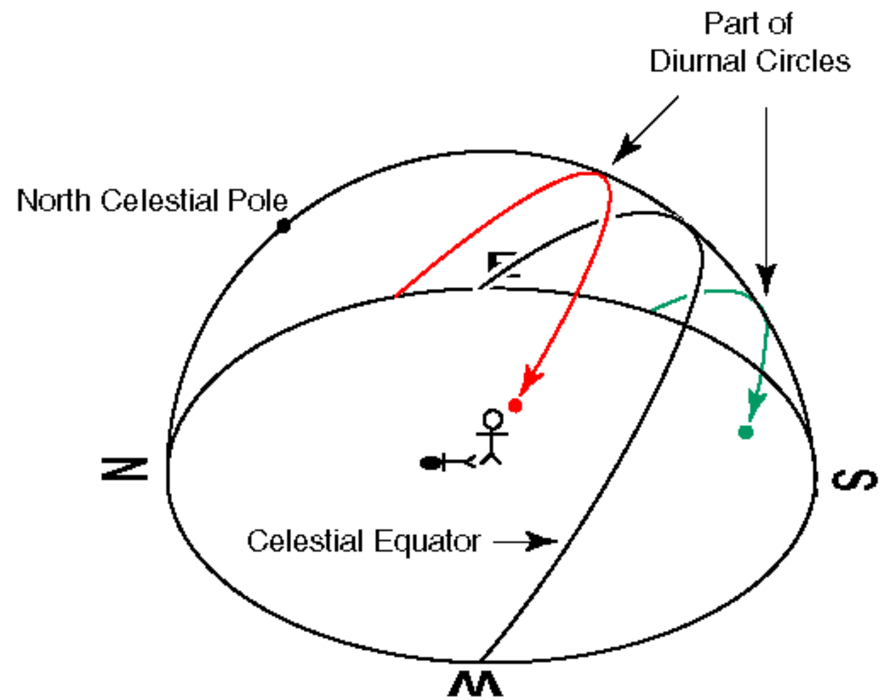
Celestial Equator



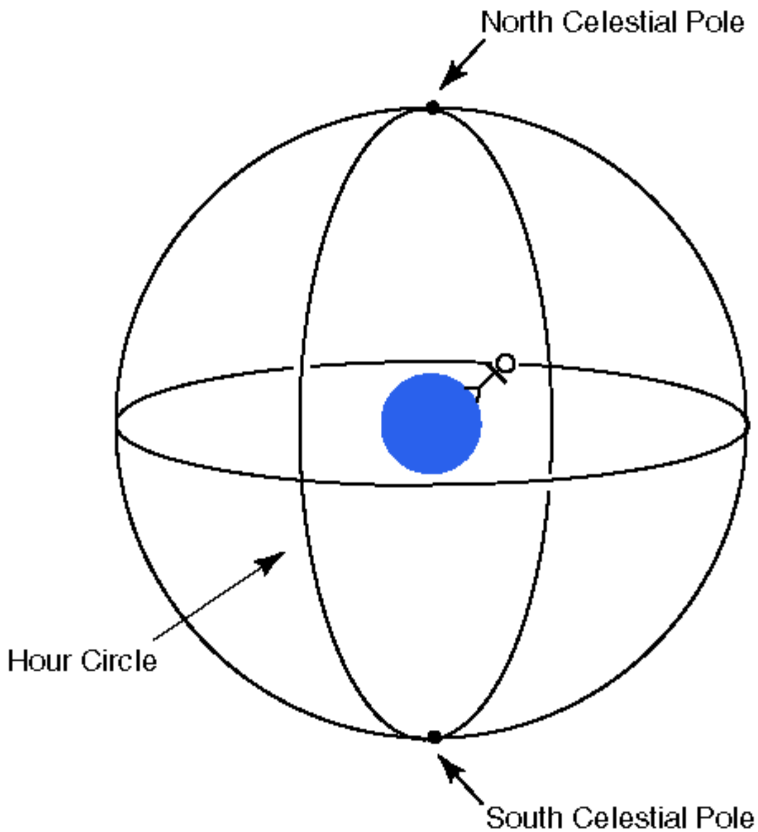


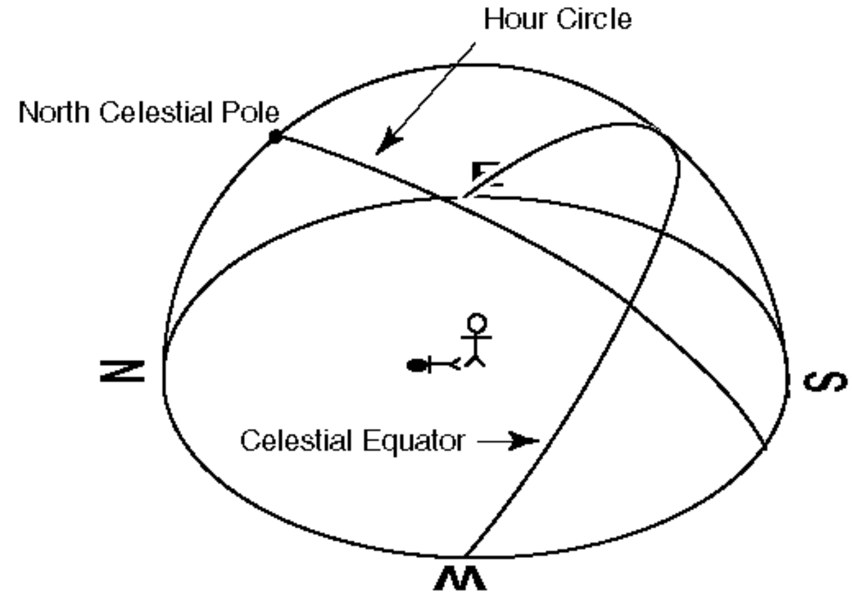
Diurnal Motion

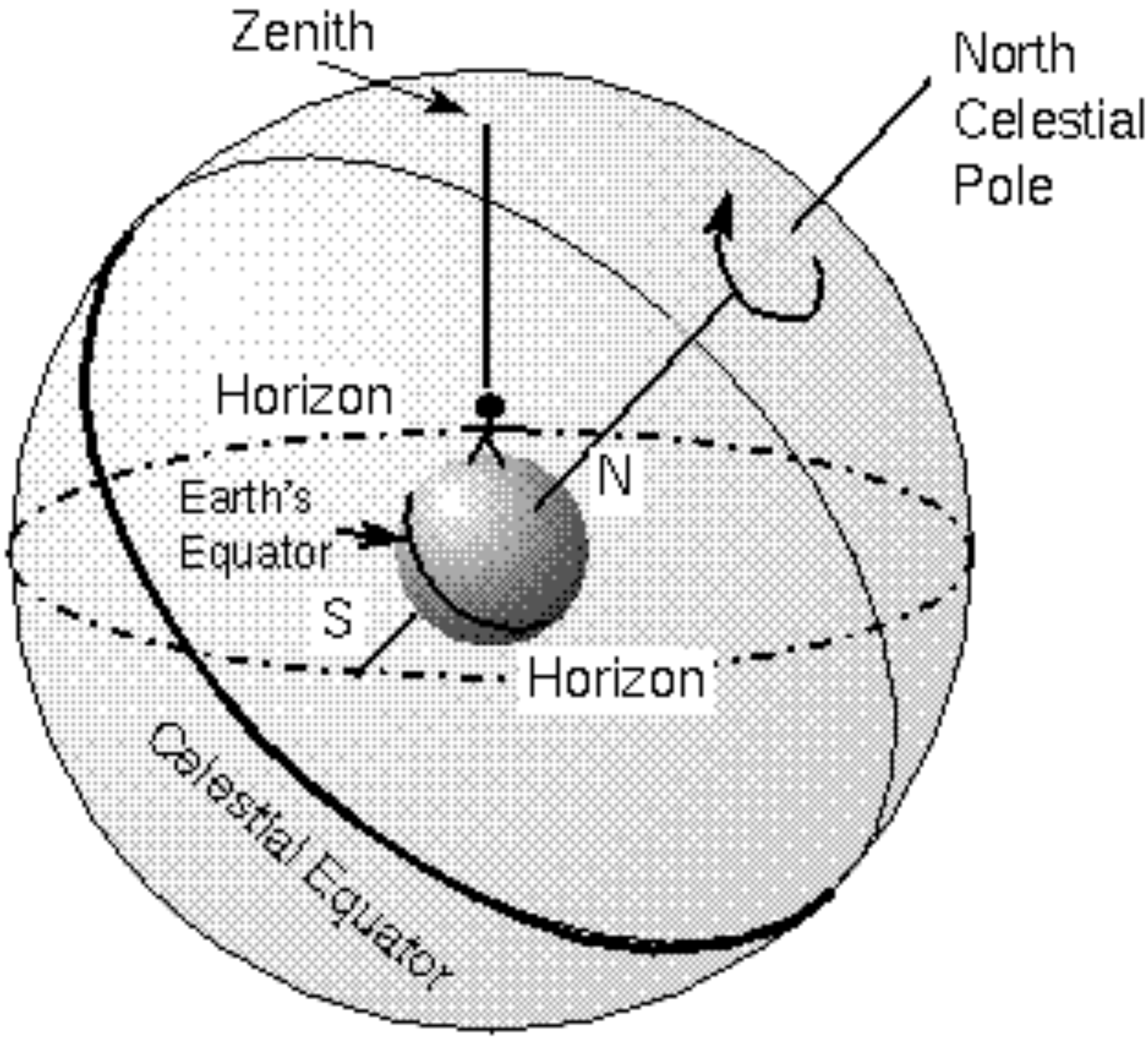




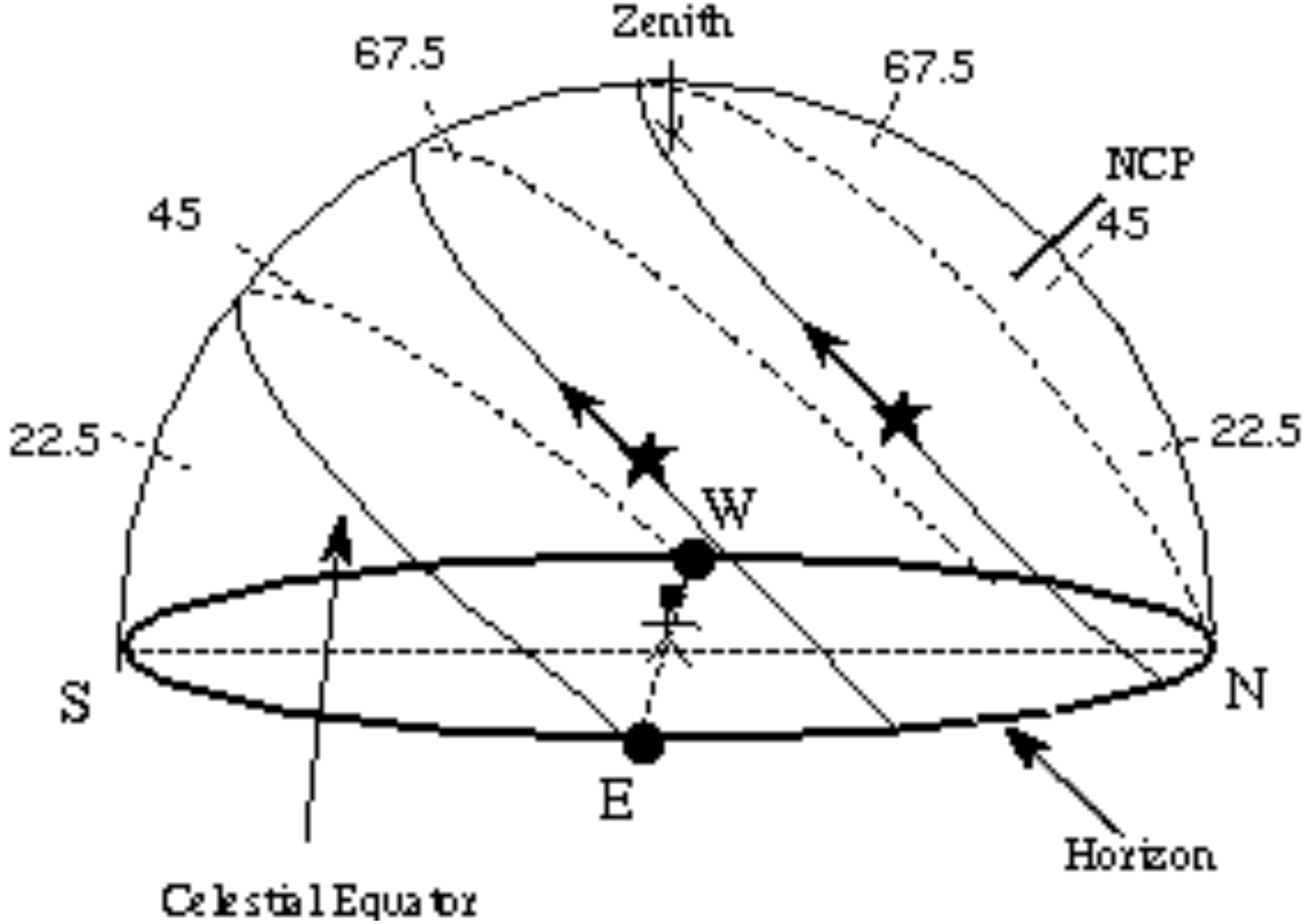
Hour Circle


North Celestial Pole
Hour Circle
South Celestial Pole


Hour Circle
North Celestial Pole
N
S
W
Celestial Equator

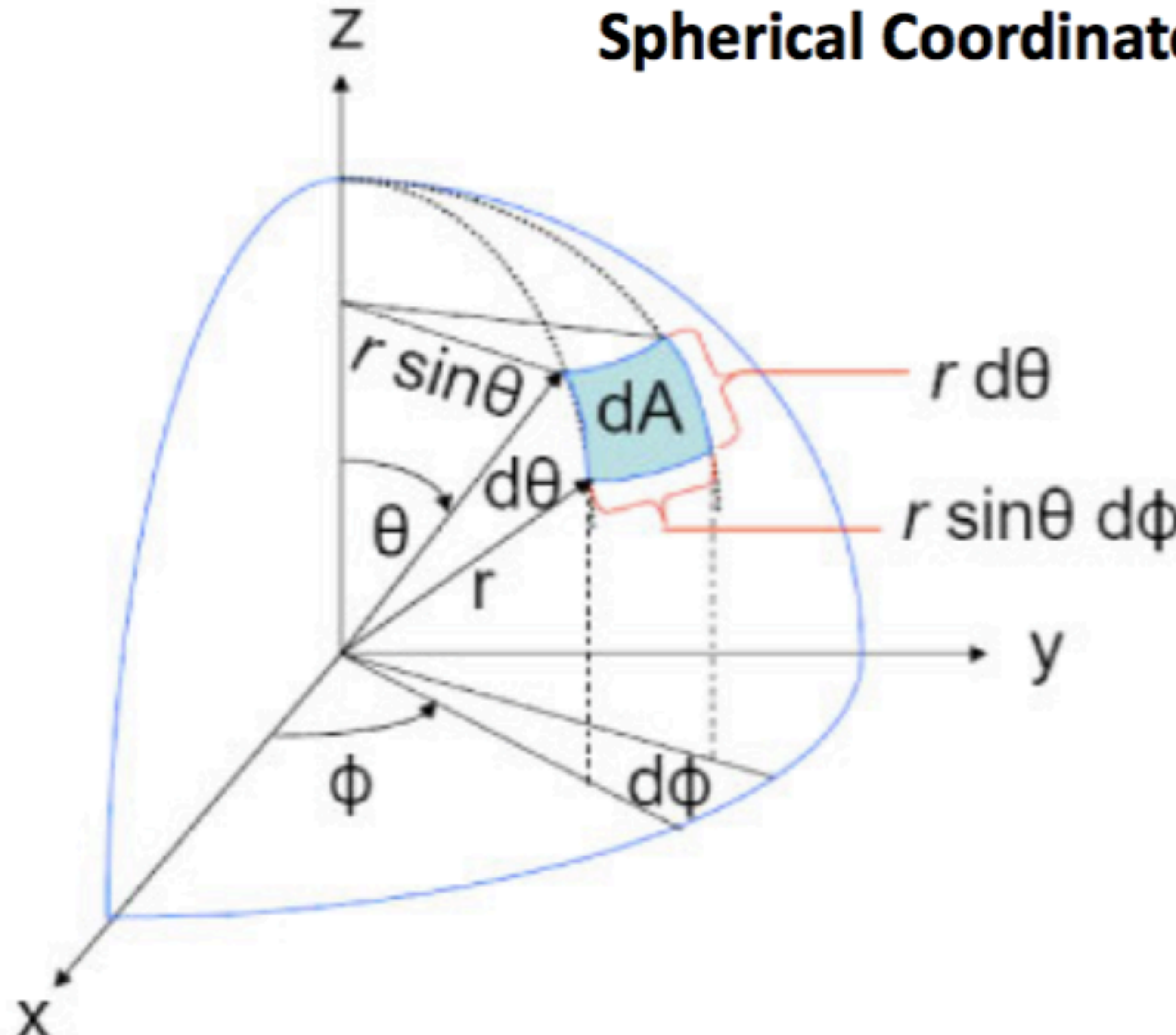


Zenith
North
Celestial
Pole
Horizon
N
Earth's
Equator
S
Horizon
Celestial Equator

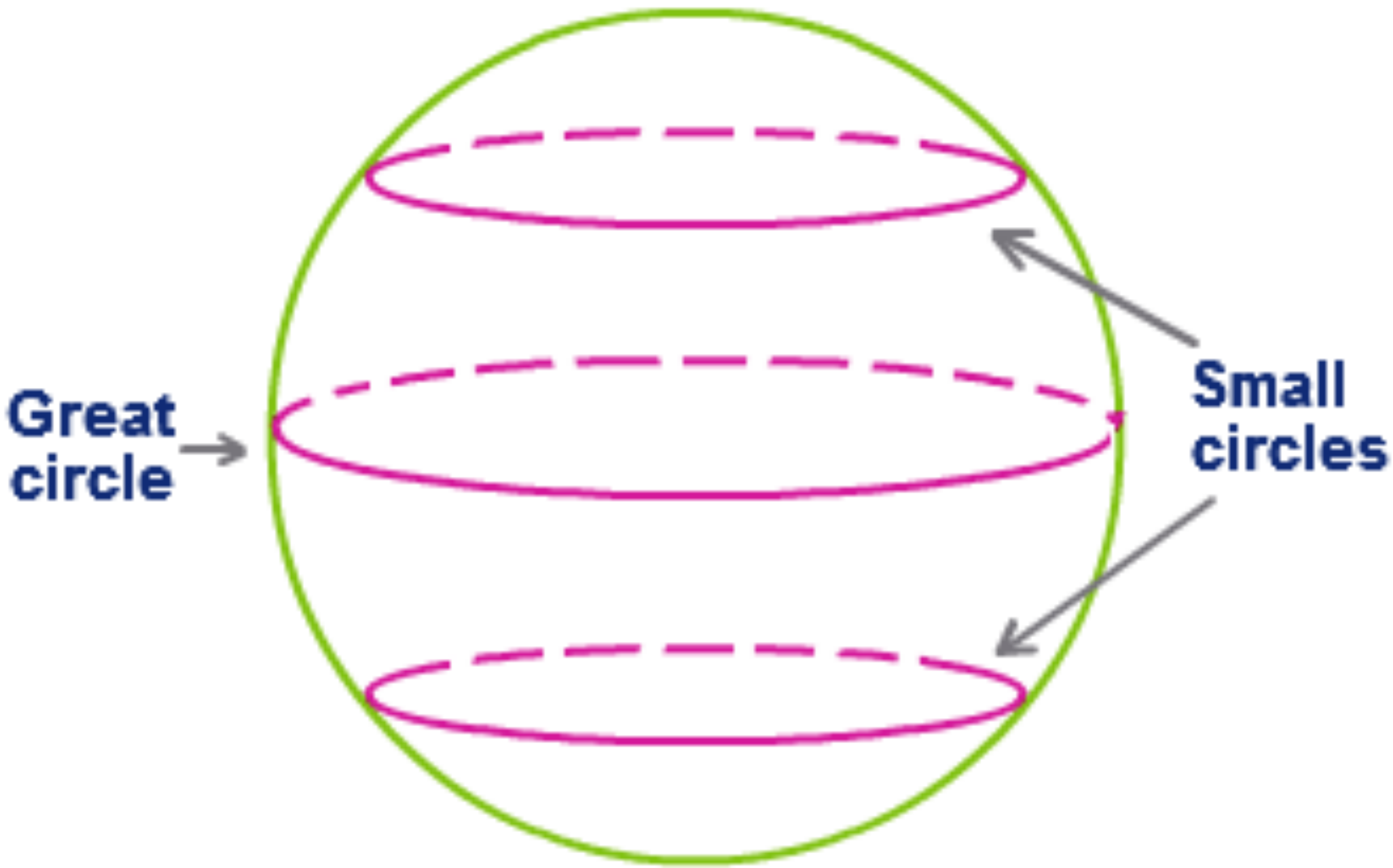


Zenith
67.5
67.5
NCP
45
45
22.5
22.5
W
S
N
E
Celestial Equator
Horizon

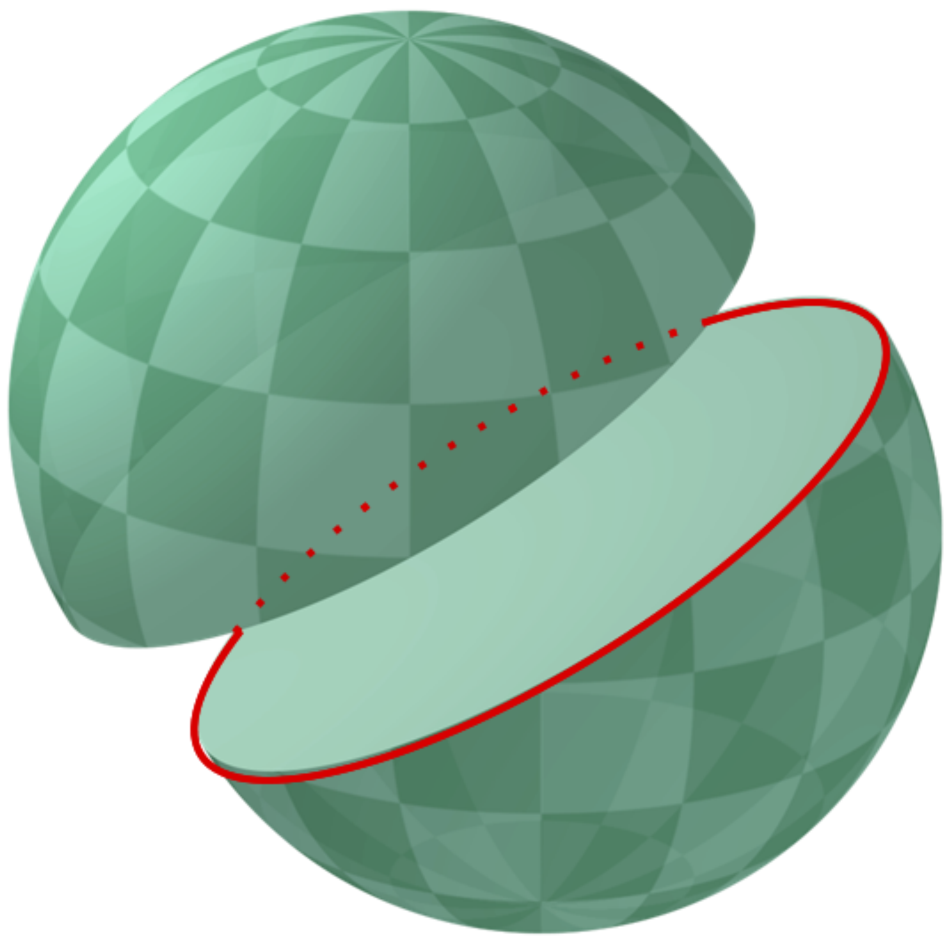
Spherical Coordinates



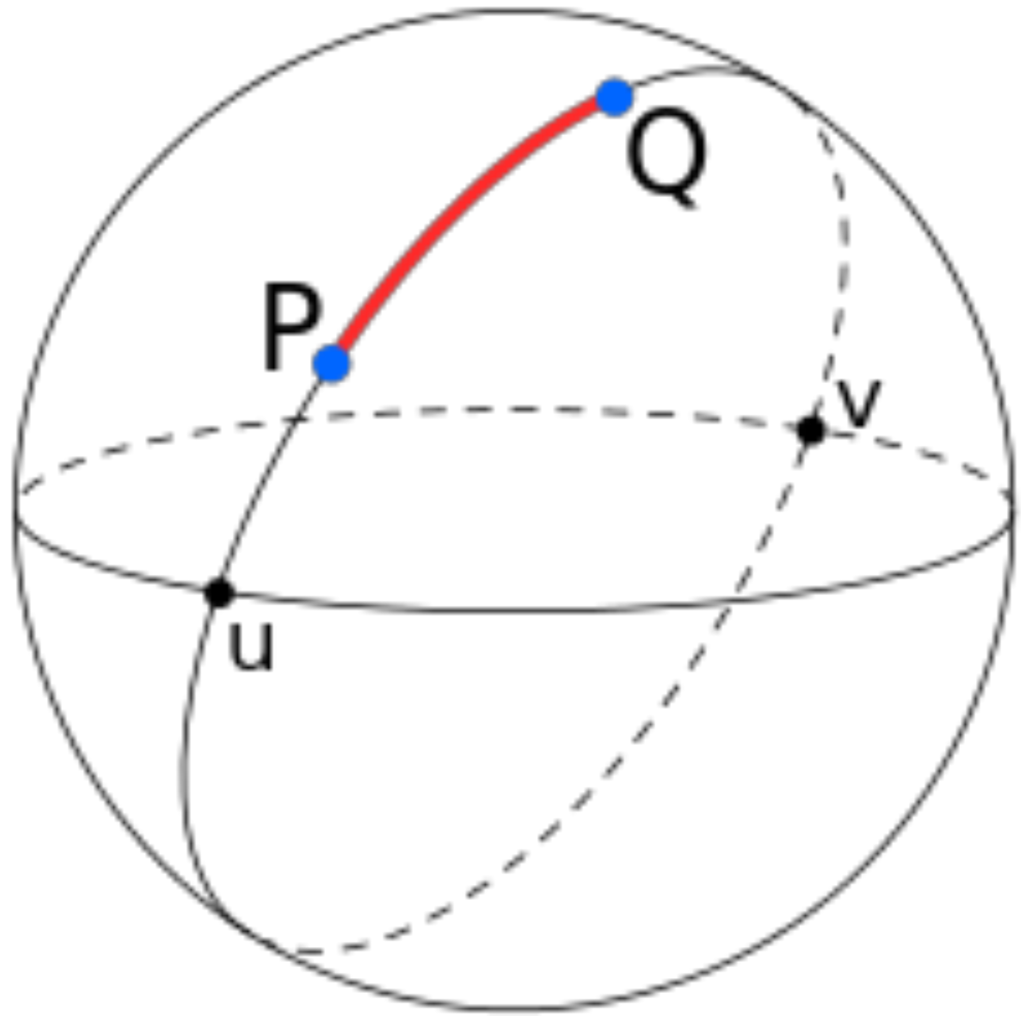
math.stackexchange.com

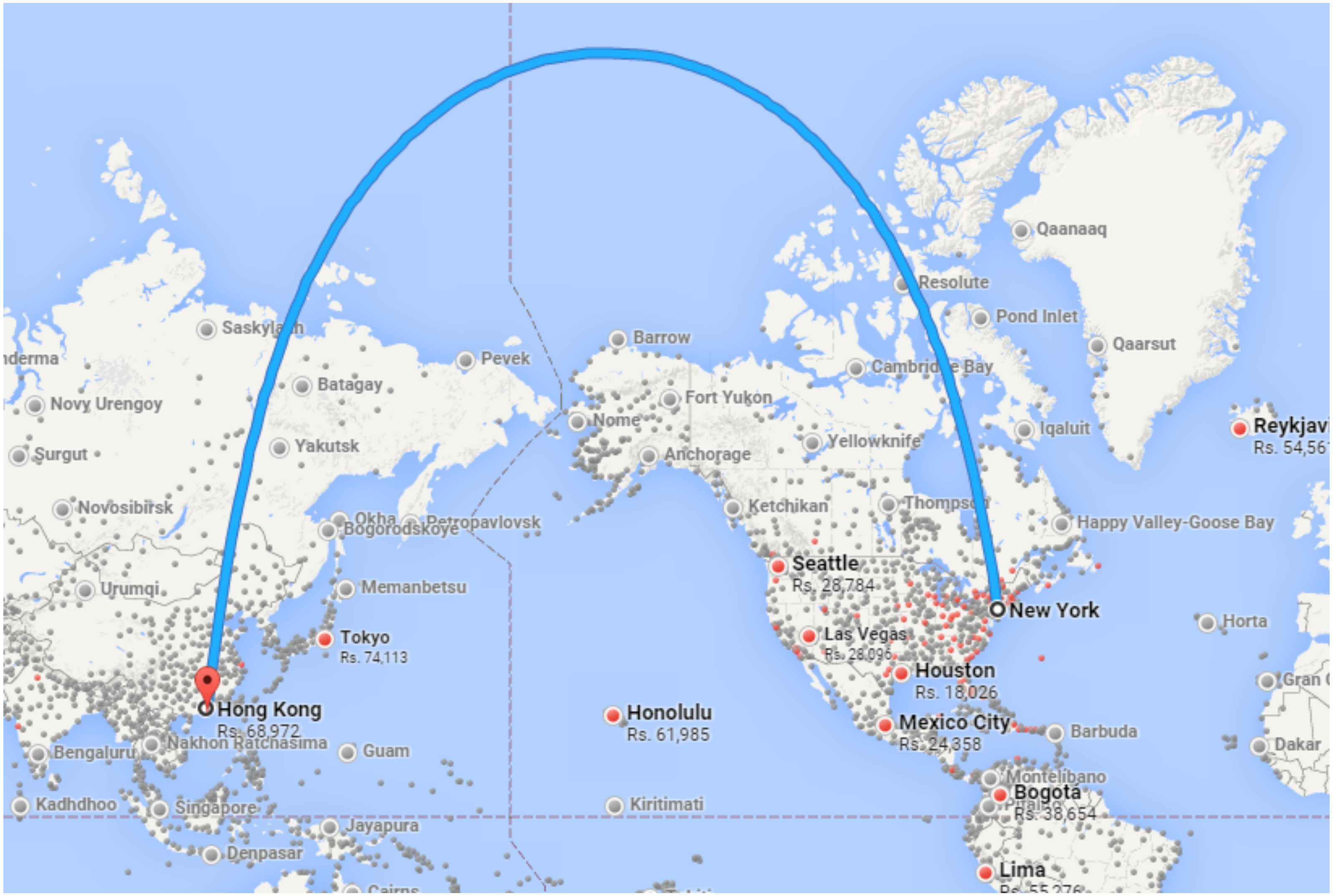

Great
circle
Small
circles

Great Circle



Shortest Distance on Sphere: Arc of Great Circle





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Rs. 68,972
New York
Tokyo
Rs. 74,113
Honolulu
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Seattle
Rs. 28,784
Las Vegas
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Houston
Rs. 18,026
Mexico City
Rs. 24,358
Bogota
Rs. 38,654
Lima
Reykjavi
Rs. 54,56
Qaanaaq
Resolute
Pond Inlet
Qaarsut
Cambridge Bay
Iqaluit
Yellowknife
Thompson
Happy Valley-Goose Bay
Barrow
Fort Yukon
Nome
Anchorage
Ketchikan
Pevek
Batagay
Yakutsk
Saskylakh
Novy Urengoy
Surgut
Novosibirsk
Urumqi
Okha
Bogorodskoye
Petropavlovsk
Memanbetsu
Guam
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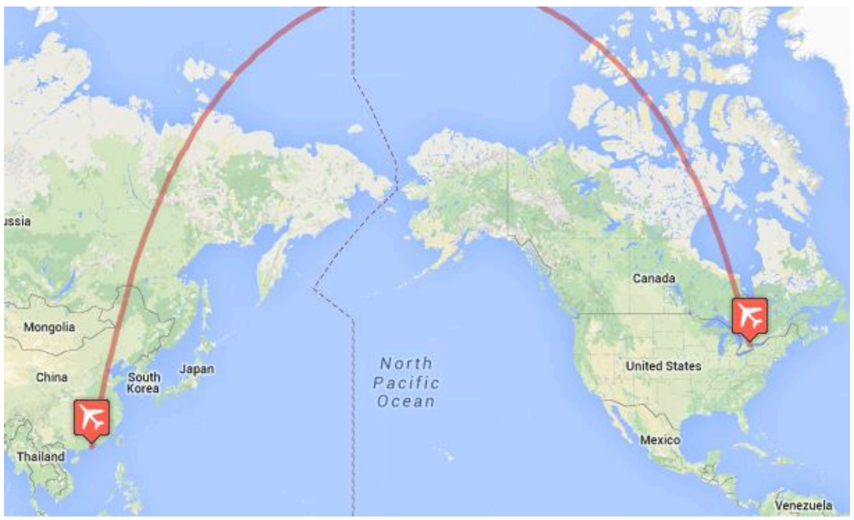
Montelibano
Horta
Dakar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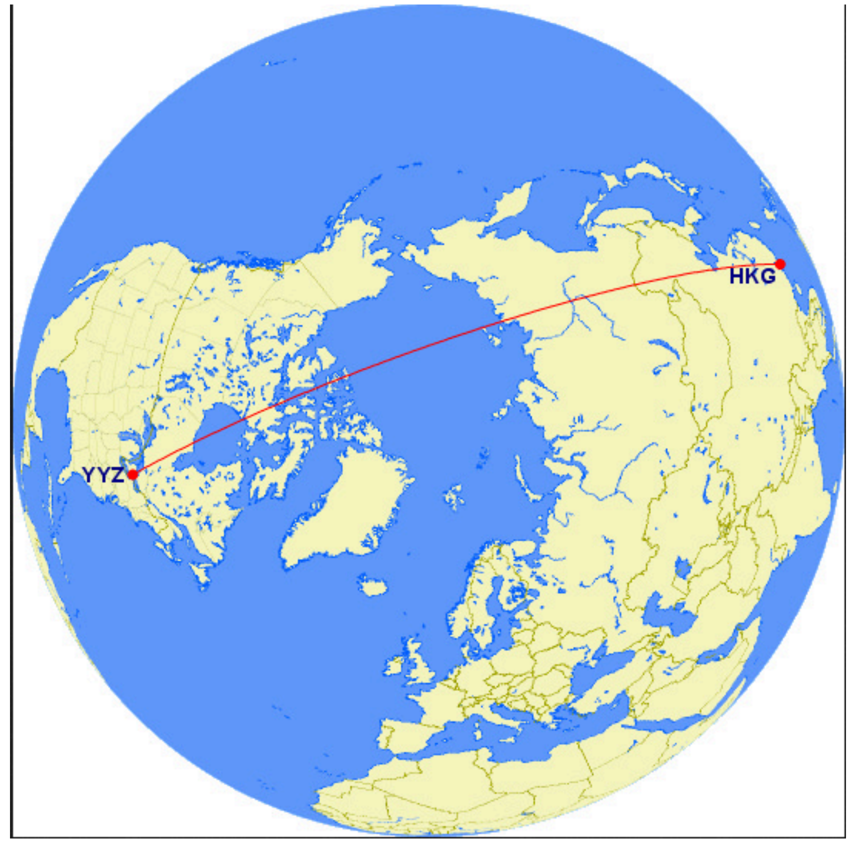
Mongolia
China
South Korea
Japan
North Pacific Ocean
United States
Mexico
Thailand
Venezuela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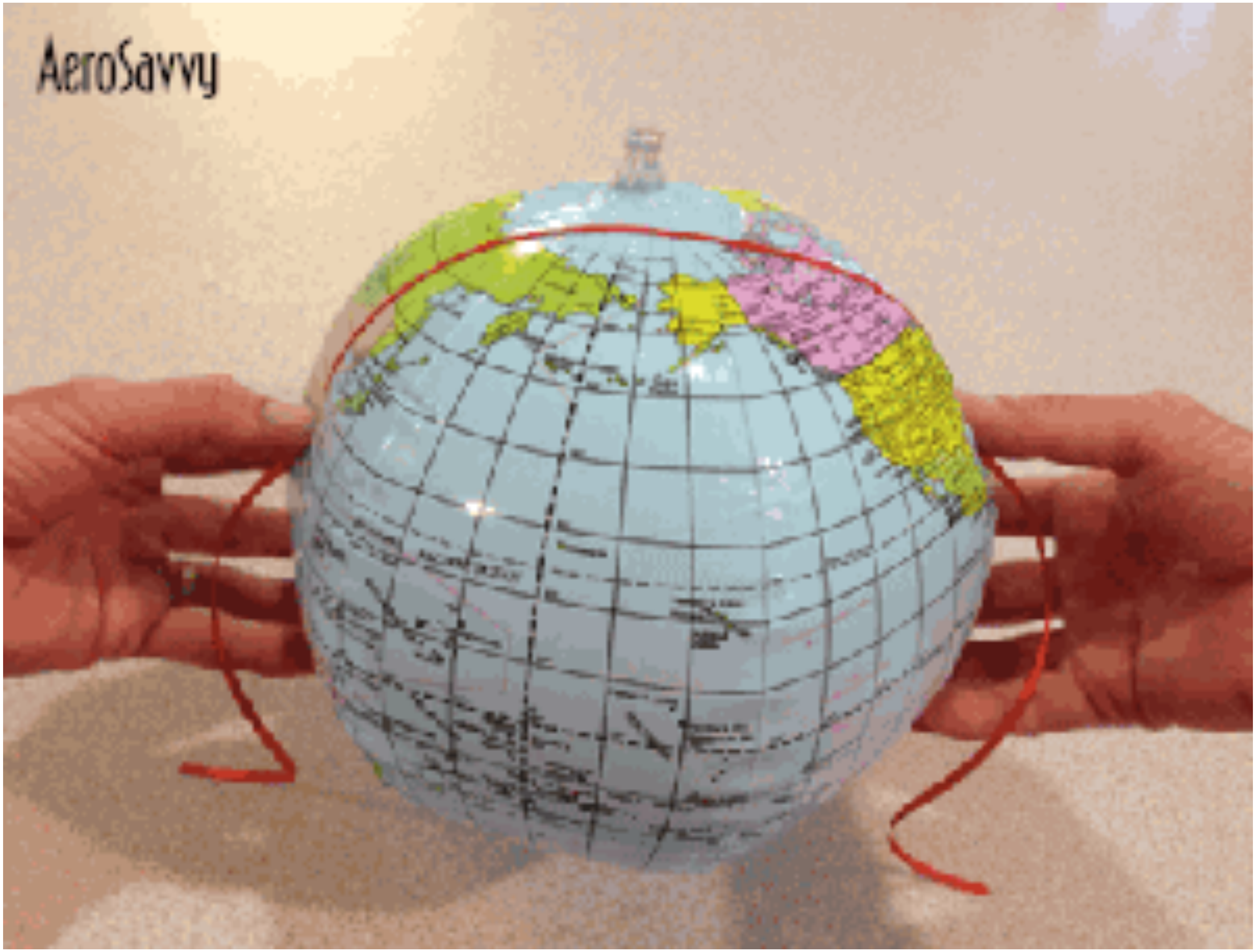
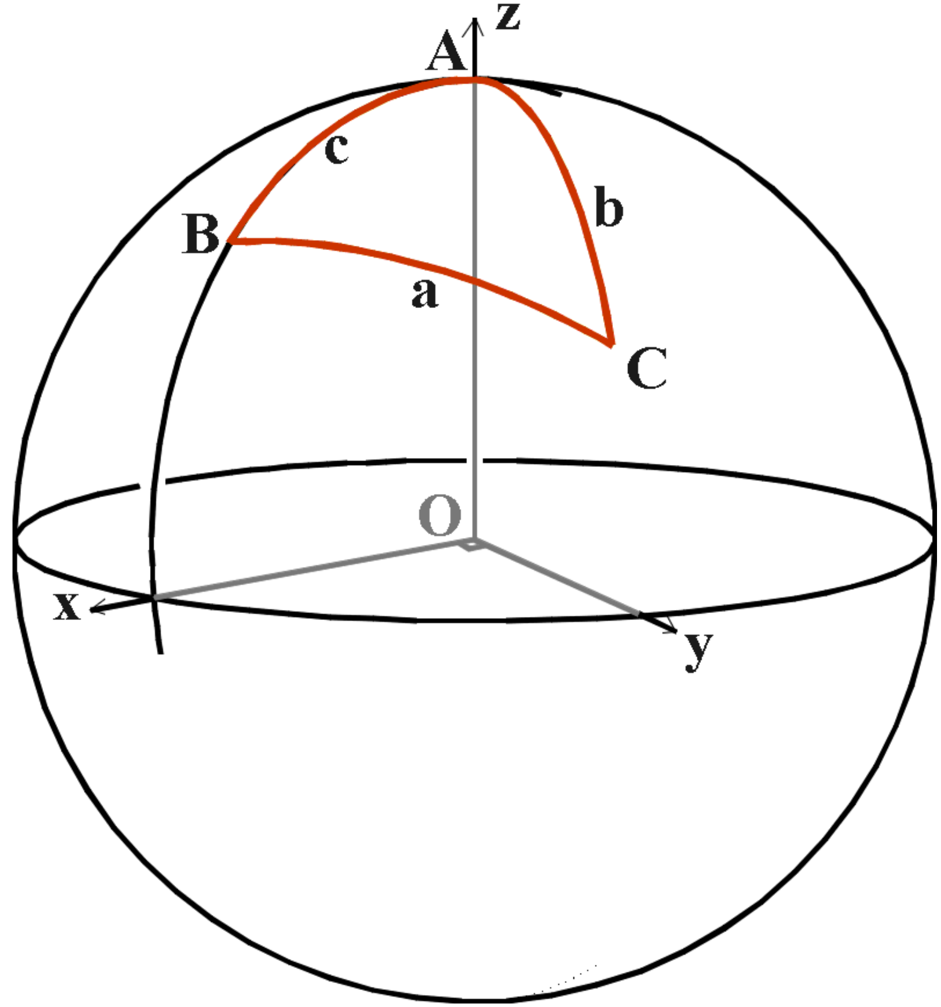
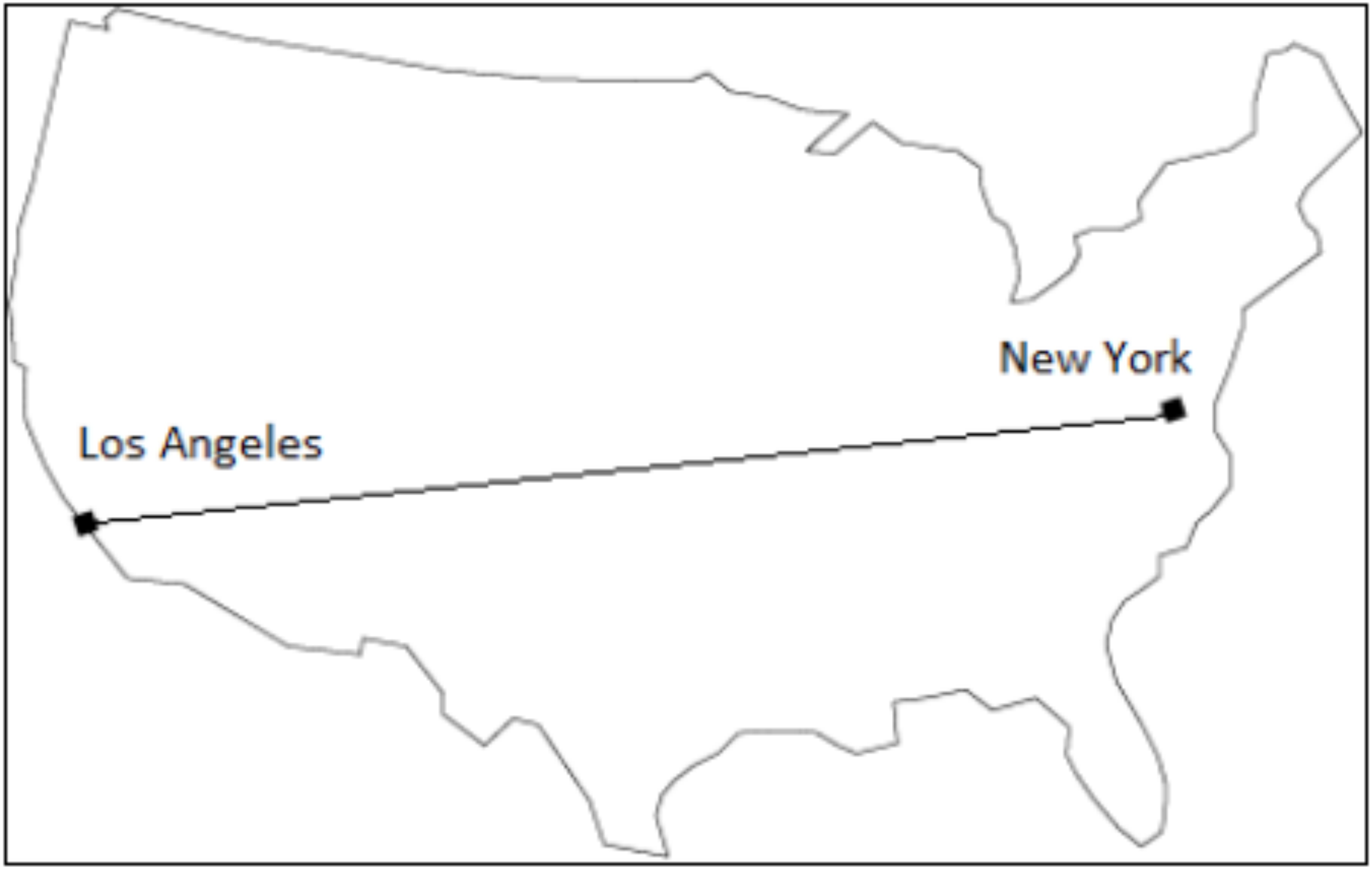
YYZ

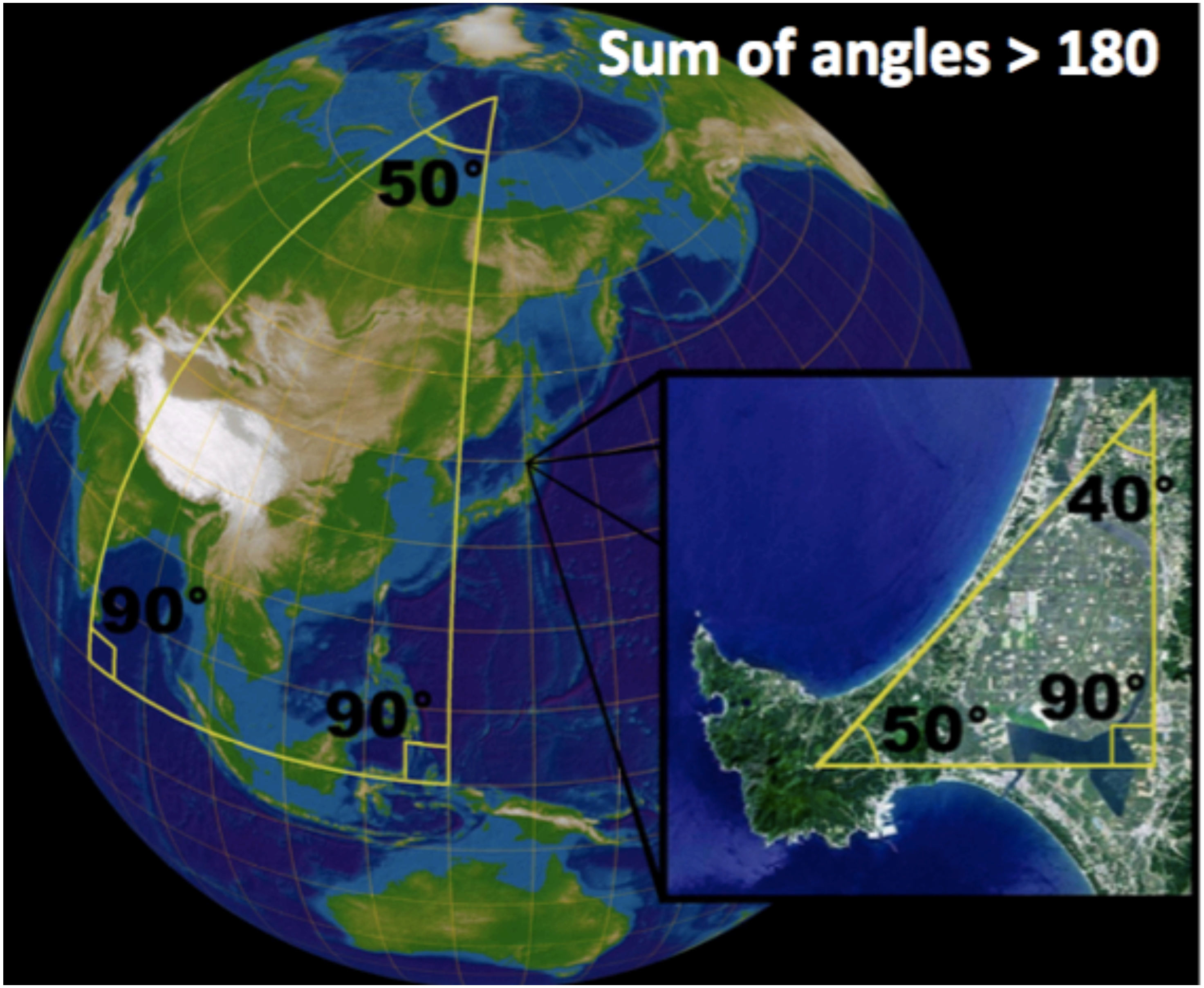

AeroSavvy

The Spherical Triangle

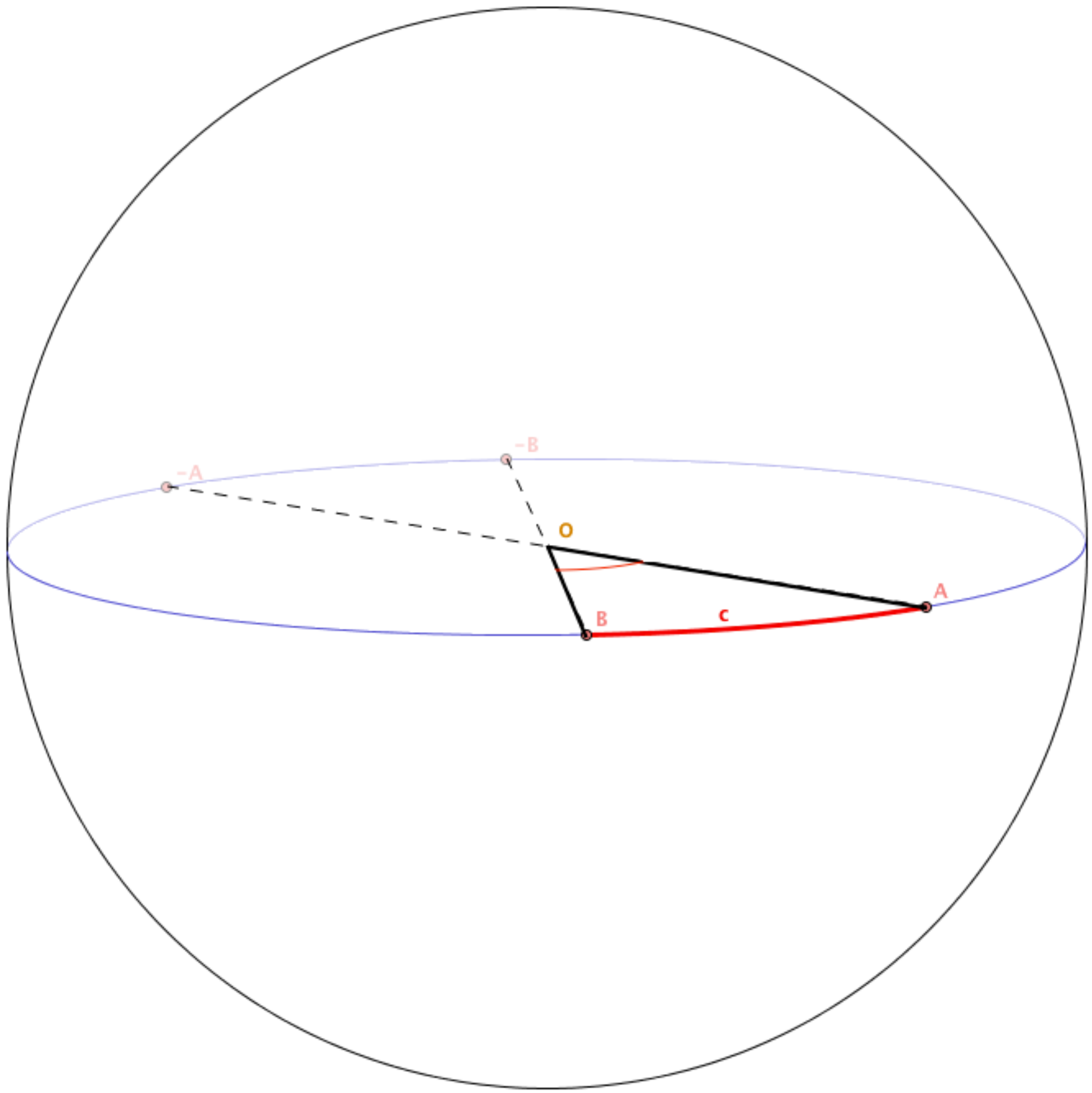



New York
Los Angeles

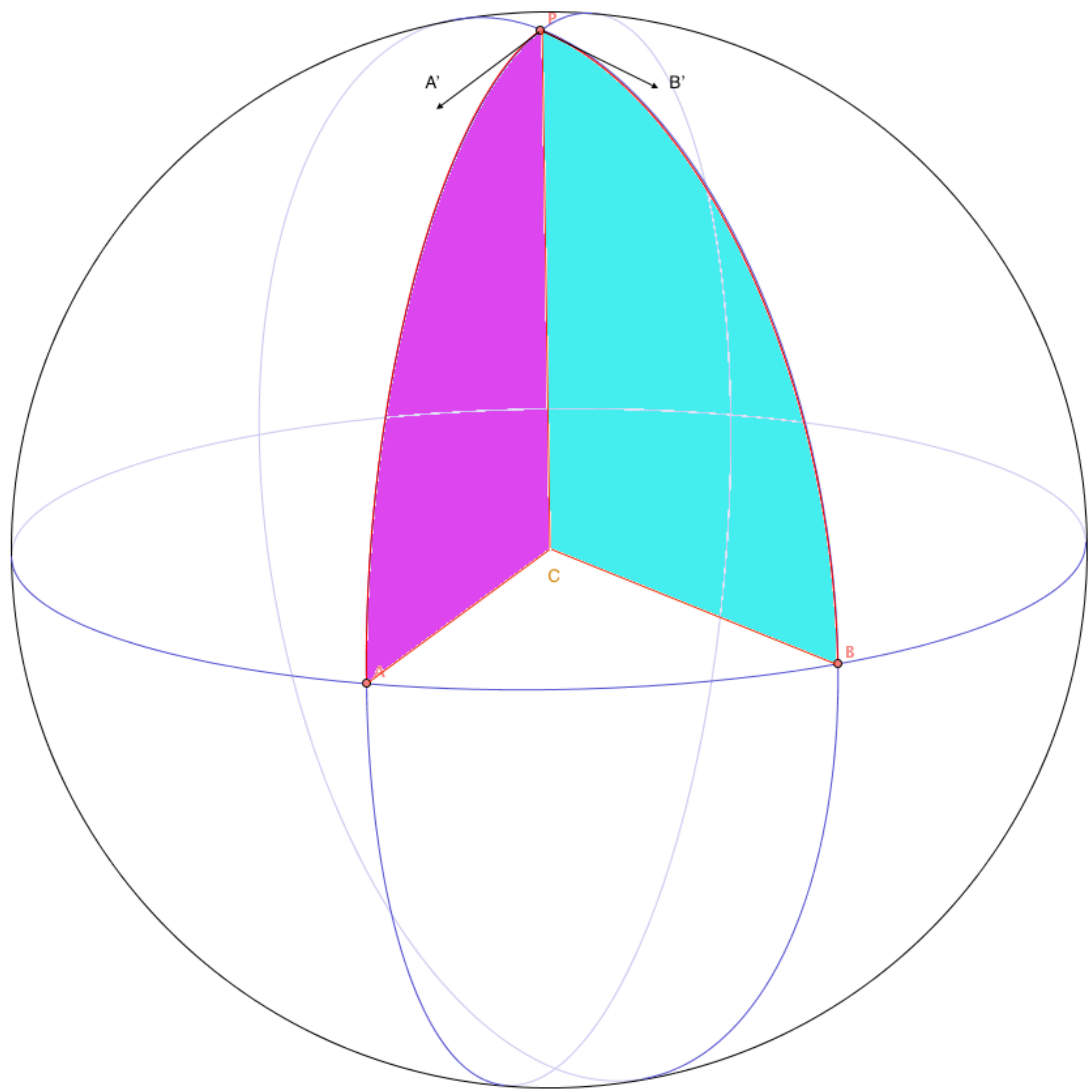

LAX
CPT



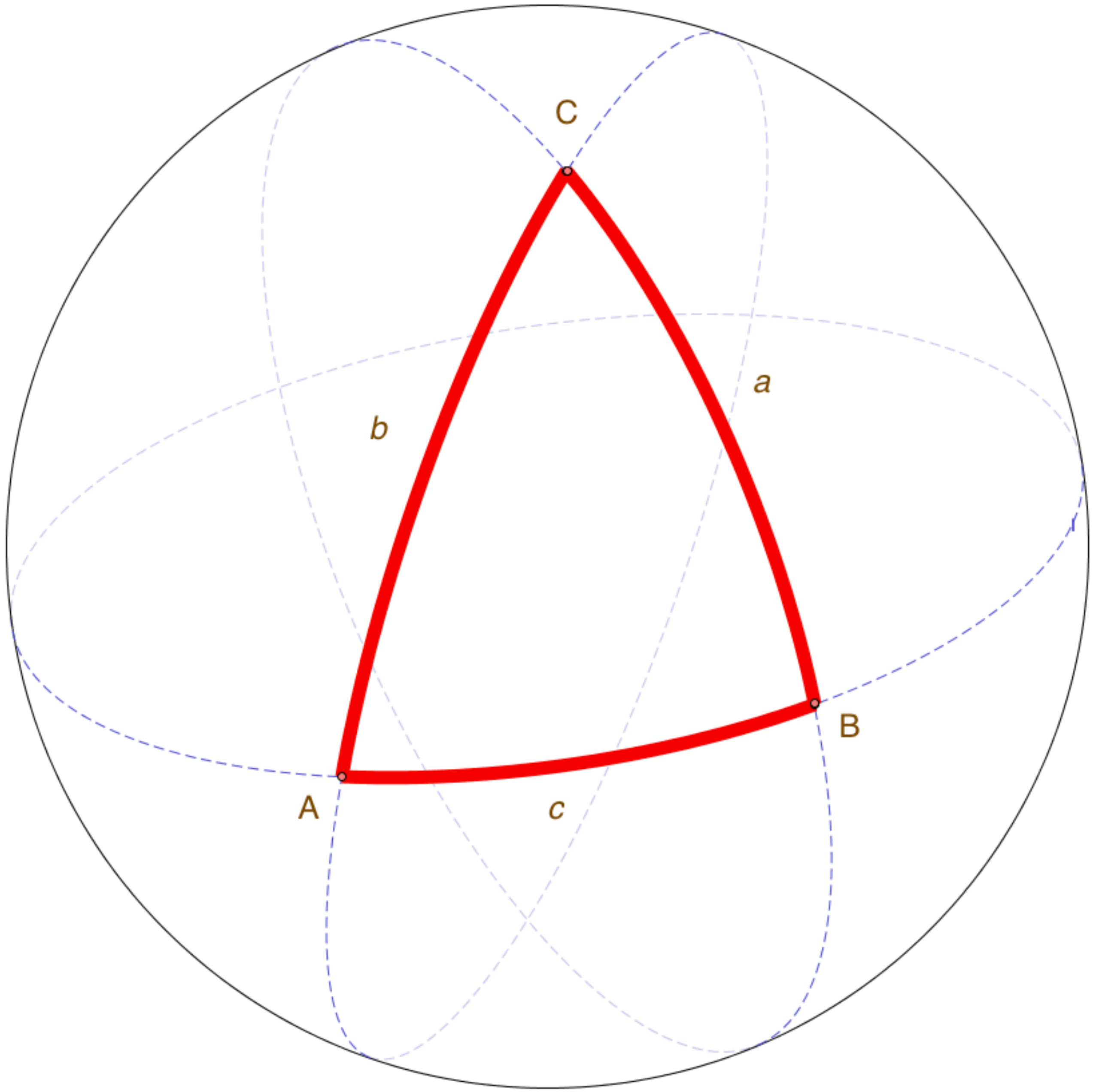
Sum of angles > 180
50°
90°
90°
40°
90°
50°

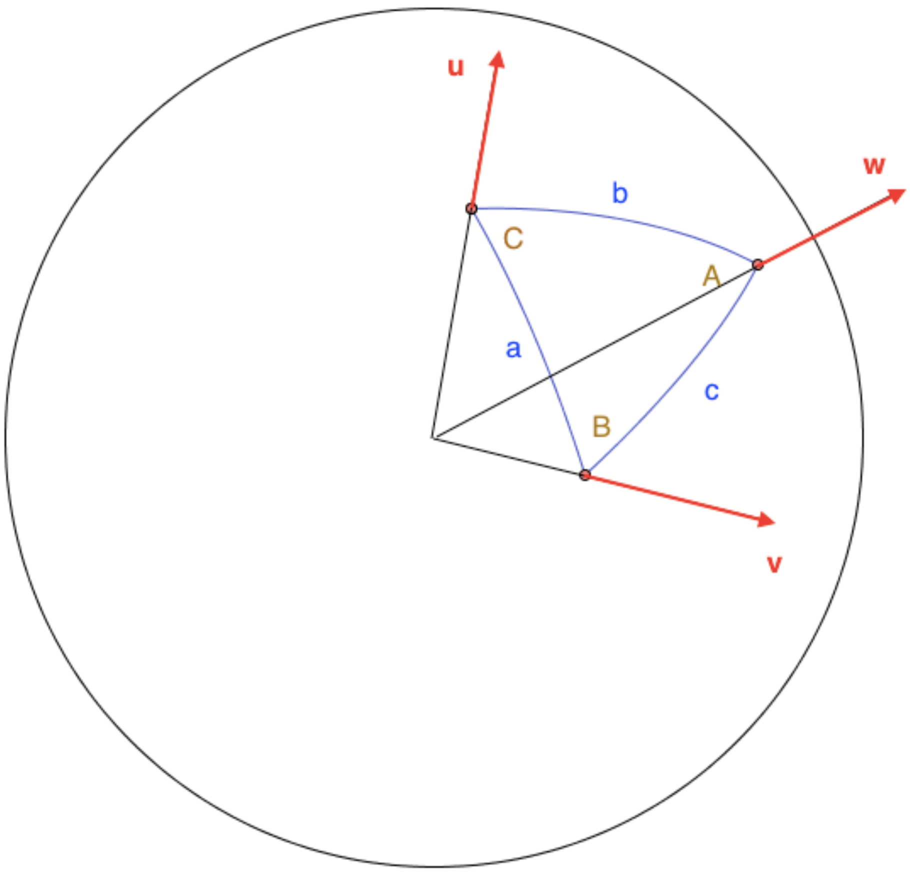


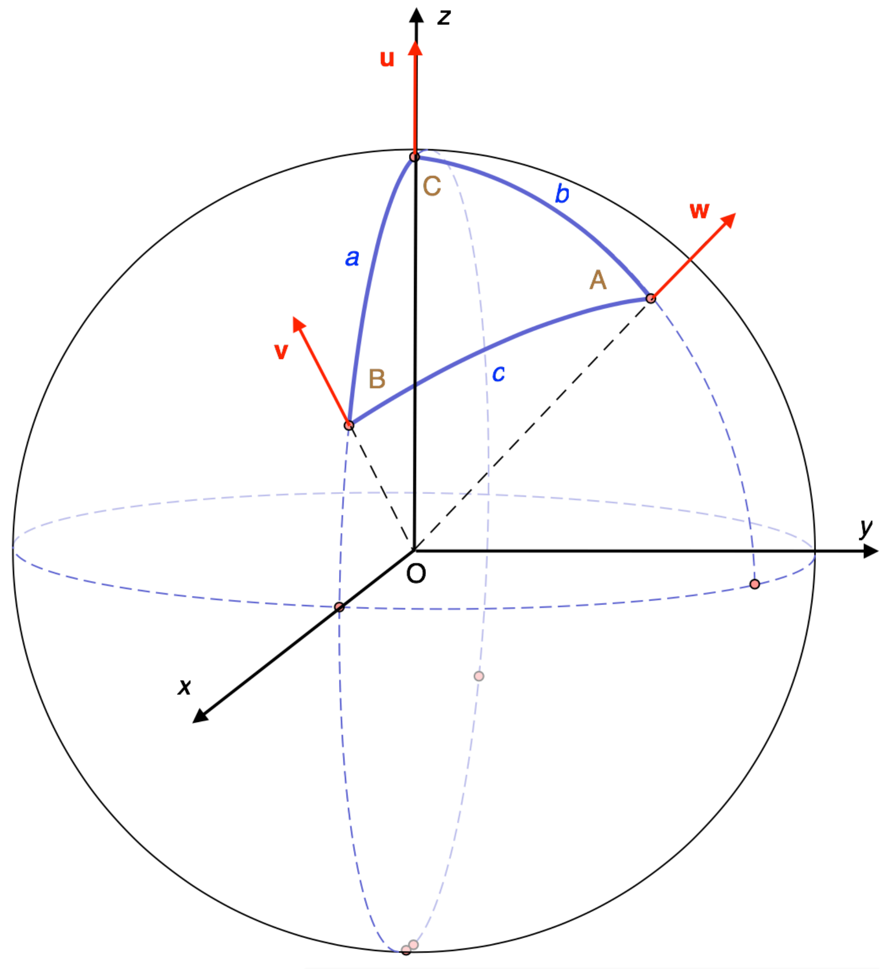
−A
−B
O
A
B
c

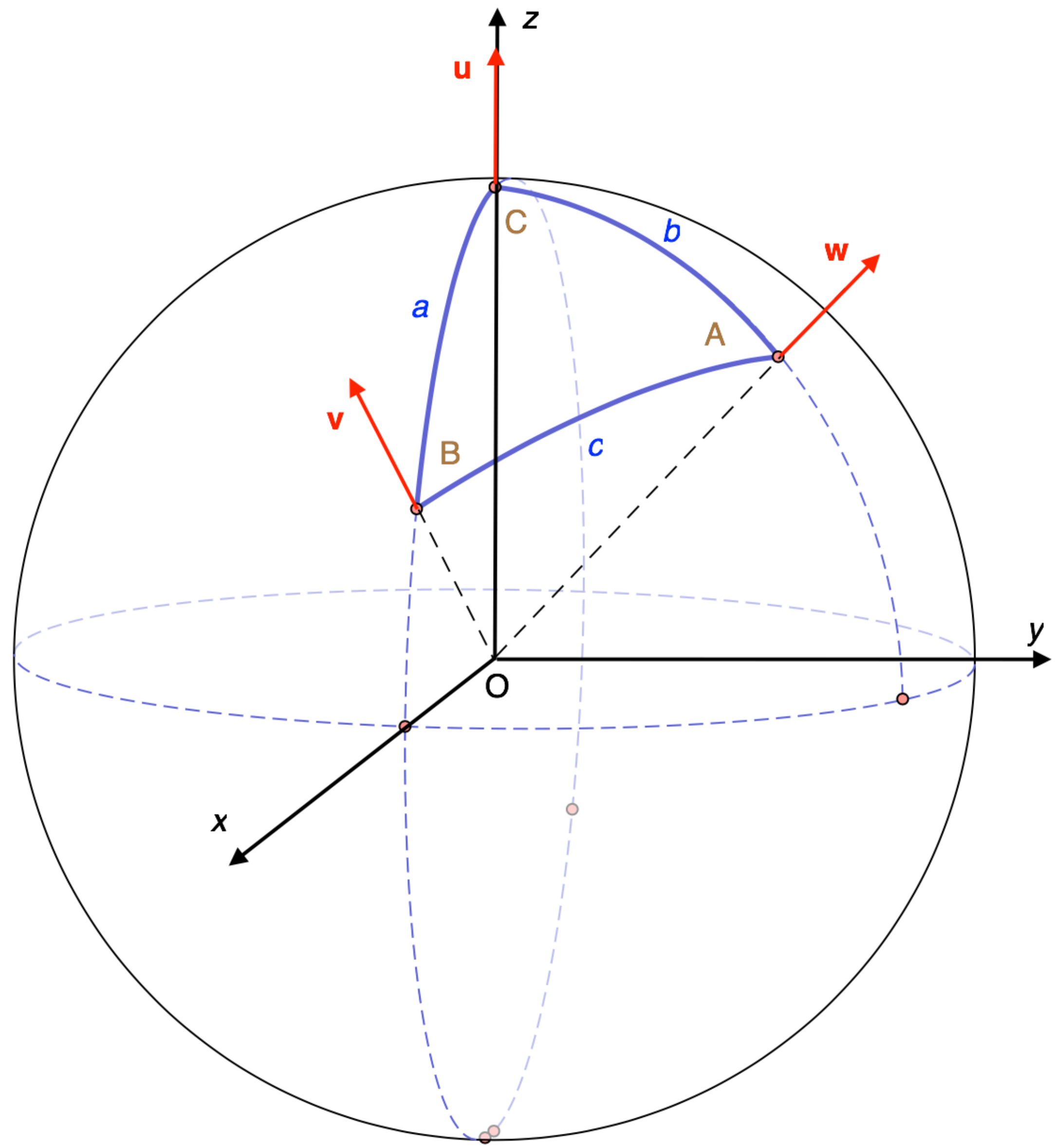


P
A'
B'
C
A
B


C
b
a
B
A
c


u
w
b
C
A
a
B
c
v


z
u
C
b
w
a
A
v
B
c
y
O
x


z
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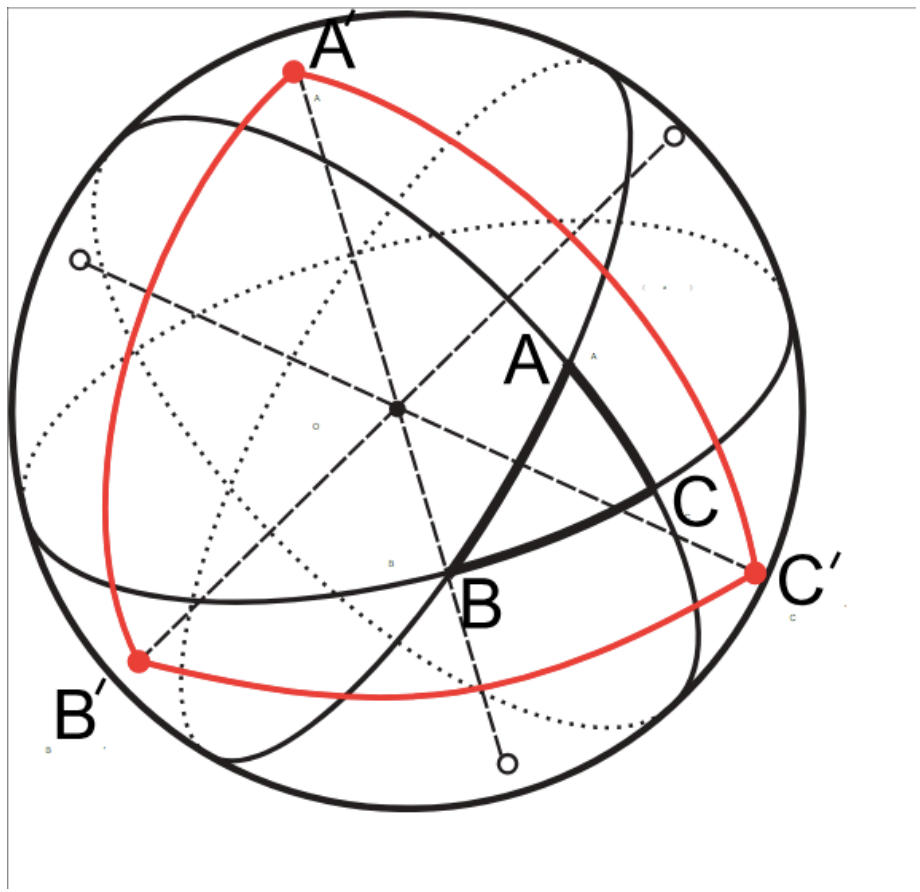
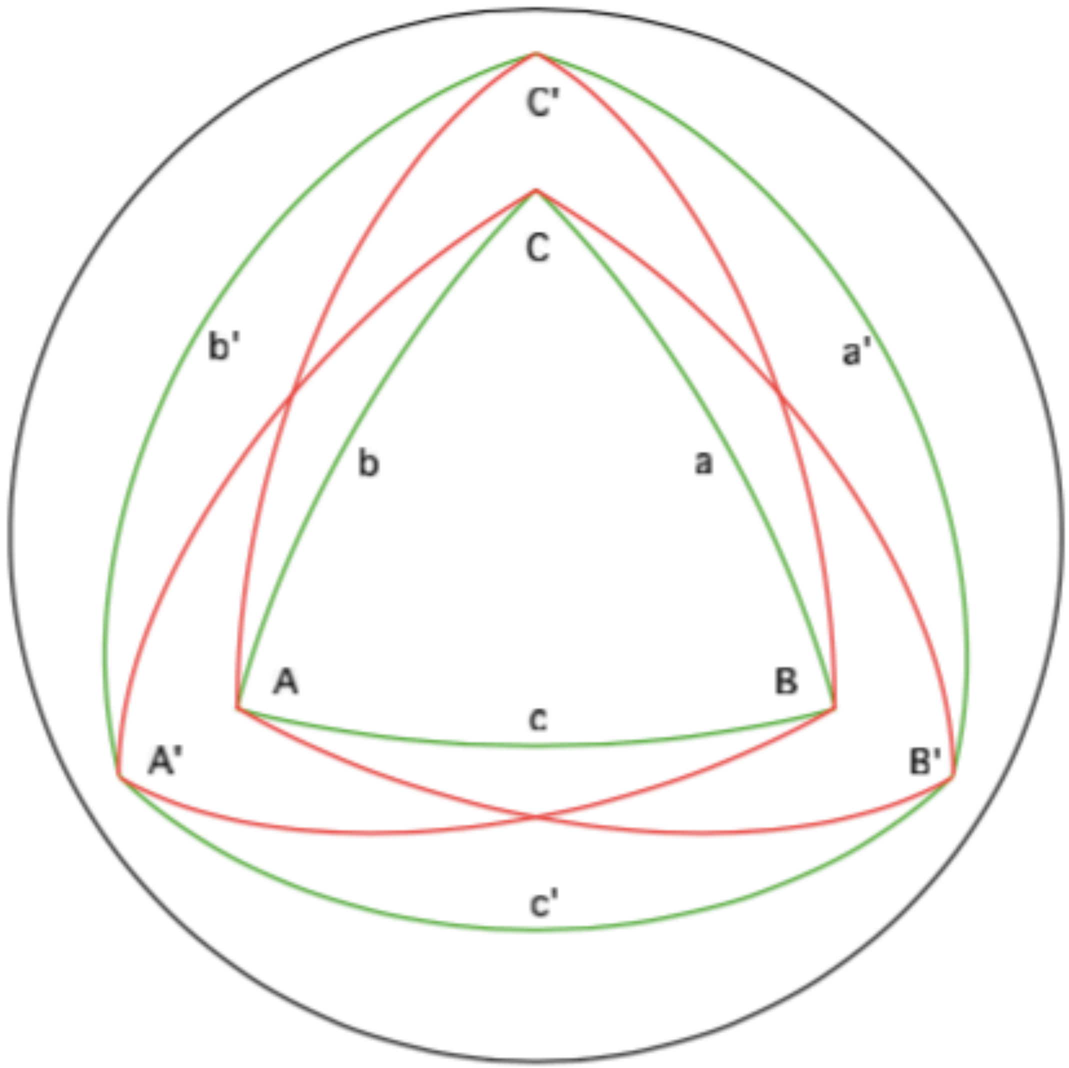
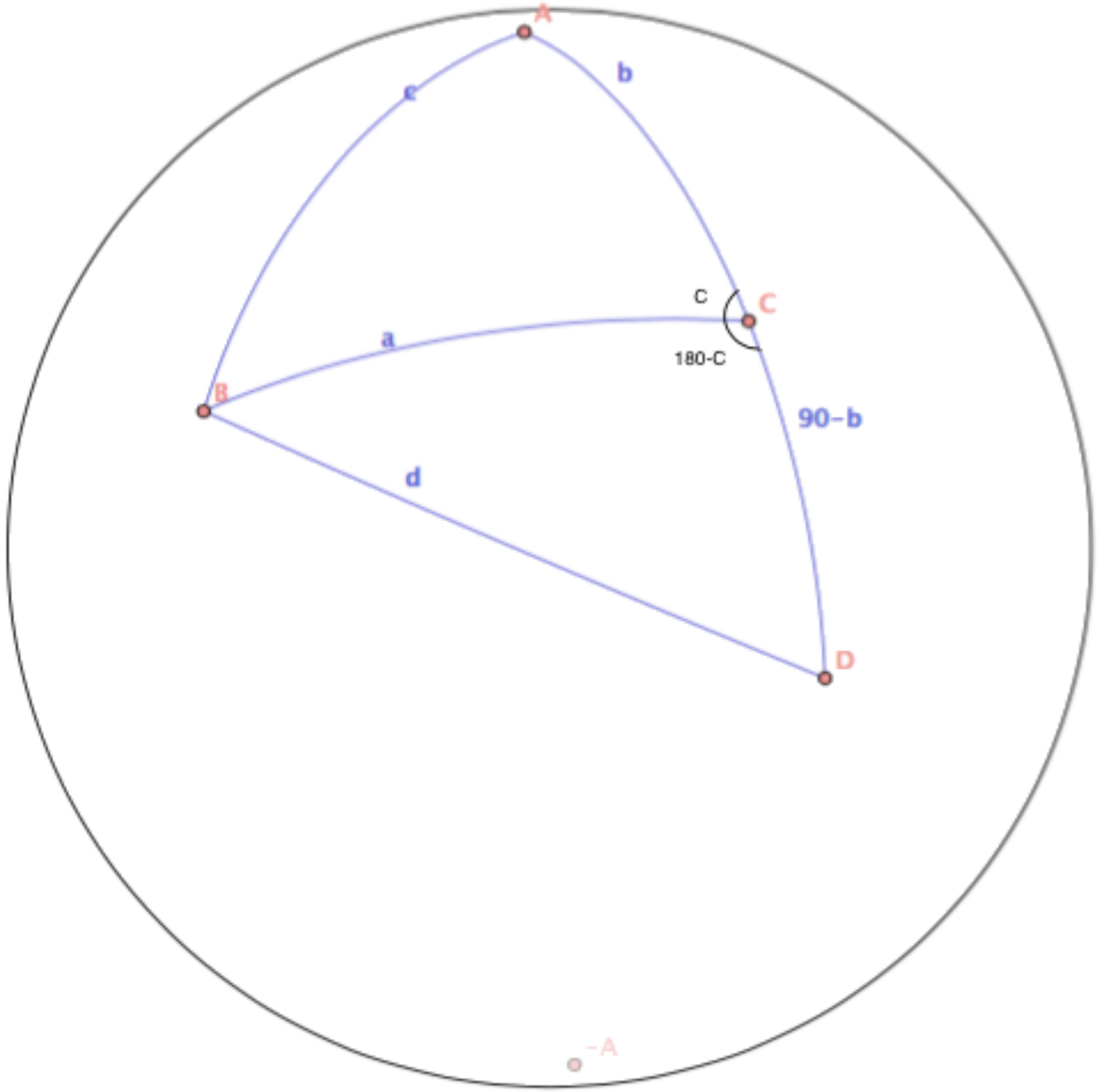
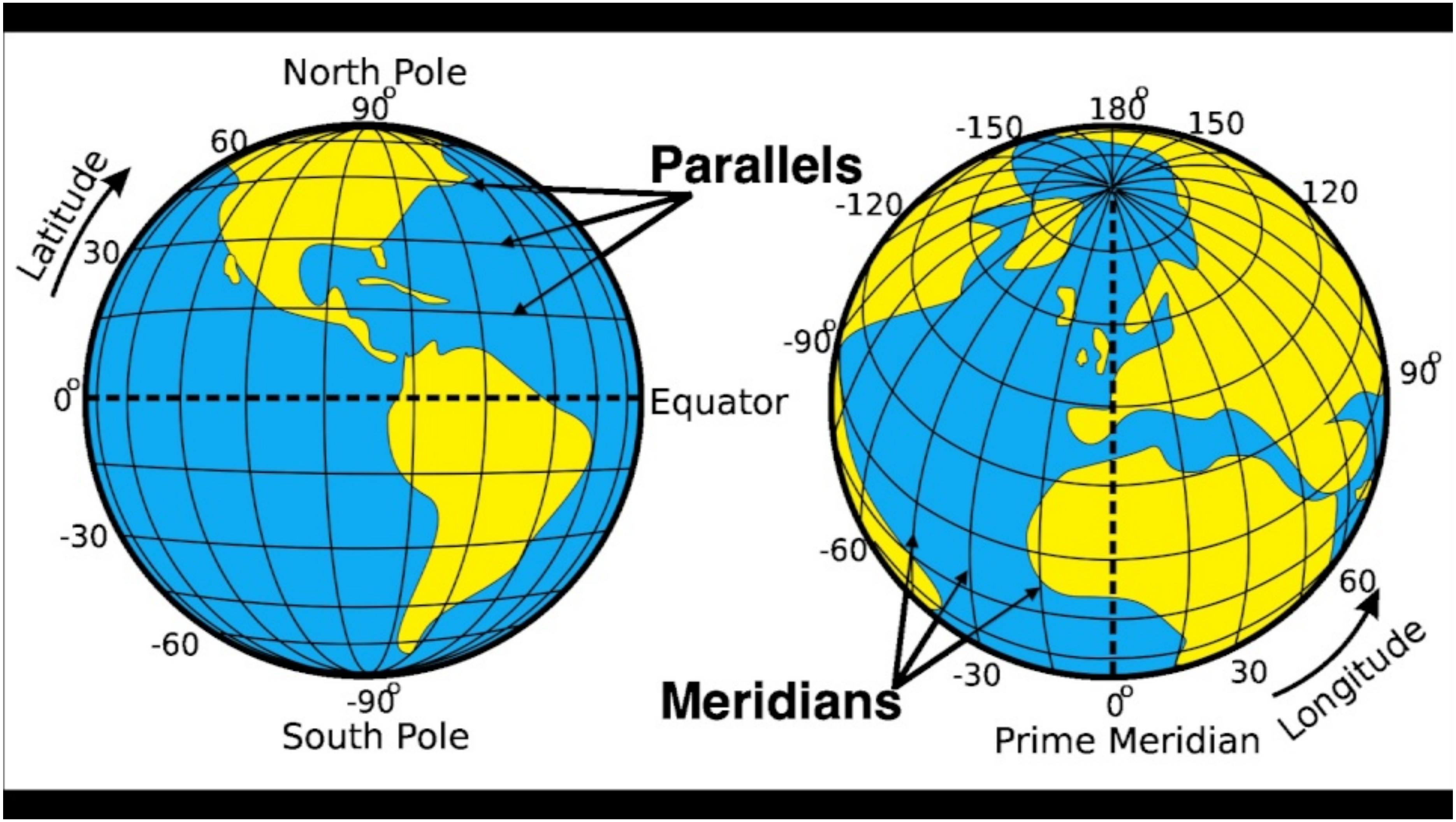
C
b
w
a
A
v
B
c
y
O
x

The dual triangle

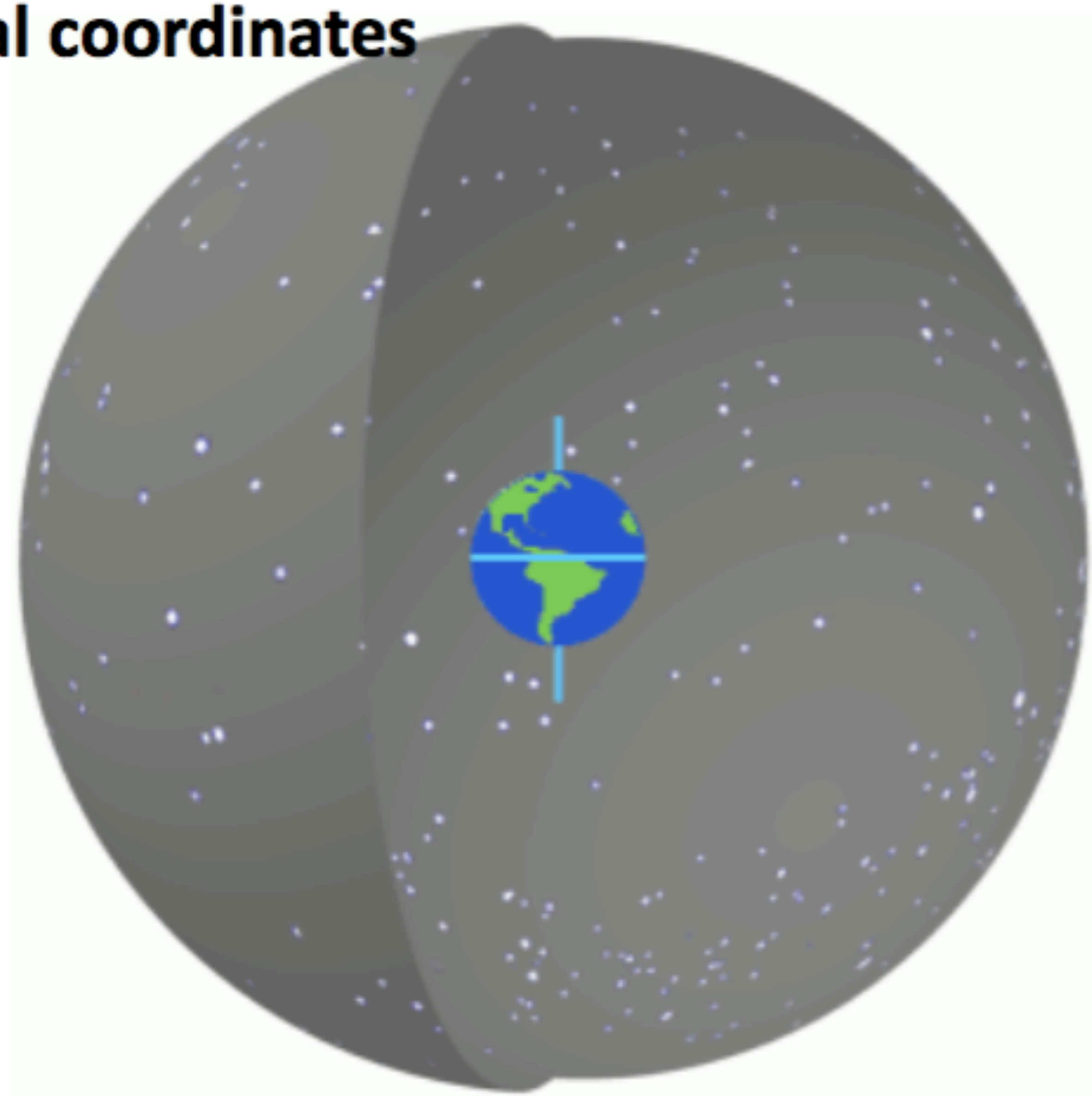



C'
C
b'
a'
b
a
A
B
c
A'
B'
c'


A
b
c
C
C
180-C
a
B
90-b
d
D
-A

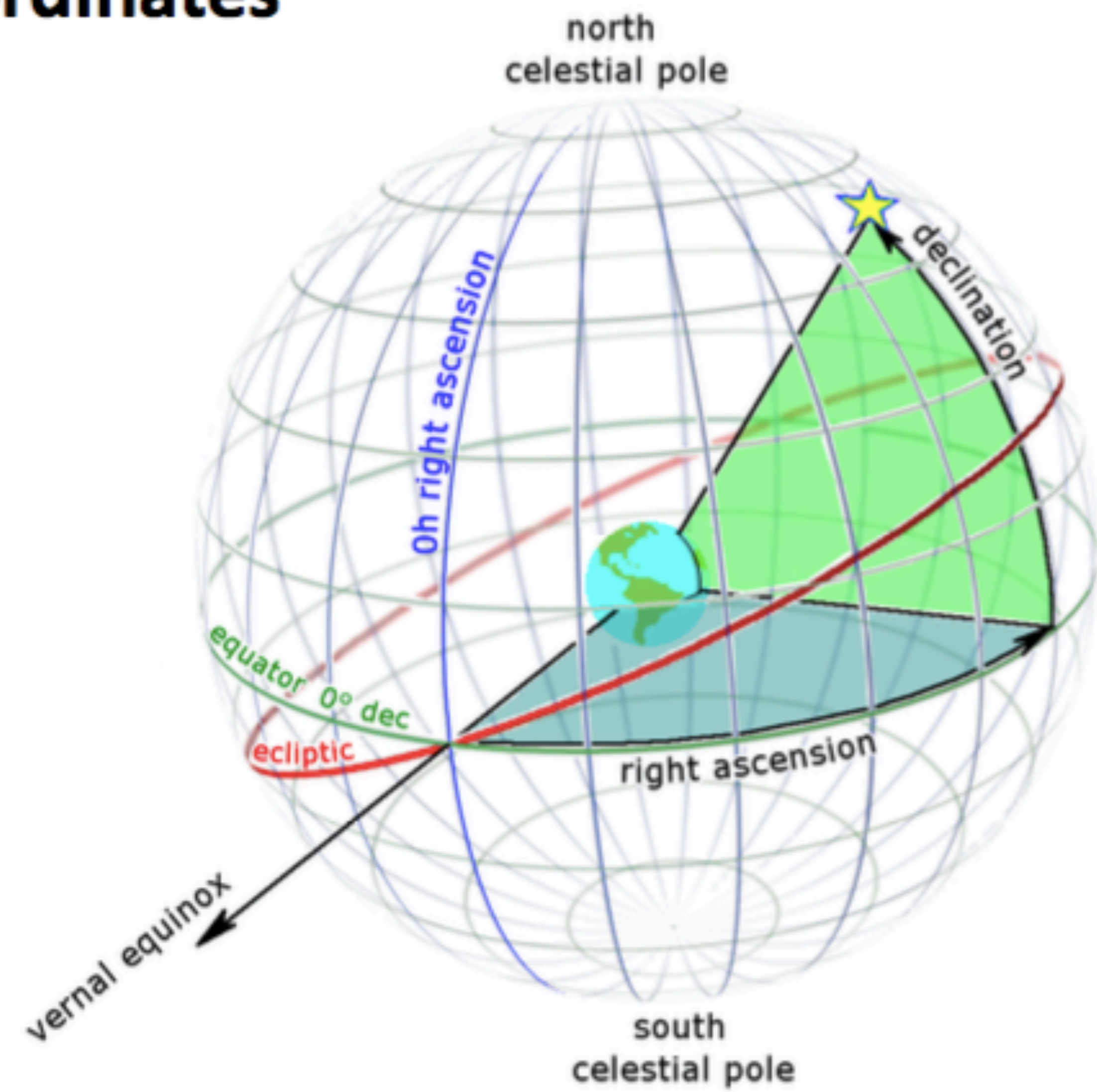

North Pole
90°
60
30
0°
-30
-60
-90°
South Pole
Latitude
Parallels
Equator
180°
-150
150
-120
120
-90°
90°
-60
60
-30
30
0°
Prime Meridian
Meridians
Longitude

Equatorial coordinates



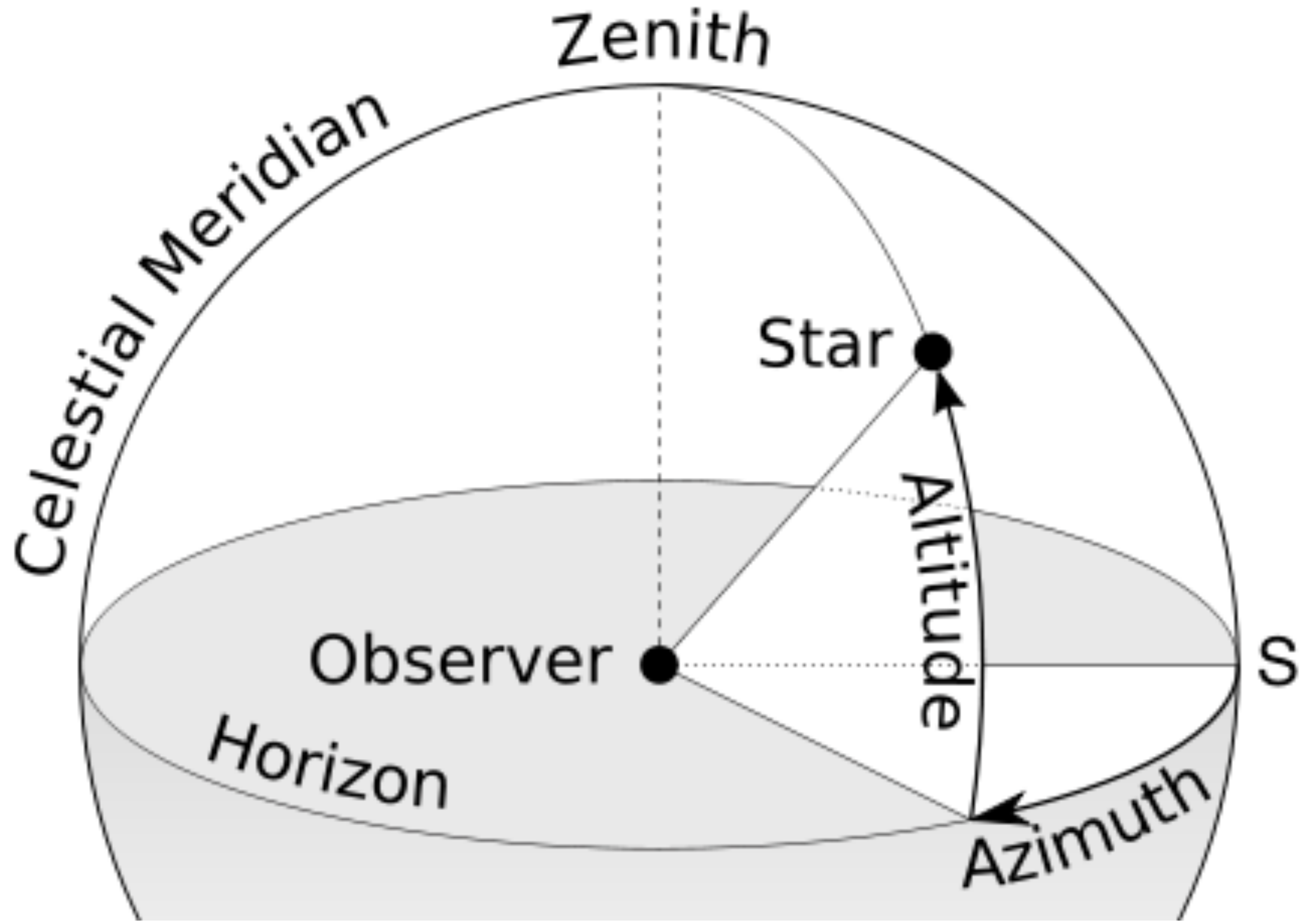
https://commons.wikimedia.org/w/index.php?curid=19127102

Equatorial coordinates

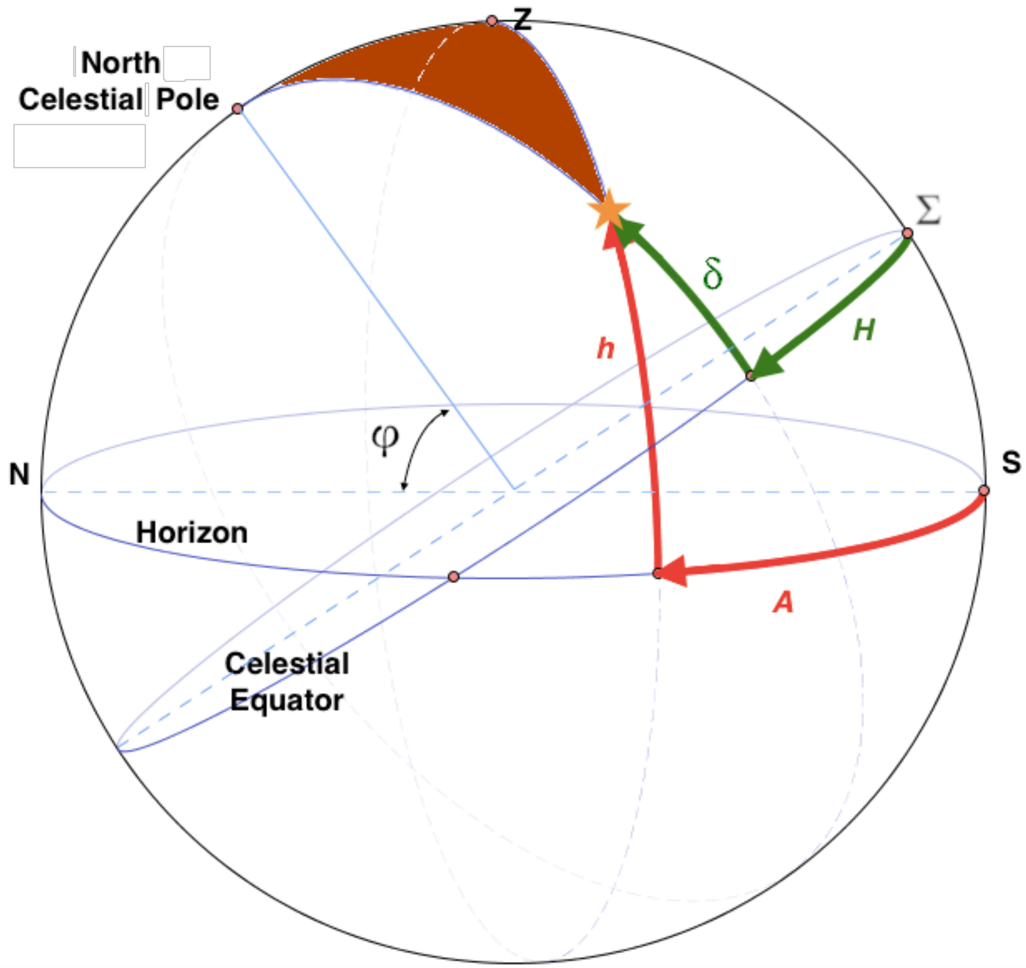


Parameter	WASP-12
RA(J2000)	06:30:32.79
Dec(J2000)	+29:40:20.4
B	12.11 ± 0.08
V	11.69 ± 0.08
I	11.03 ± 0.08
J	10.477 ± 0.021
H	10.228 ± 0.022
K	10.188 ± 0.020
$T_{\rm eff}$	6300^{+200}_{-100} K
[M/H]	$0.30^{+0.05}_{-0.15}$
$\log g$	4.38 ± 0.10
$v \sin i$	$< 2.2 \pm 1.5$ km/s

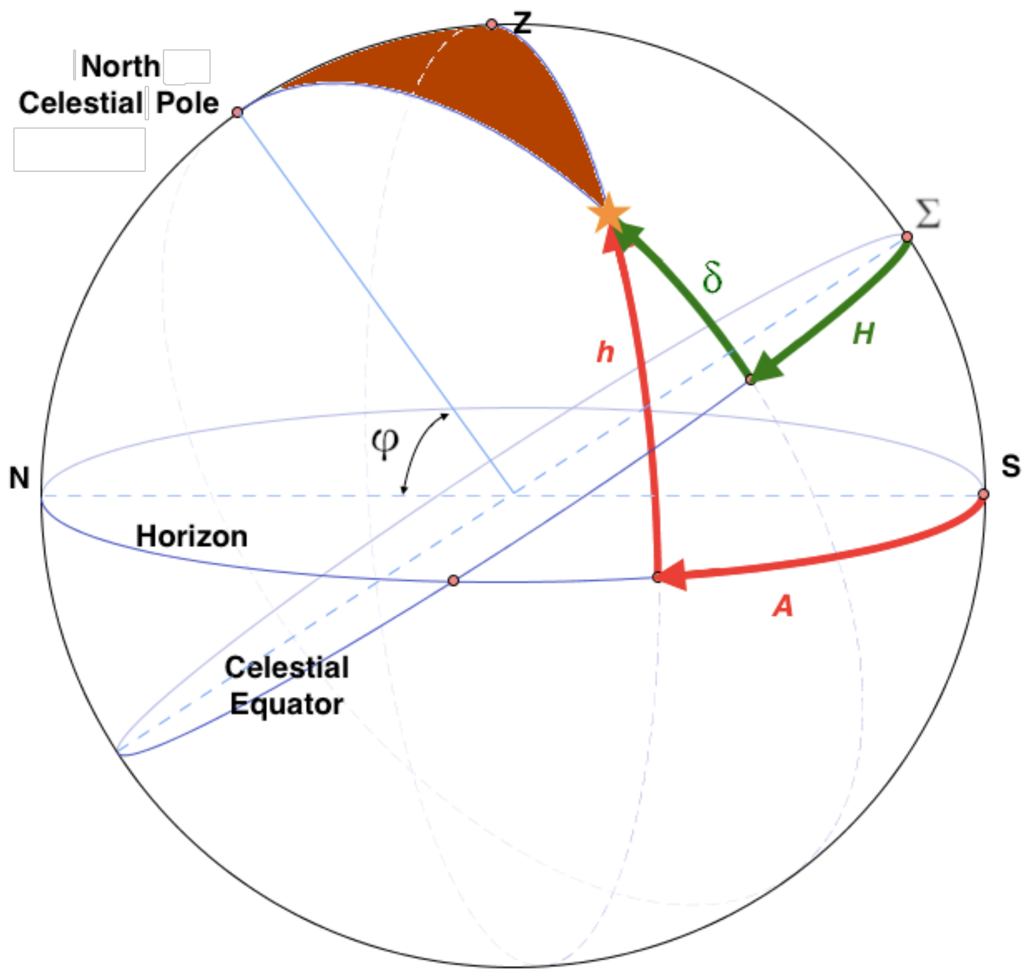
Alt-azimuthal (Horizontal) Coordinates

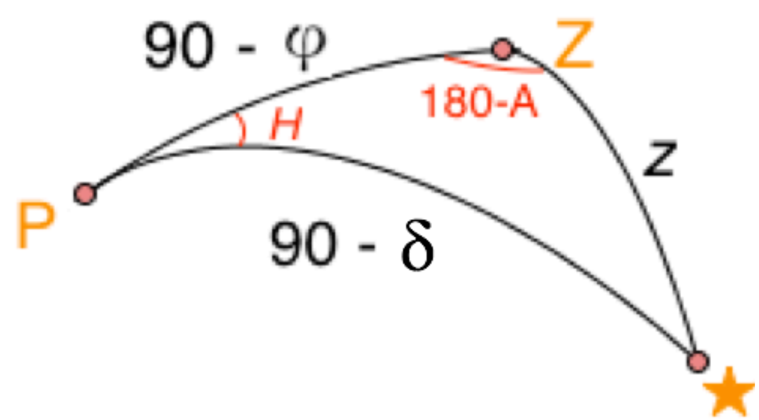


Time (hour) Coordinates and Horizontal Coordinates

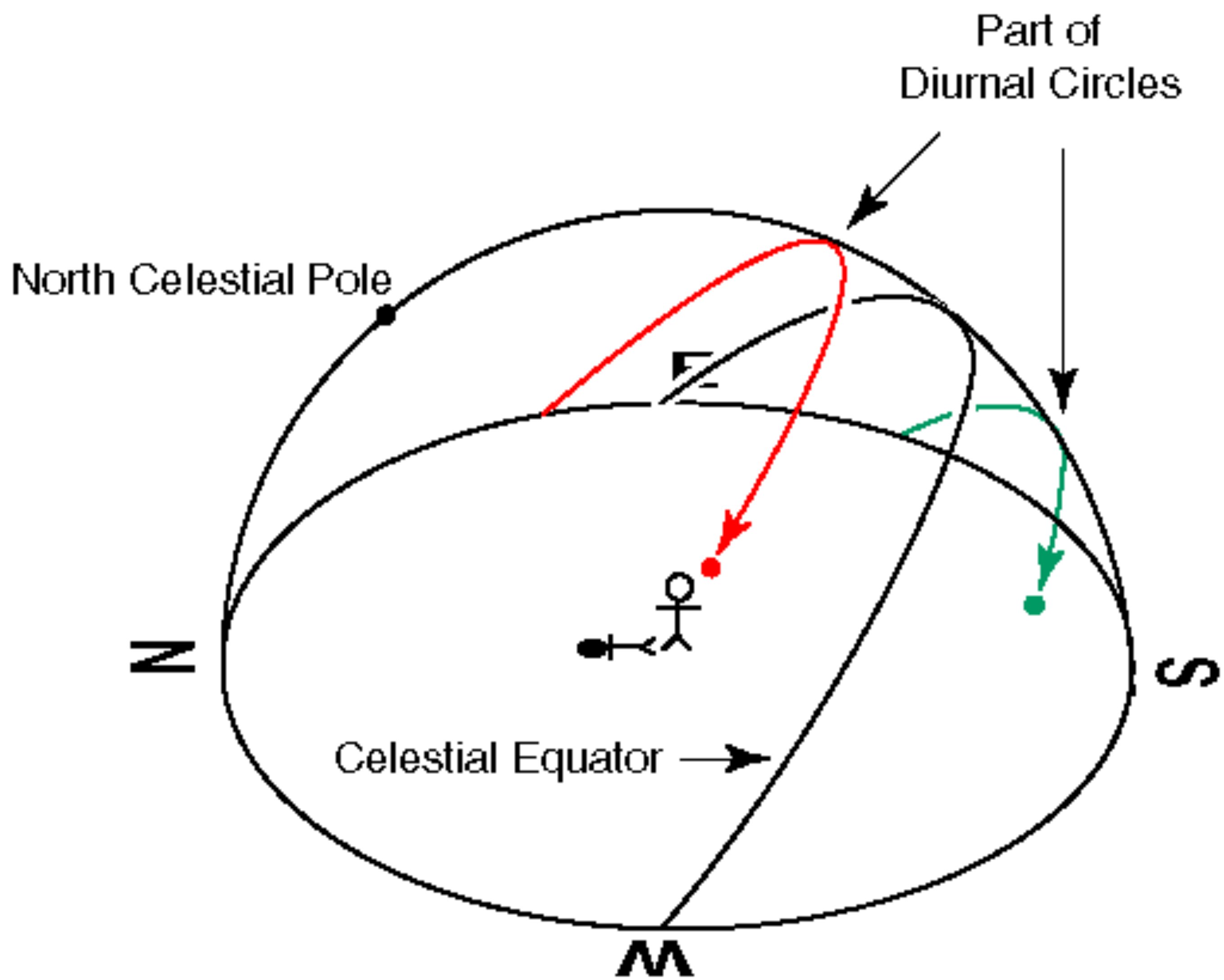


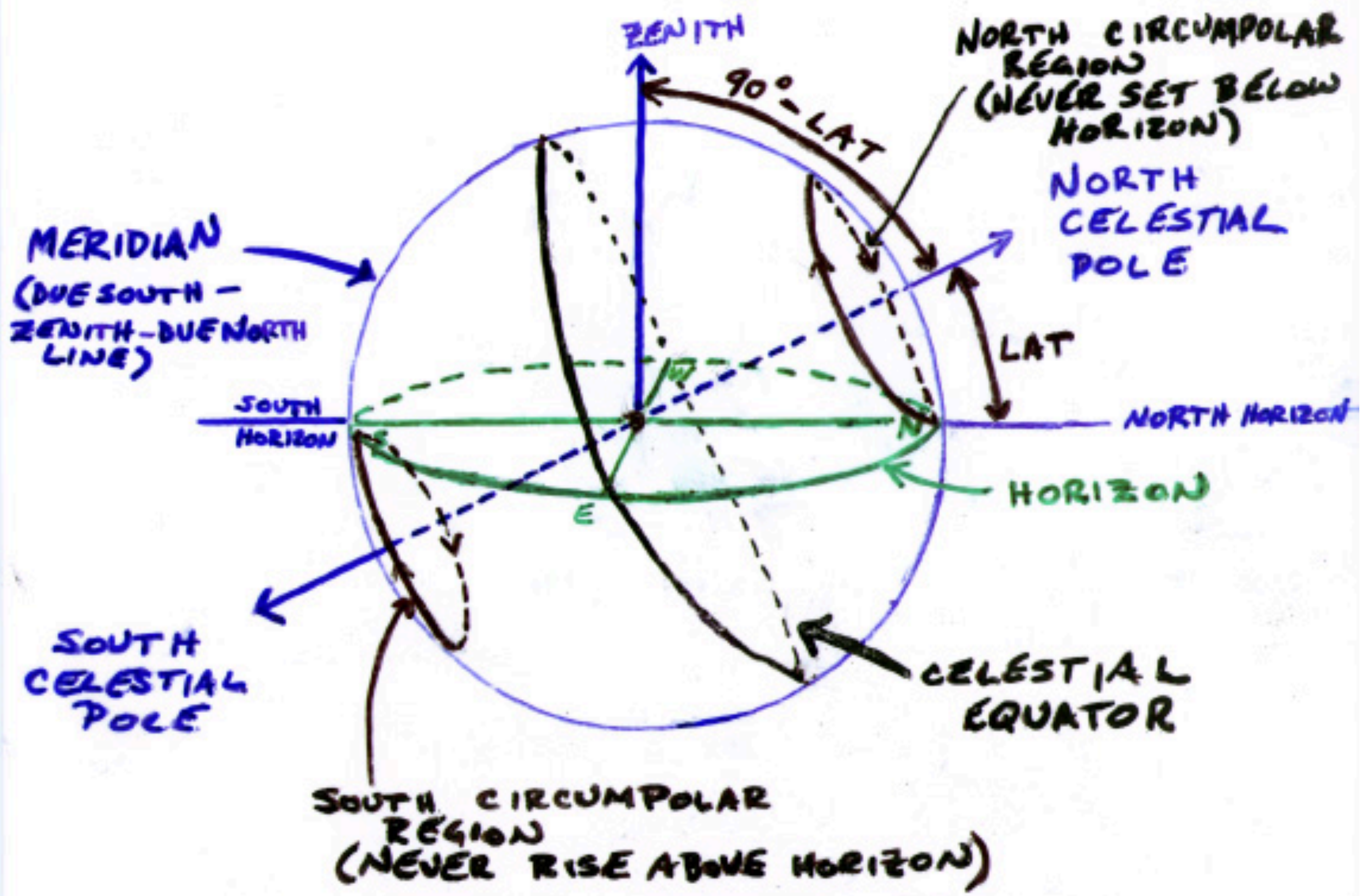
Time (hour) Coordinates and Horizontal Coordinates



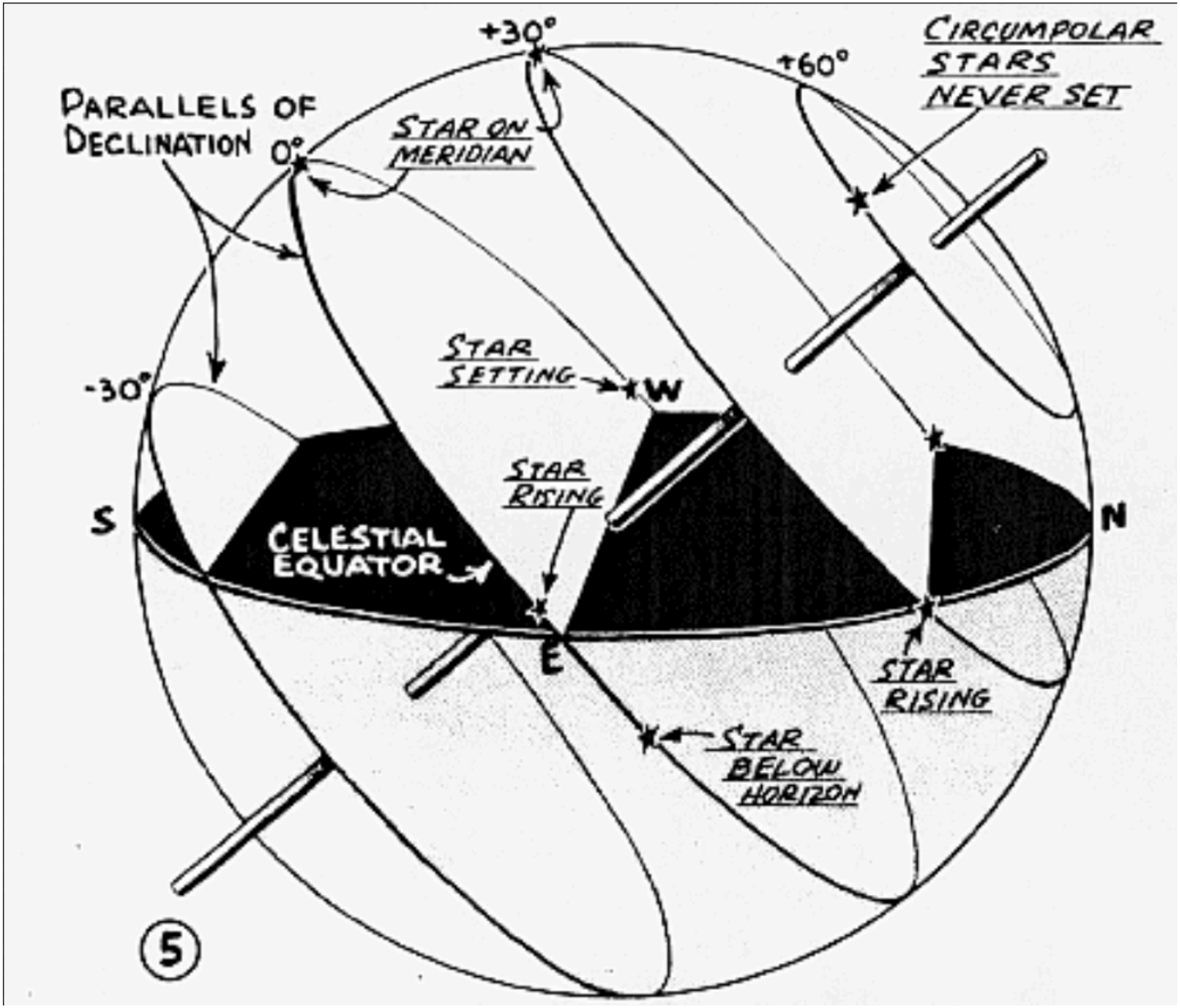


Maximum and minimum altitudes



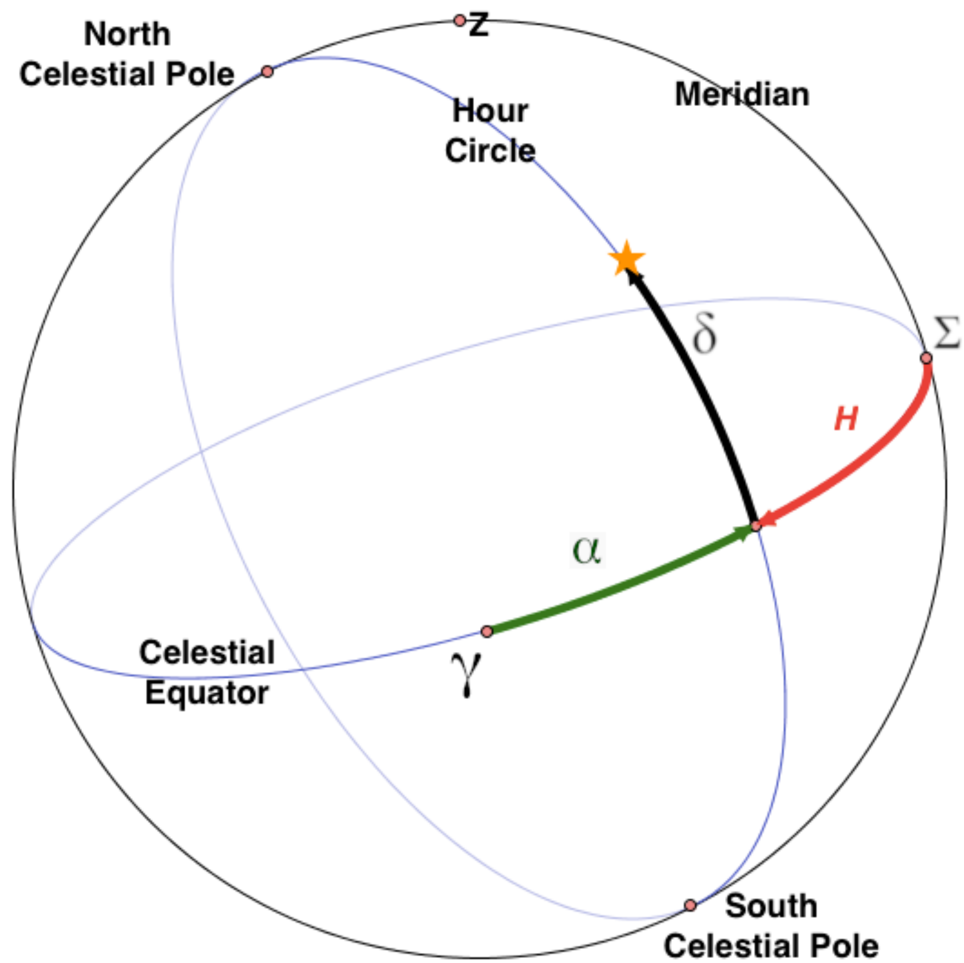


ZENITH
90° - LAT
NORTH CIRCUMPOLAR REGION (NEVER SET BELOW HORIZON)
NORTH CELESTIAL POLE
MERIDIAN (DUE SOUTH - ZENITH - DUE NORTH LINE)
LAT
SOUTH HORIZON
N
NORTH HORIZON
HORIZON
E
SOUTH CELESTIAL POLE
CELESTIAL EQUATOR
SOUTH CIRCUMPOLAR REGION (NEVER RISE ABOVE HORIZON)

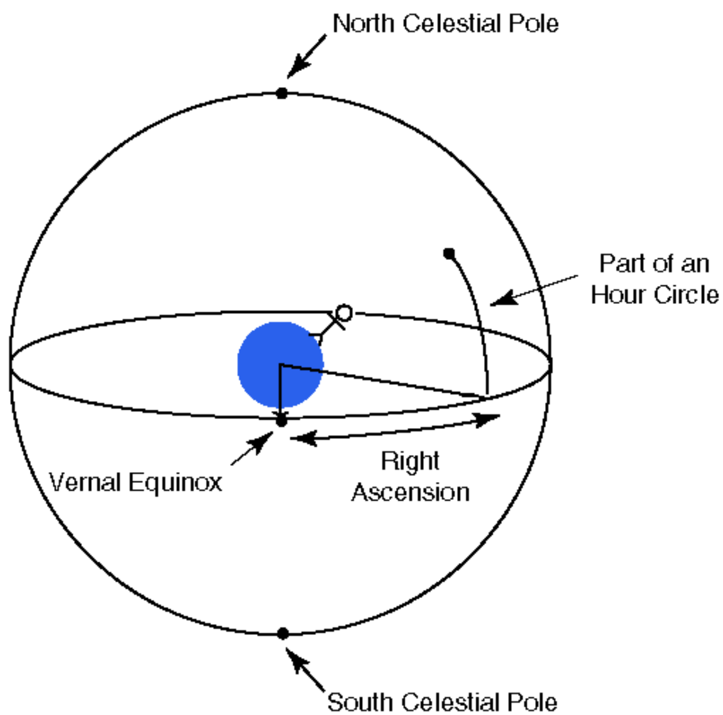


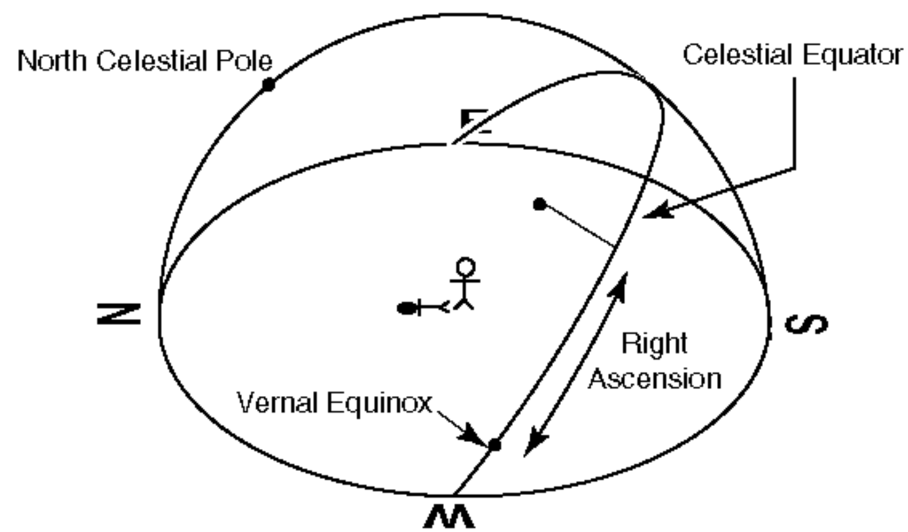
PARALLELS OF DECLINATION
+30°
+60°
0°
-30°
CIRCUMPOLAR STARS NEVER SET
STAR ON MERIDIAN
STAR SETTING
W
STAR RISING
S
N
CELESTIAL EQUATOR
E
STAR RISING
STAR BELOW HORIZON
5

Hour Coordinates and Equatorial Coordinates

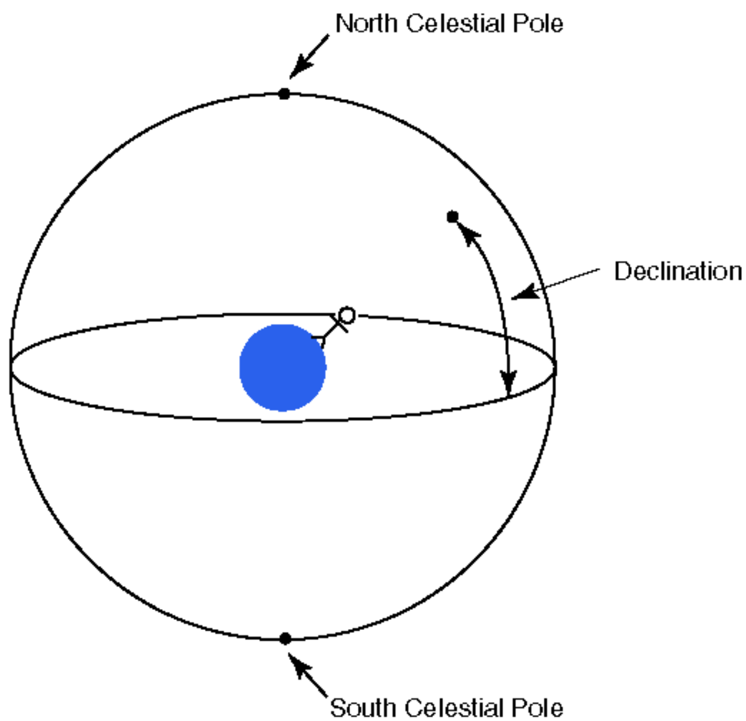


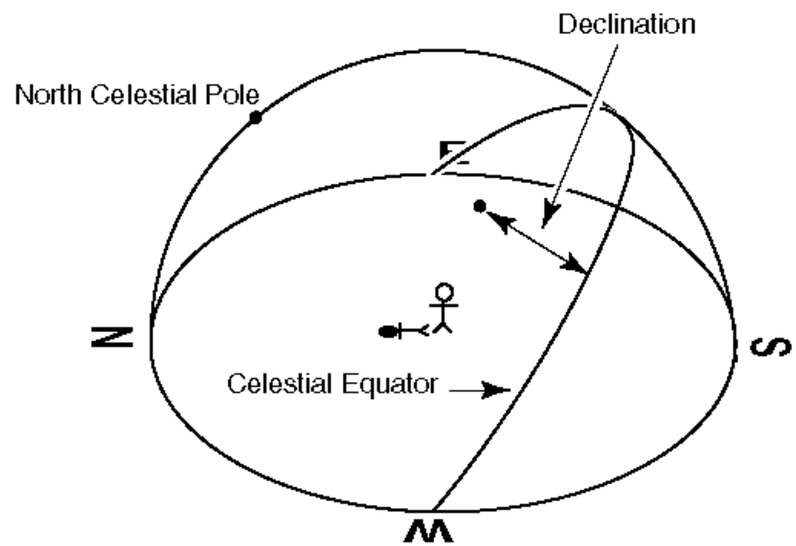
Right Ascension

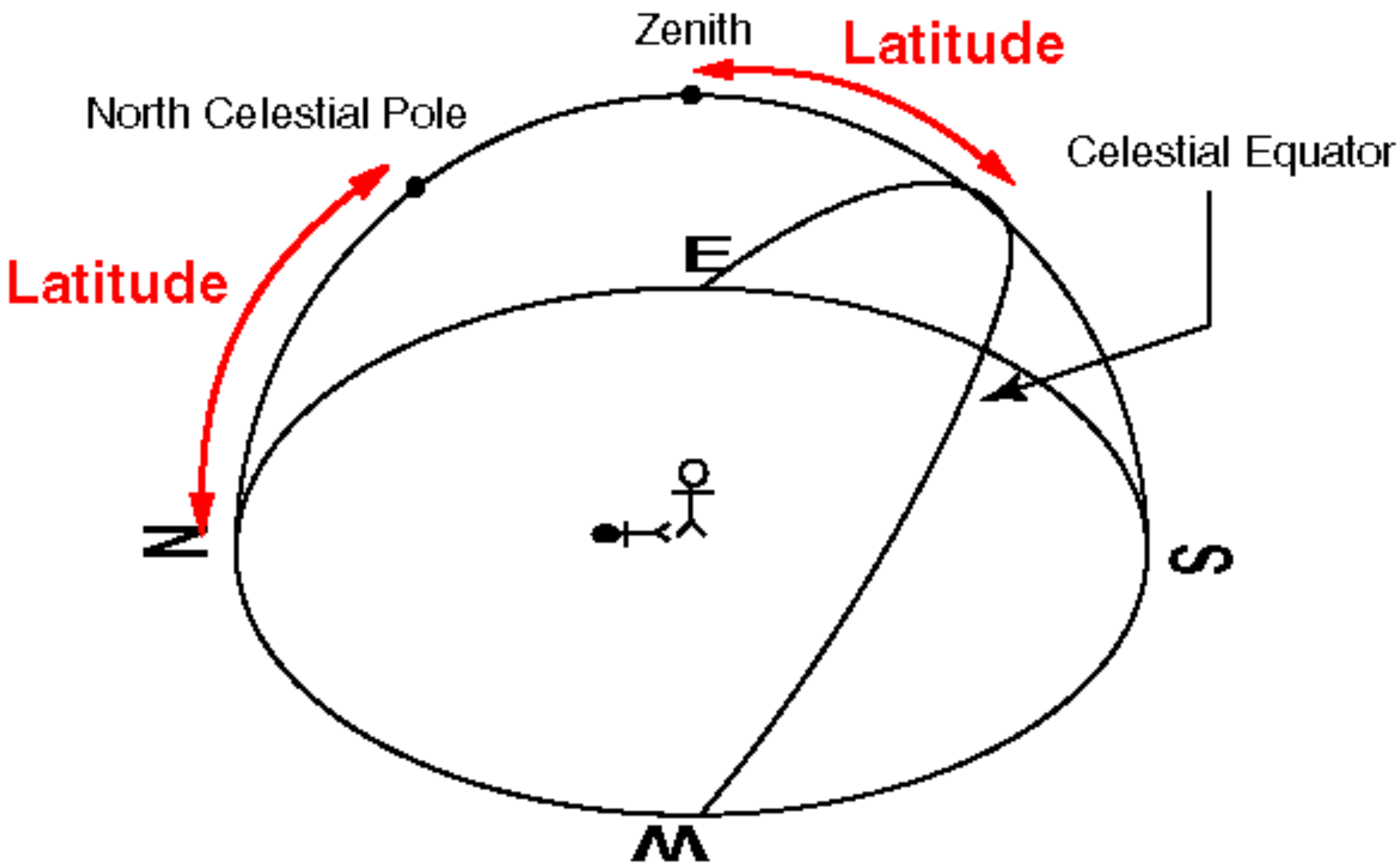




Declination

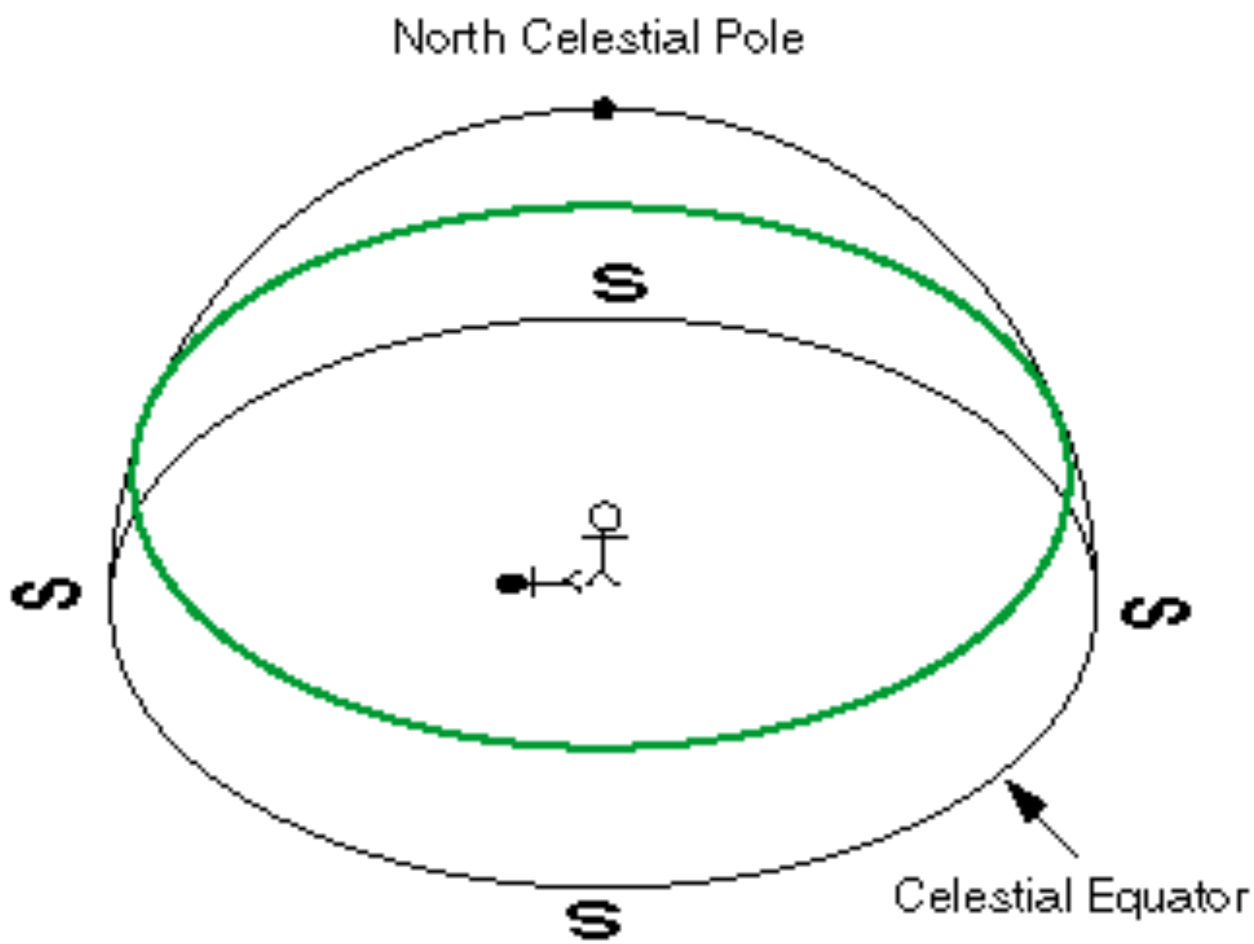




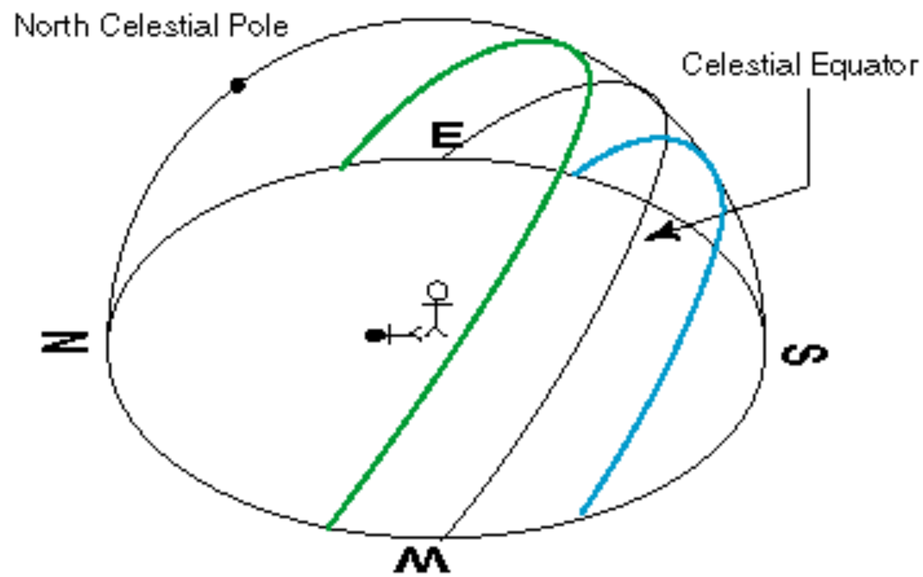


Zenith
Latitude
North Celestial Pole
Celestial Equator
Latitude
E
N
S
W

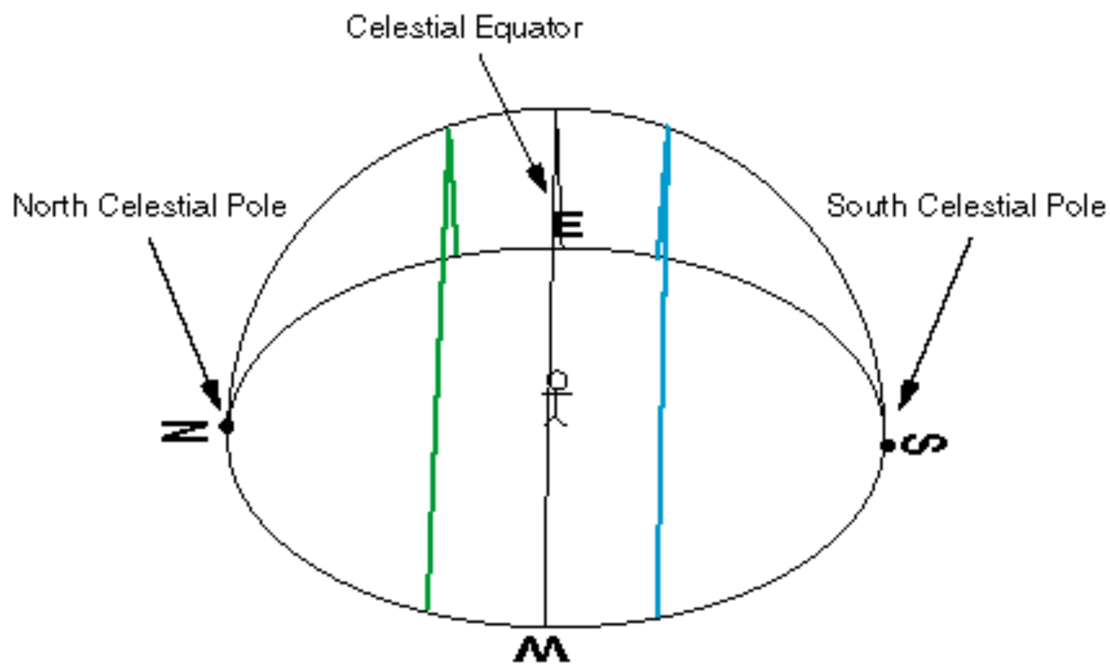
Observer at the pole



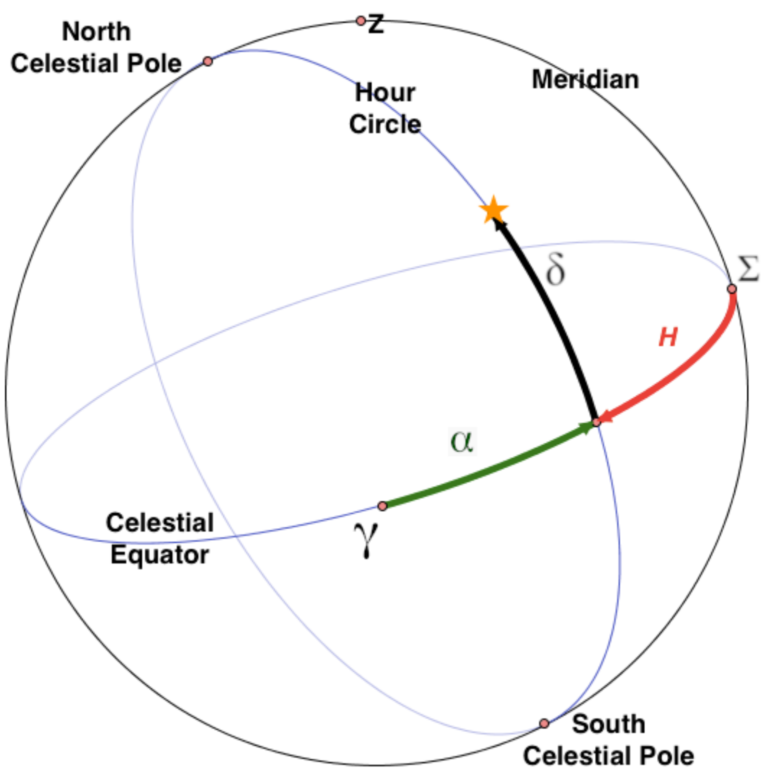
Observer at arbitrary latitude

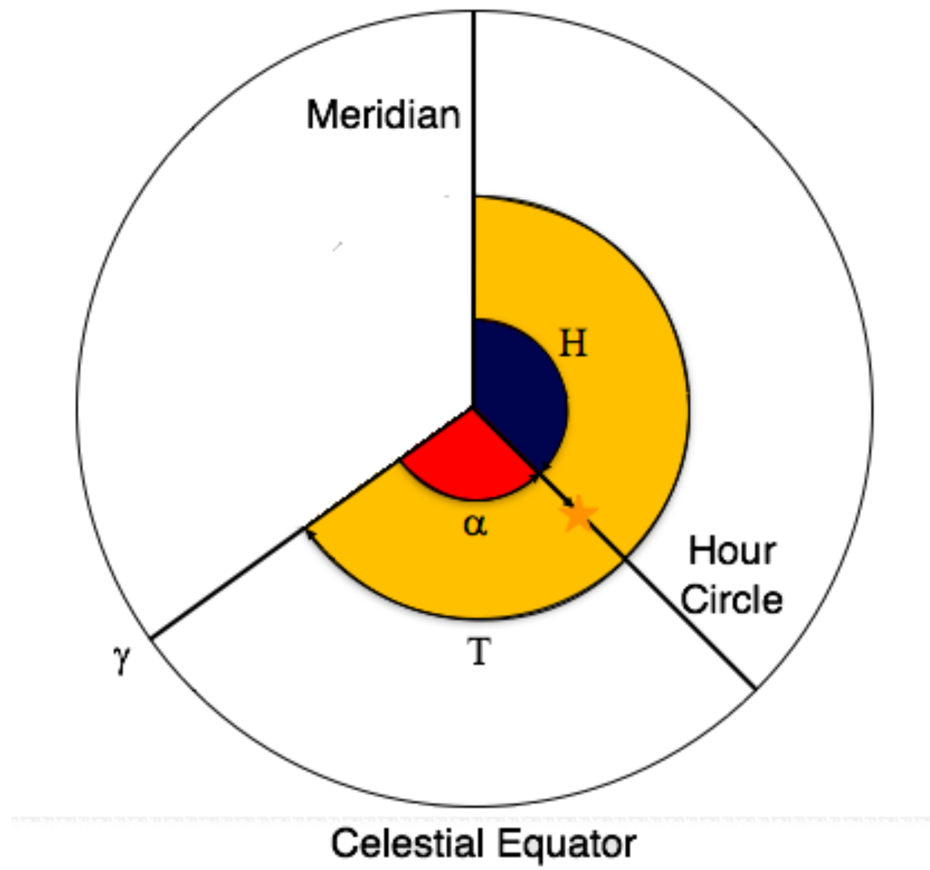


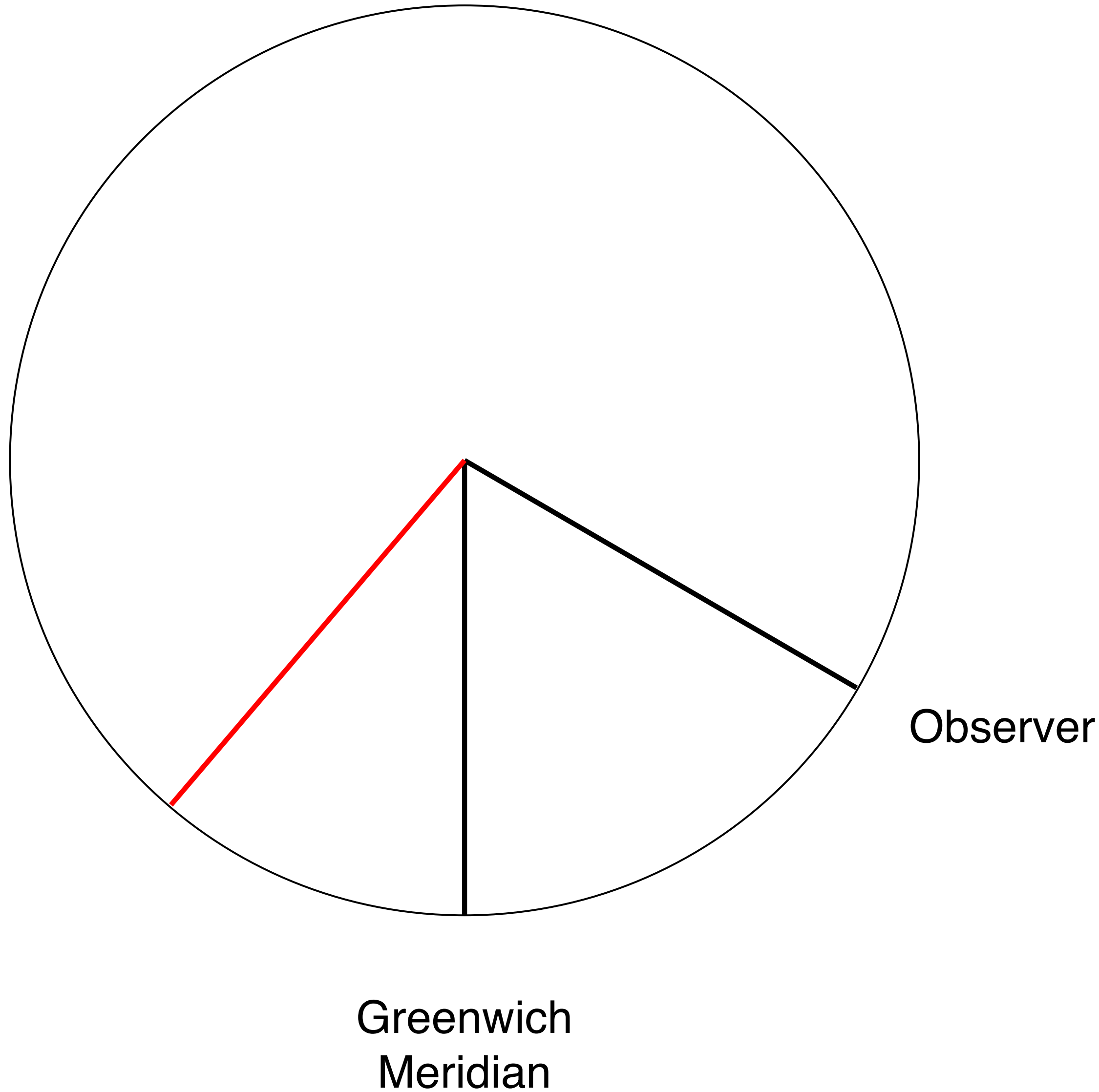
Observer on equator

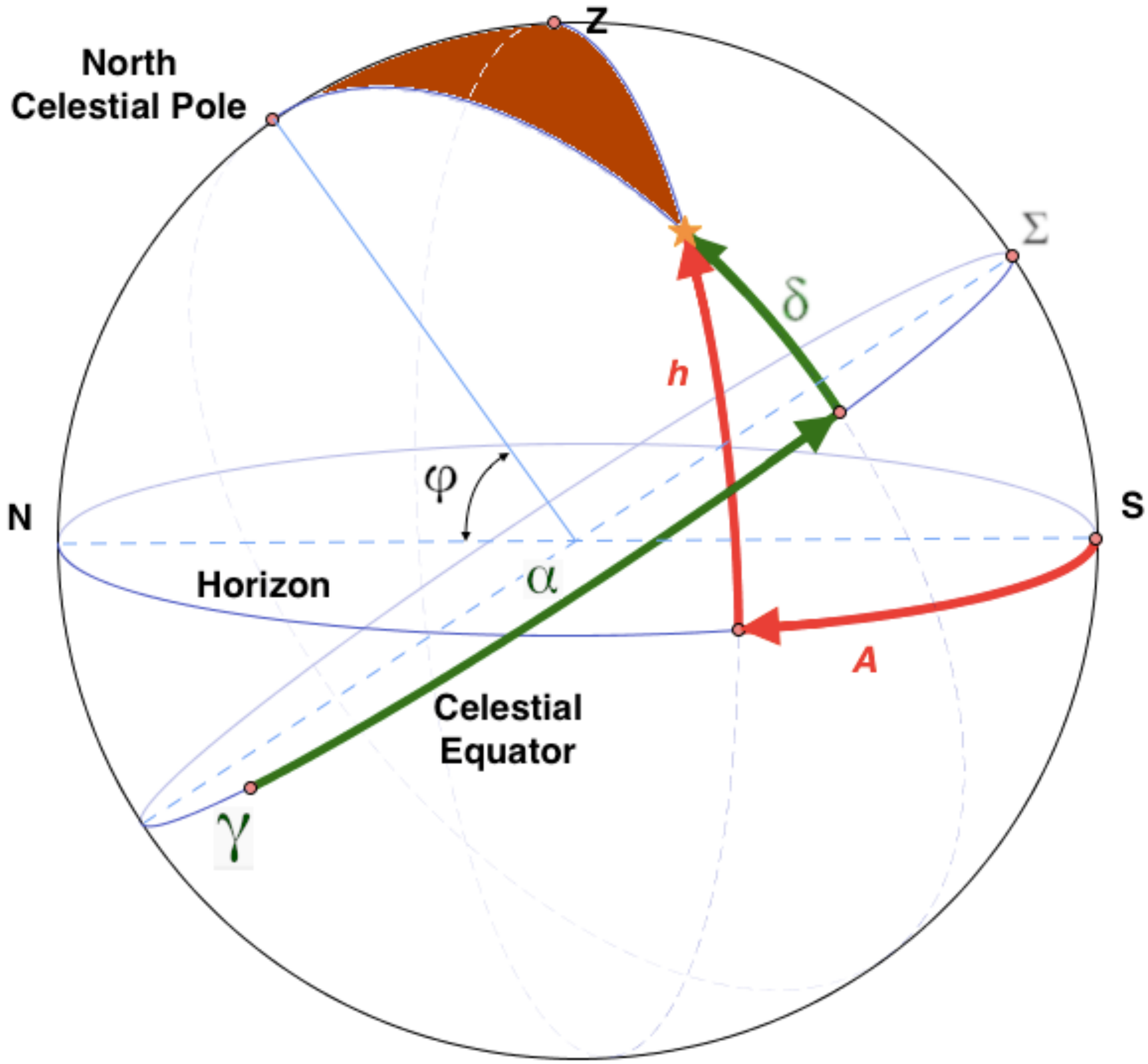


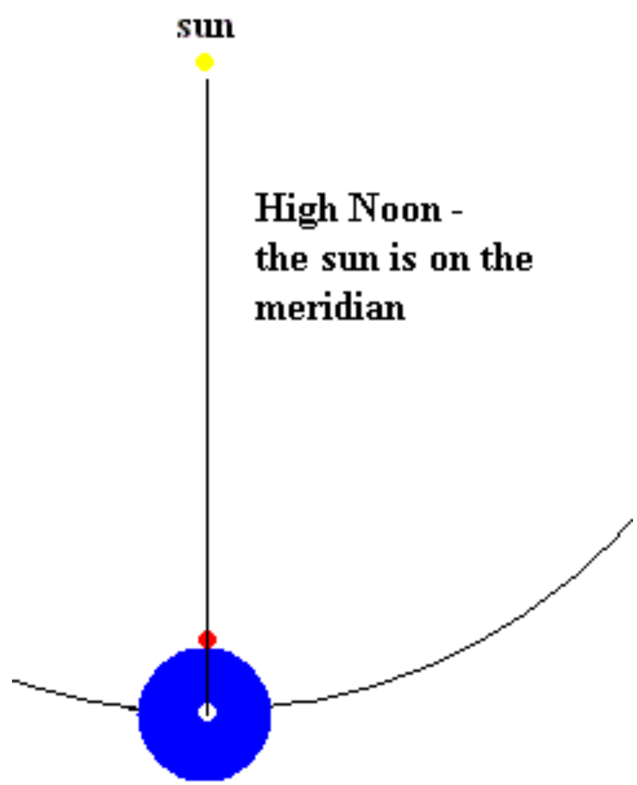
Hour Coordinates and Equatorial Coordinates

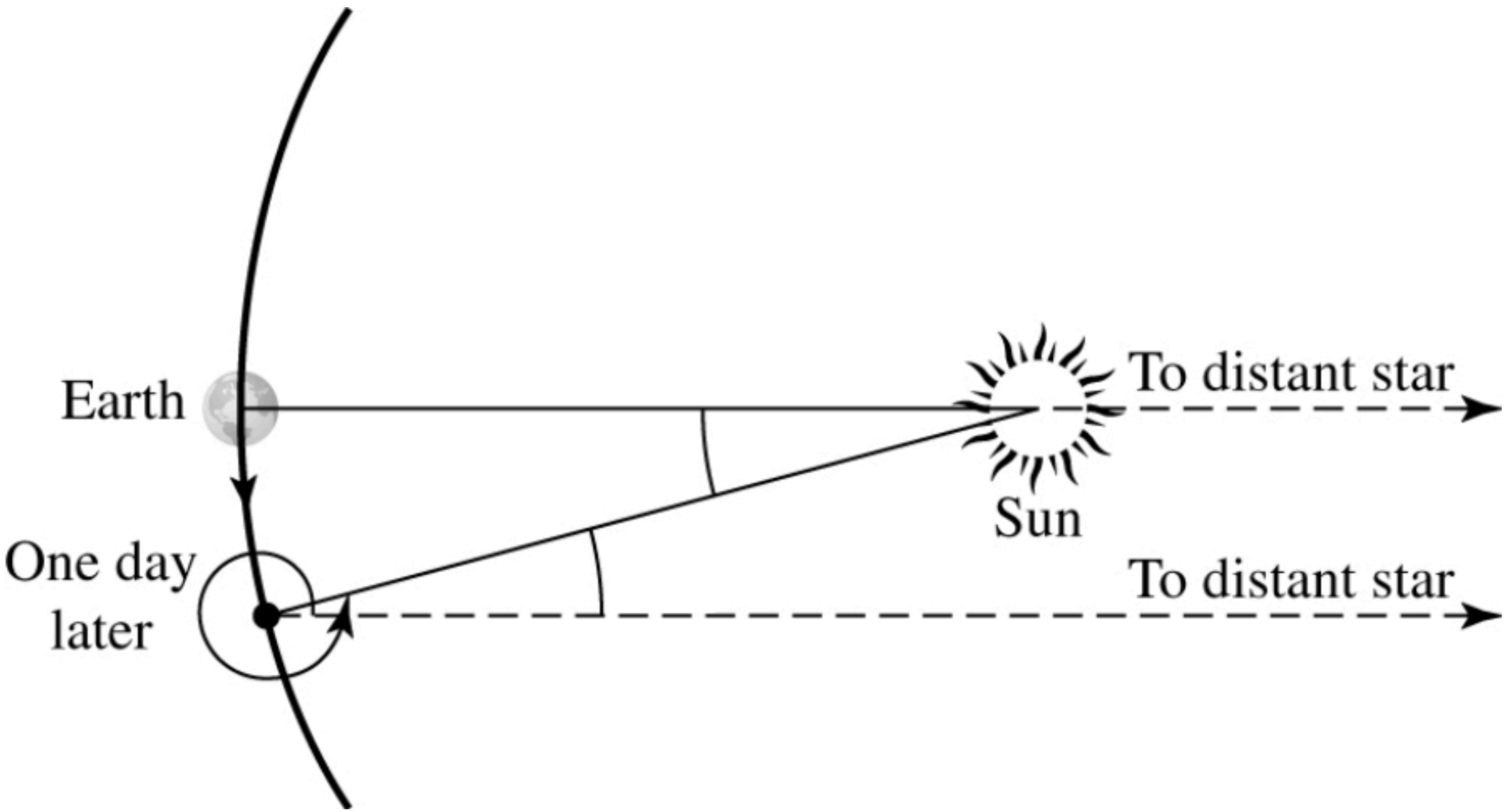


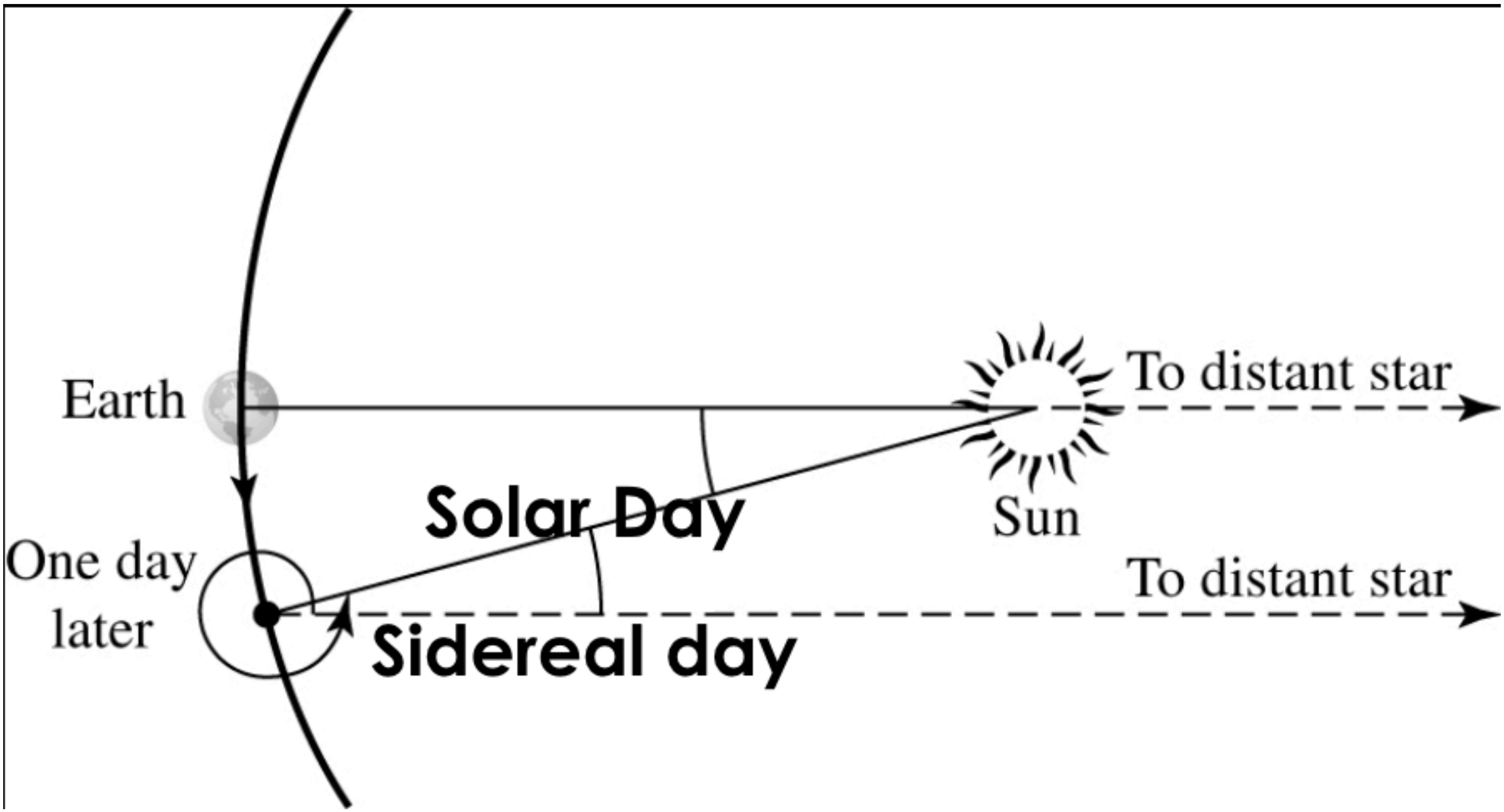


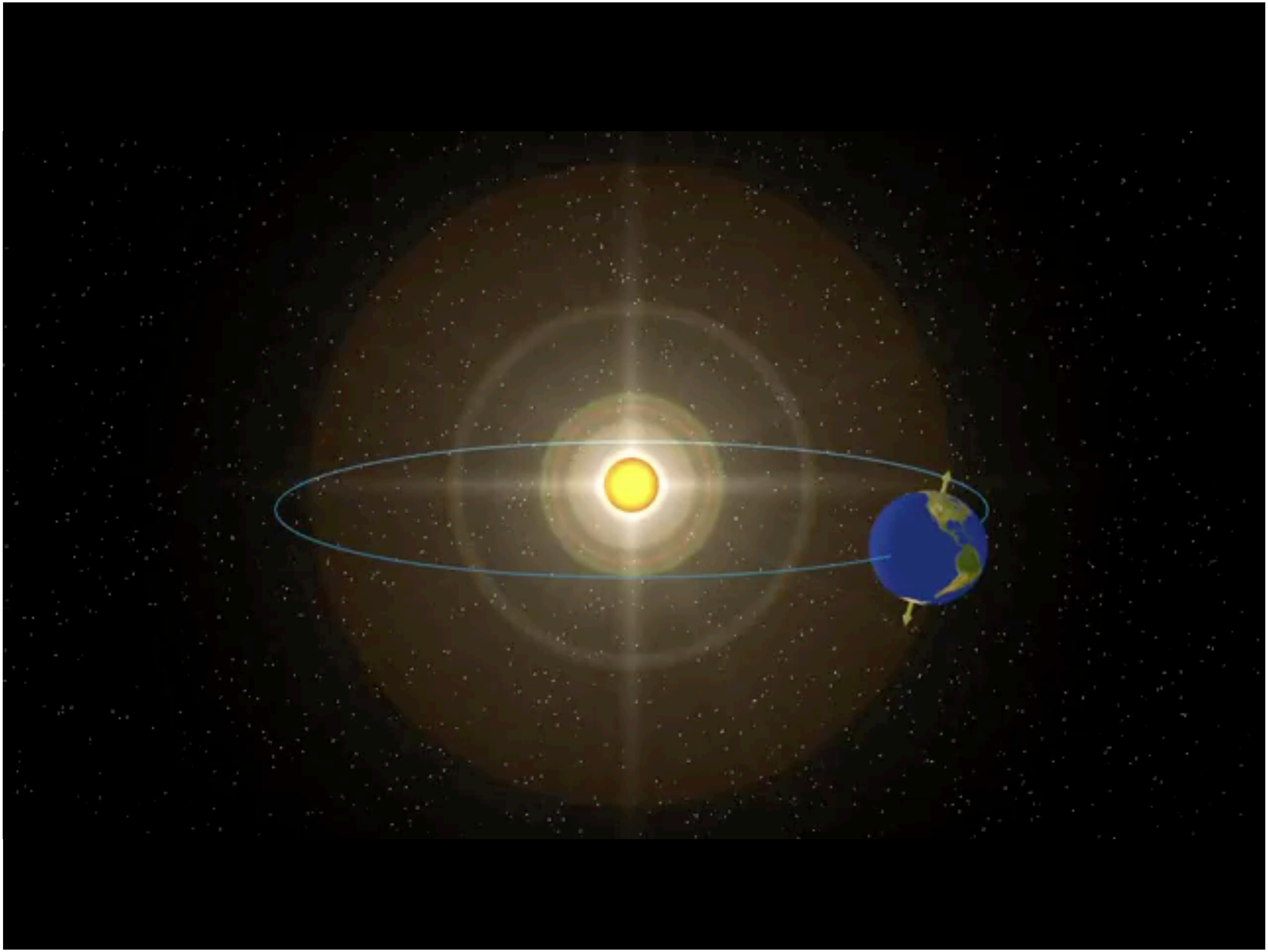

Observer
Greenwich
Meridian


Z
North
Celestial Pole
Σ
δ
h
φ
N
S
Horizon
α
A
Celestial
Equator
γ

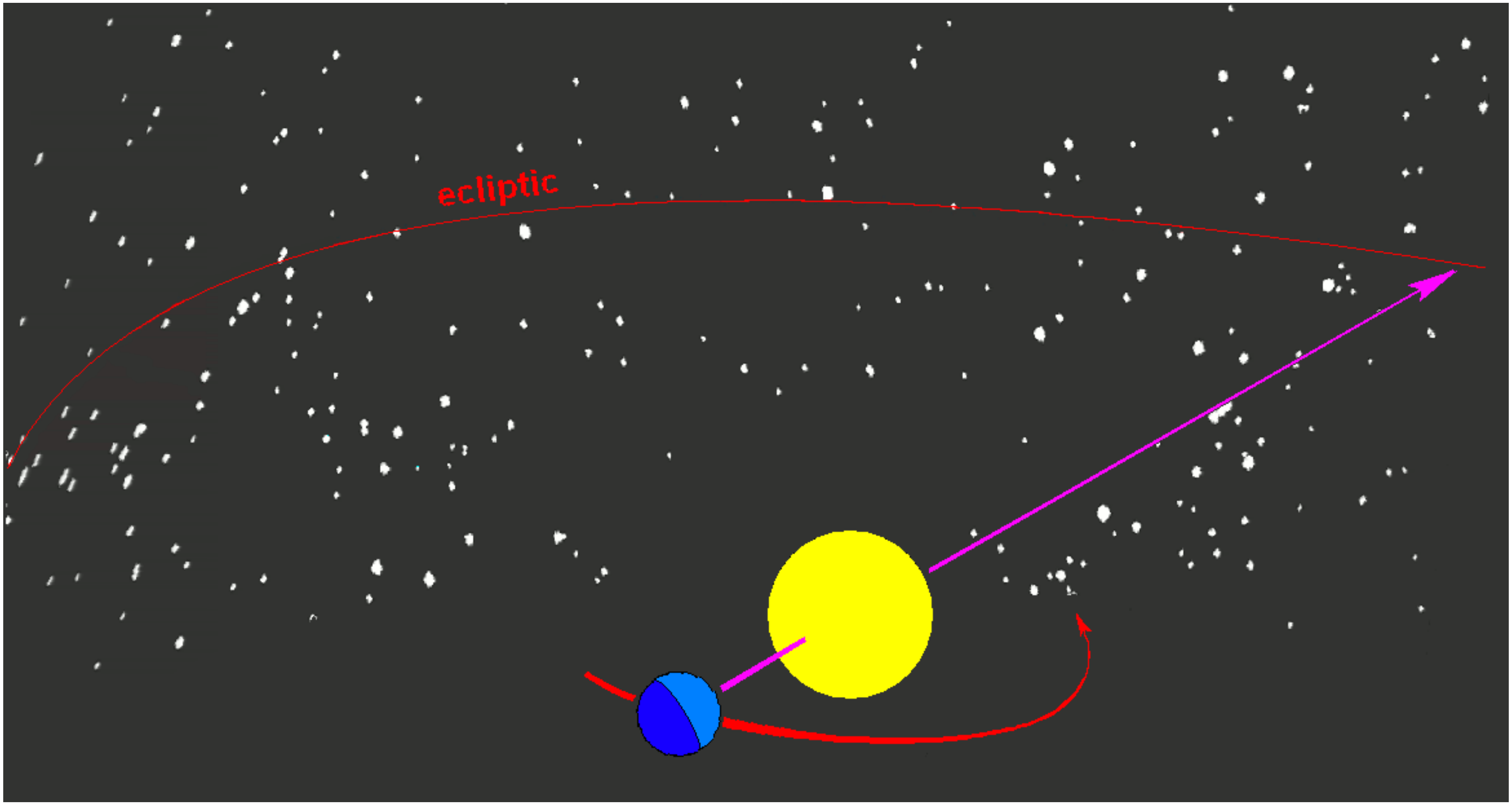

sun
High Noon -
the sun is on the
meridian


Earth
To distant star
Sun
One day
later
To distant star

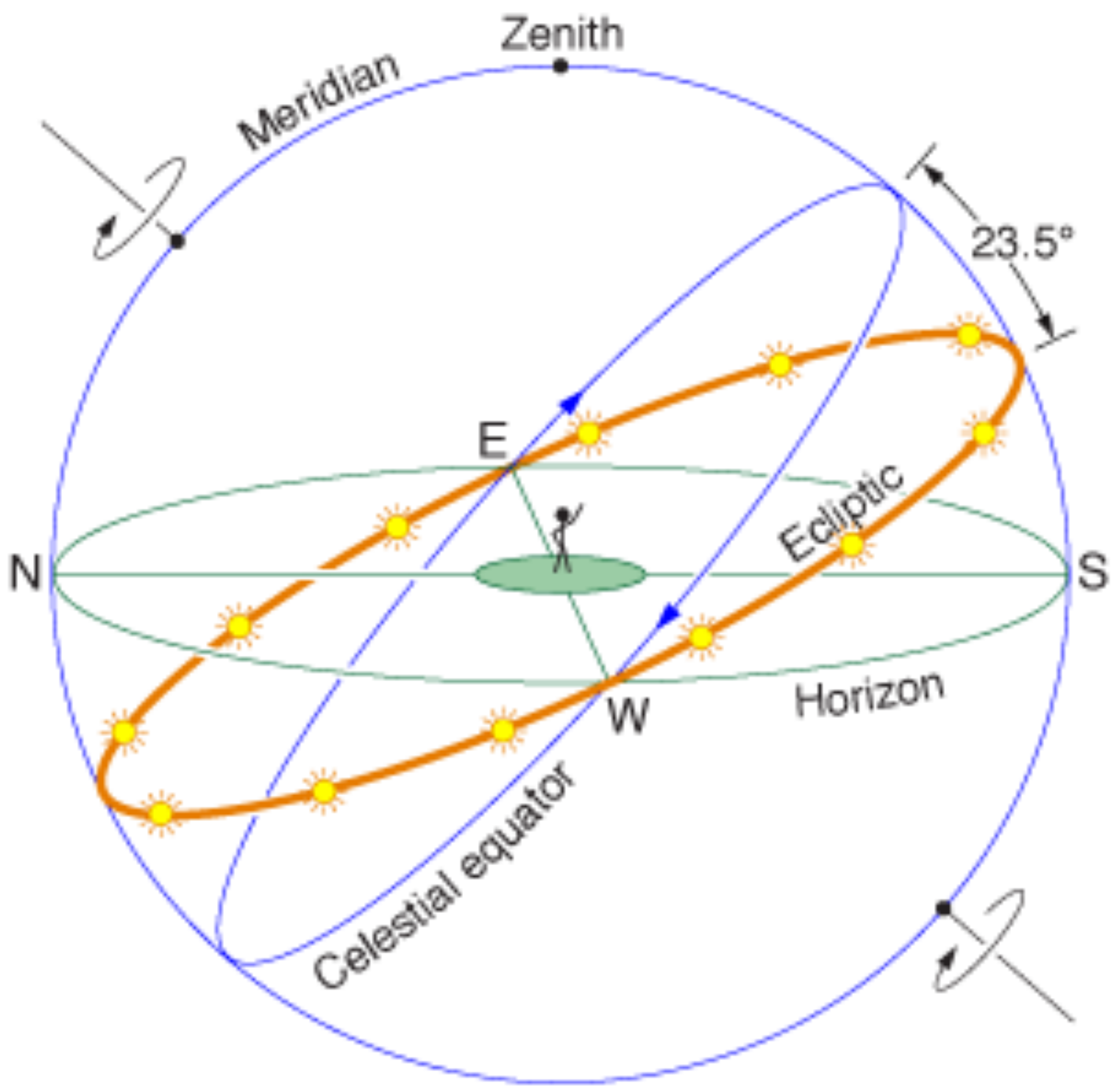

Earth
To distant star
Solar Day
Sun
One day later
To distant star
Sidereal day



Ecliptic

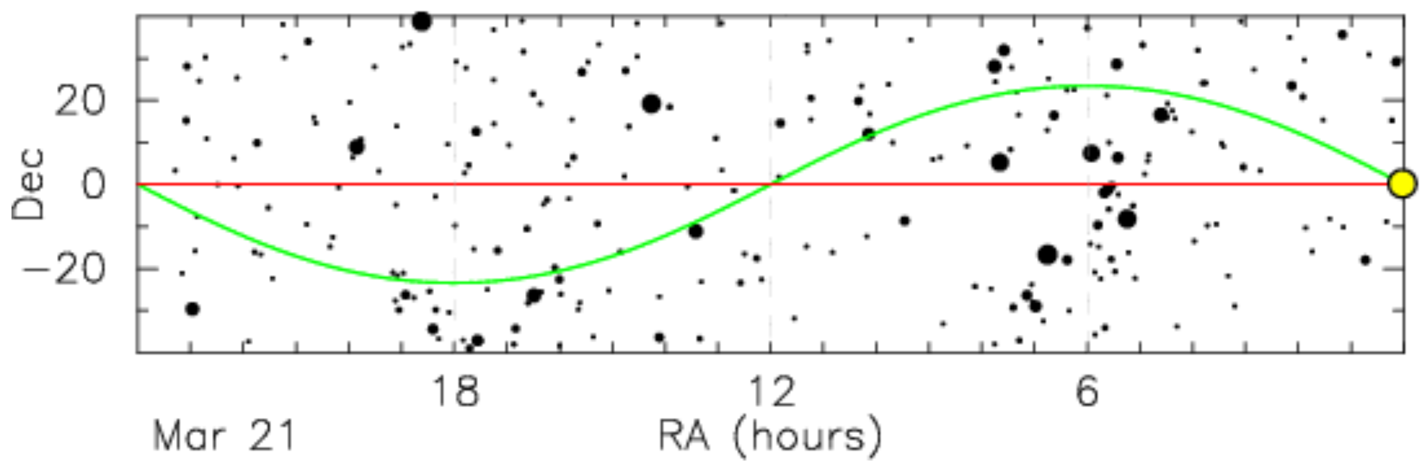


Ecliptic

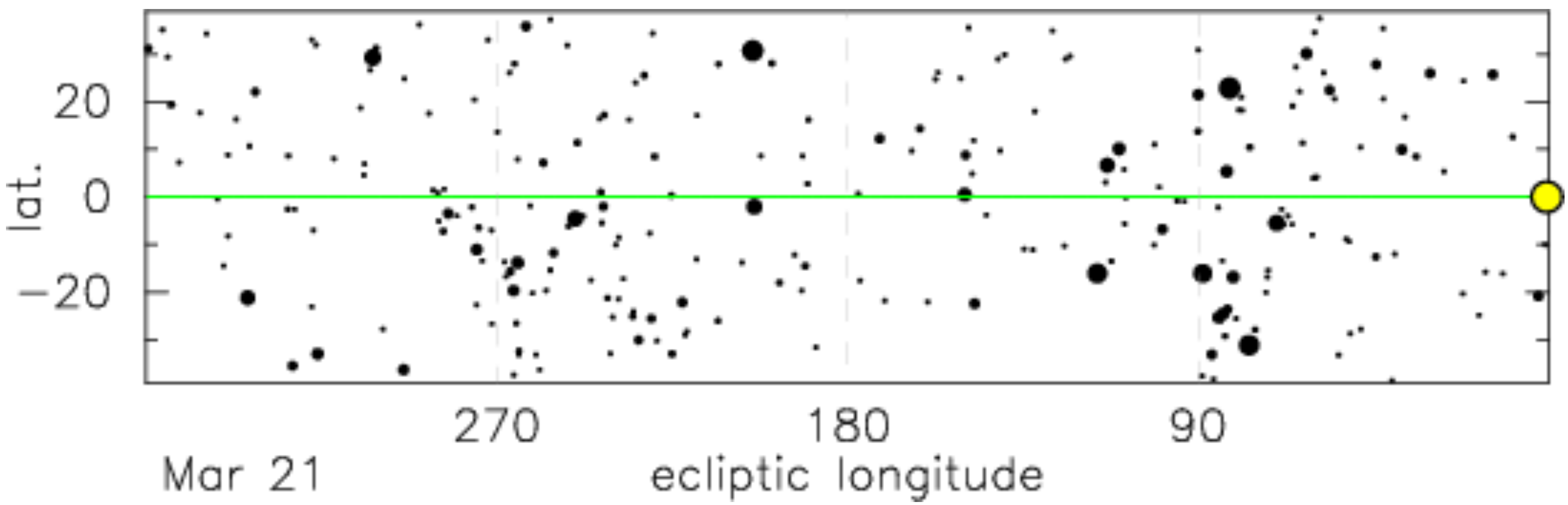


Zenith
Meridian
23.5°
E
N
S
Ecliptic
W
Horizon
Celestial equator

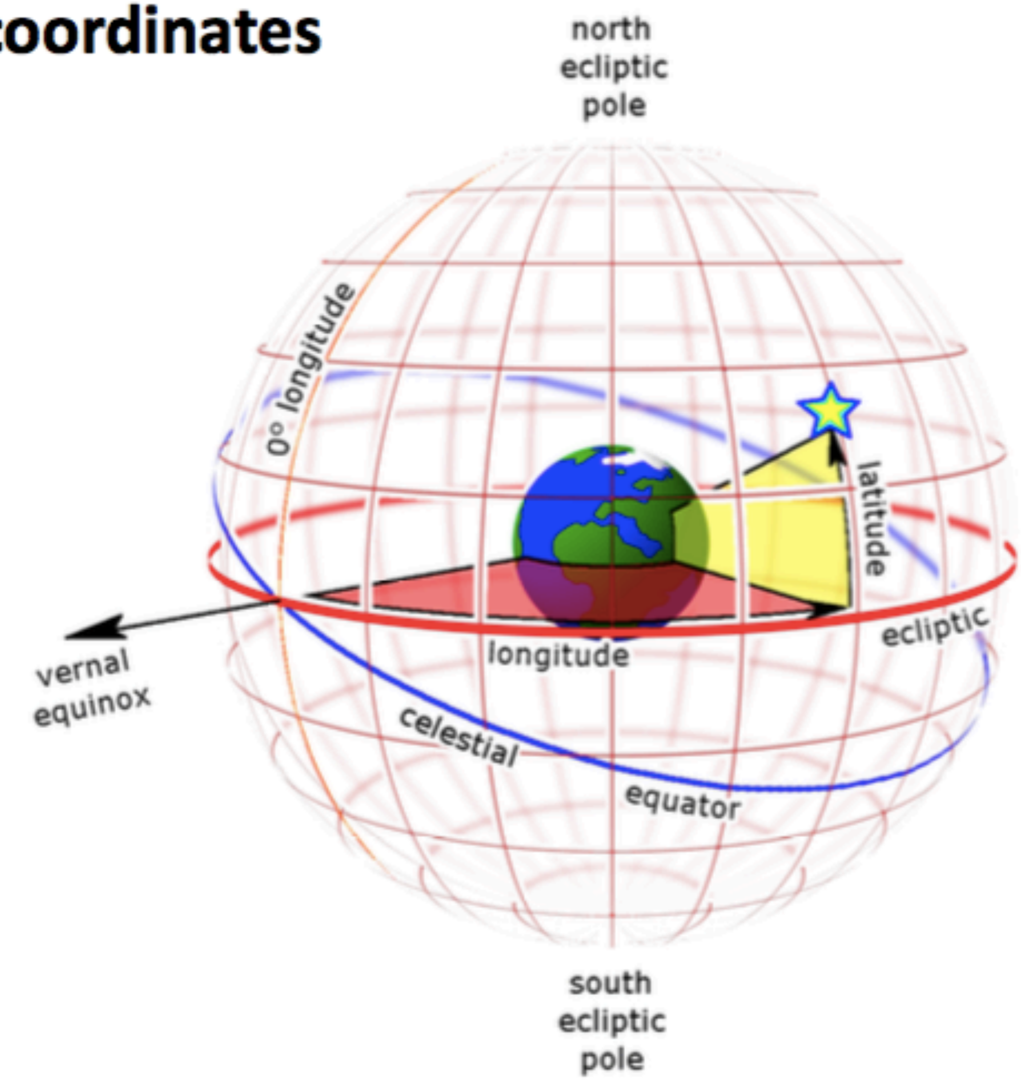
Solar path in Equatorial Coordinates



Solar path in Ecliptic coordinates

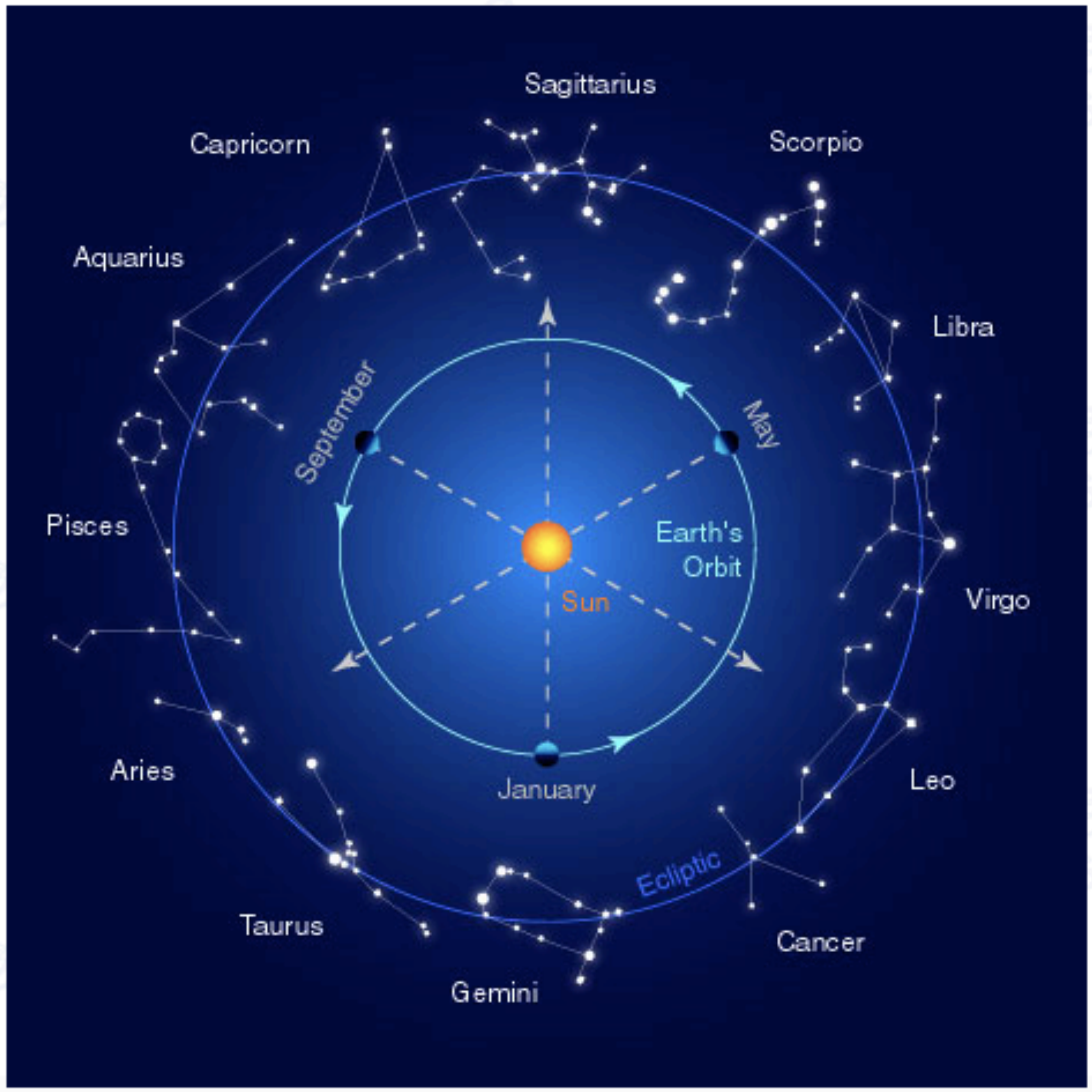


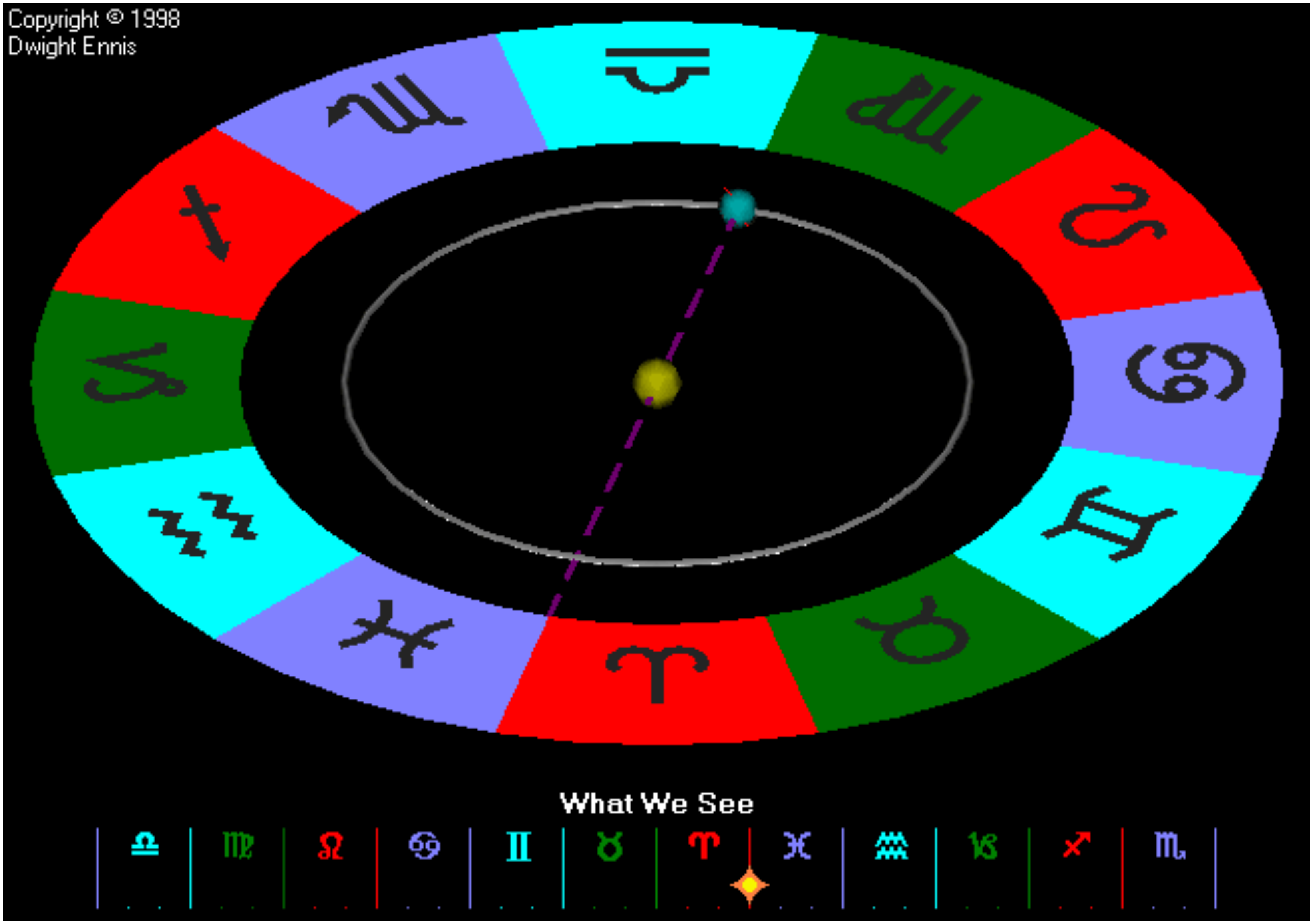
Ecliptic coordinates



https://en.wikipedia.org/wiki/Ecliptic_coordinate_system

The Zodiac : Constellations arbitrarily defined on the Ecliptic





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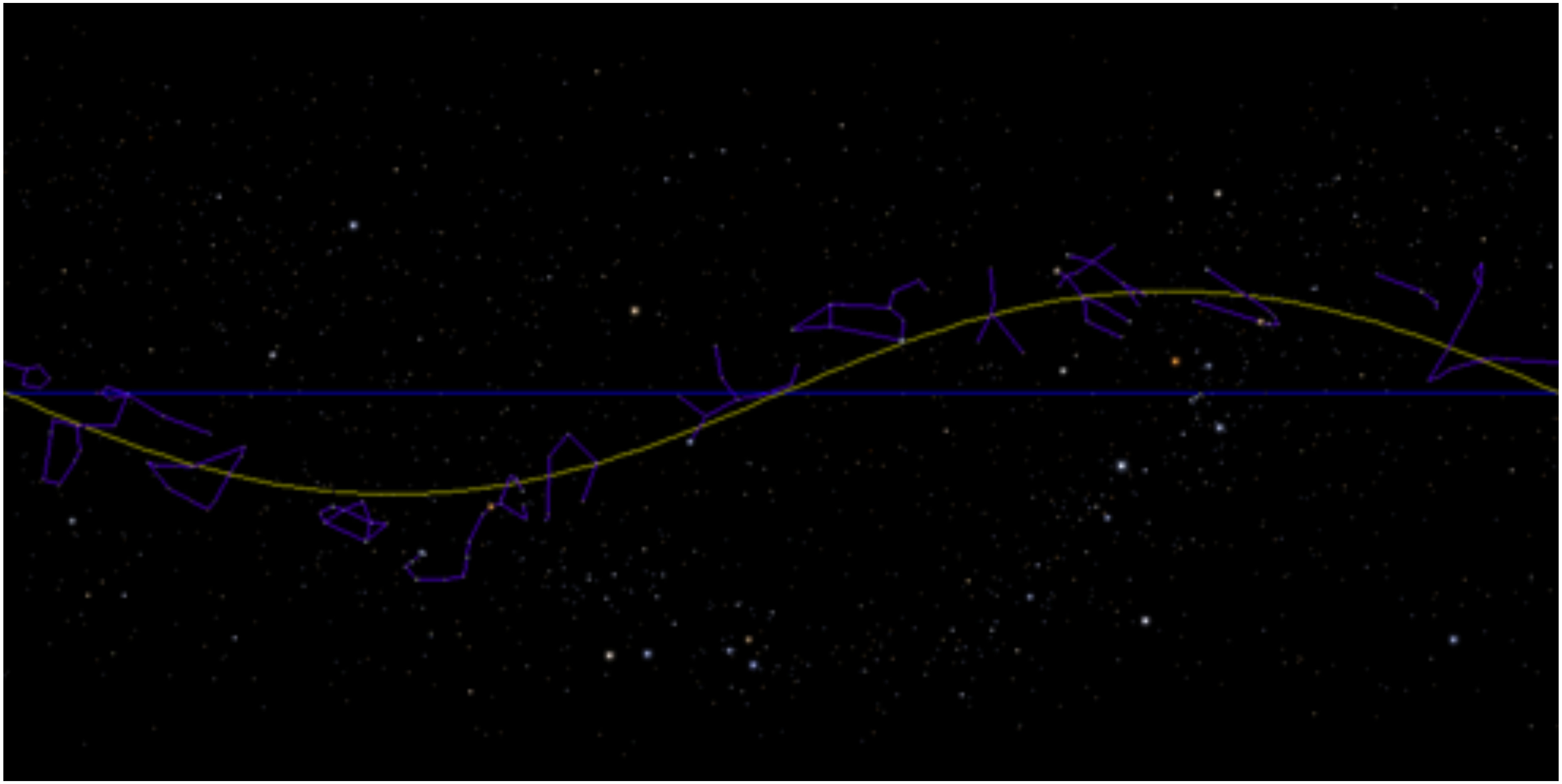
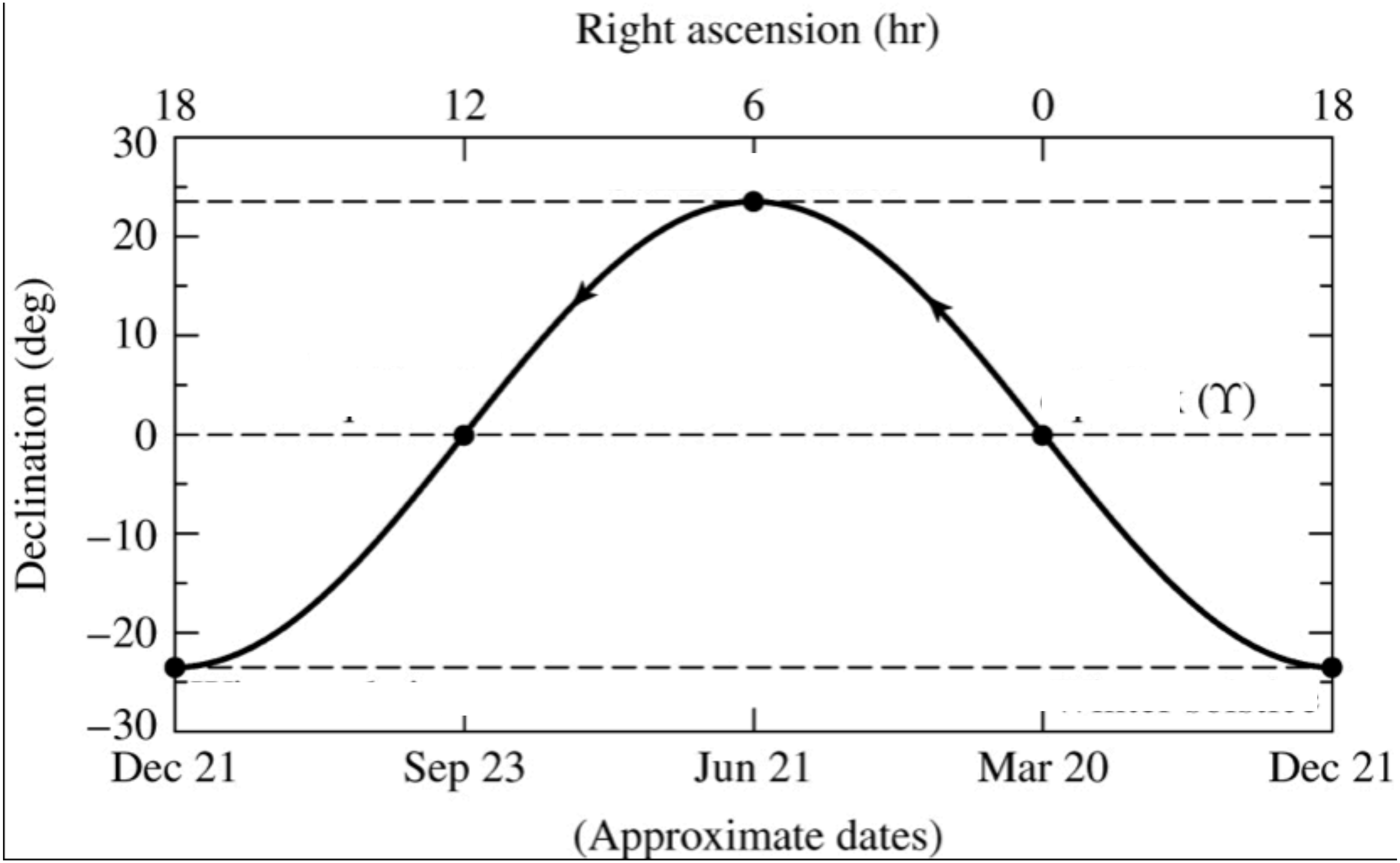
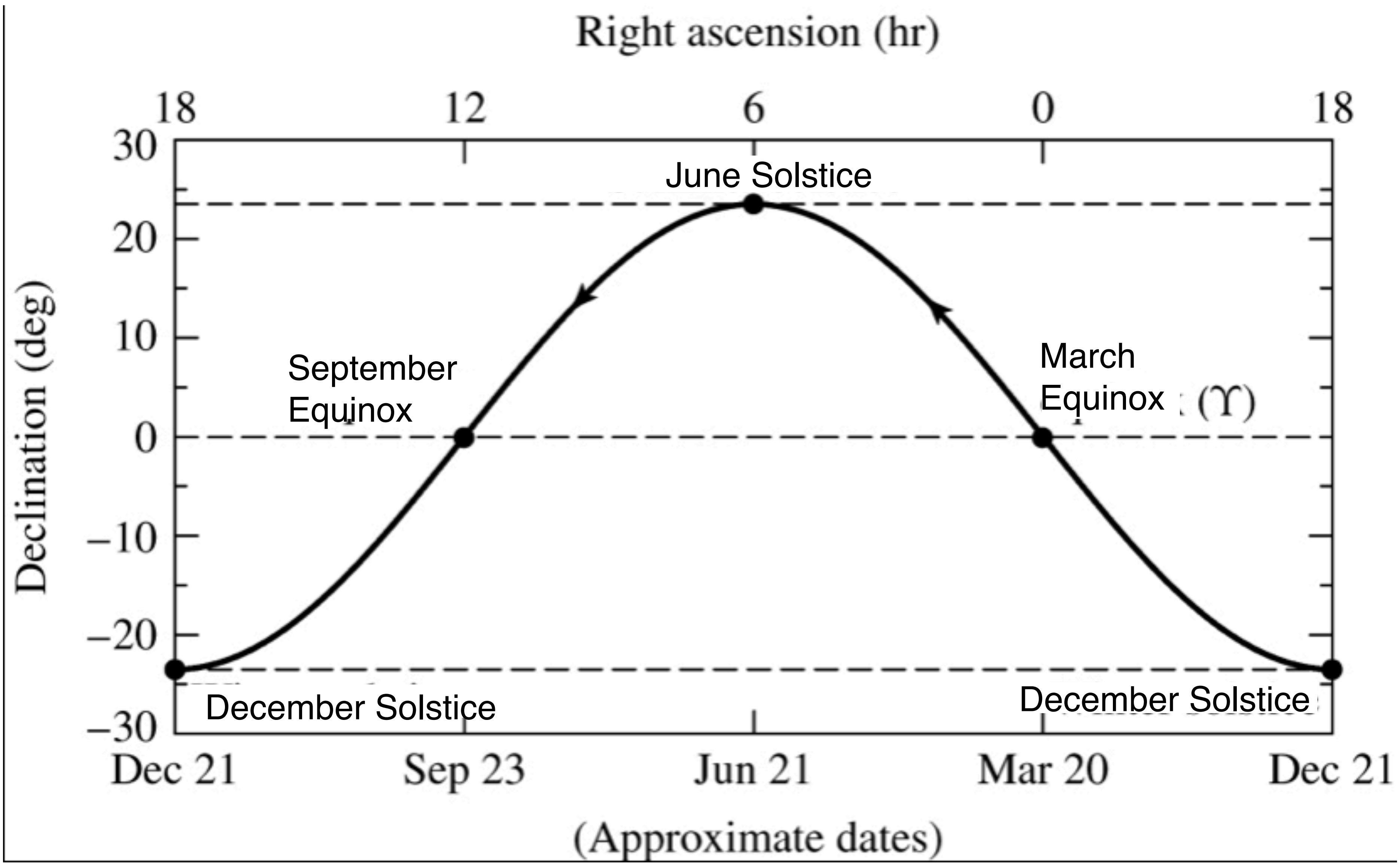
Dwight Ennis
What We See

Ecliptic



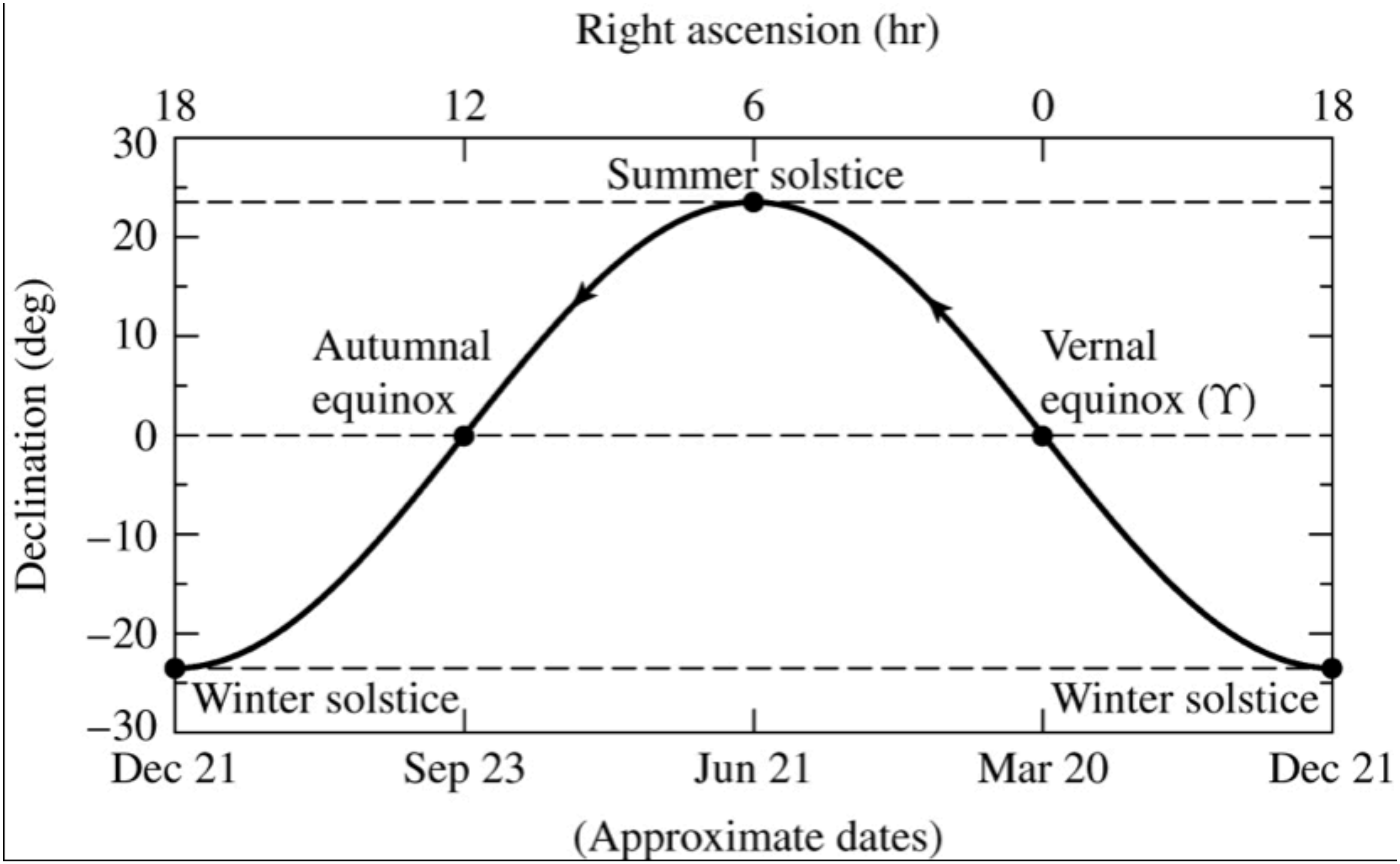


Right ascension (hr)
18
12
6
0
18
30
20
10
0
−10
−20
−30
Declination (deg)
(ϒ)
Dec 21
Sep 23
Jun 21
Mar 20
Dec 21
(Approximate dates)

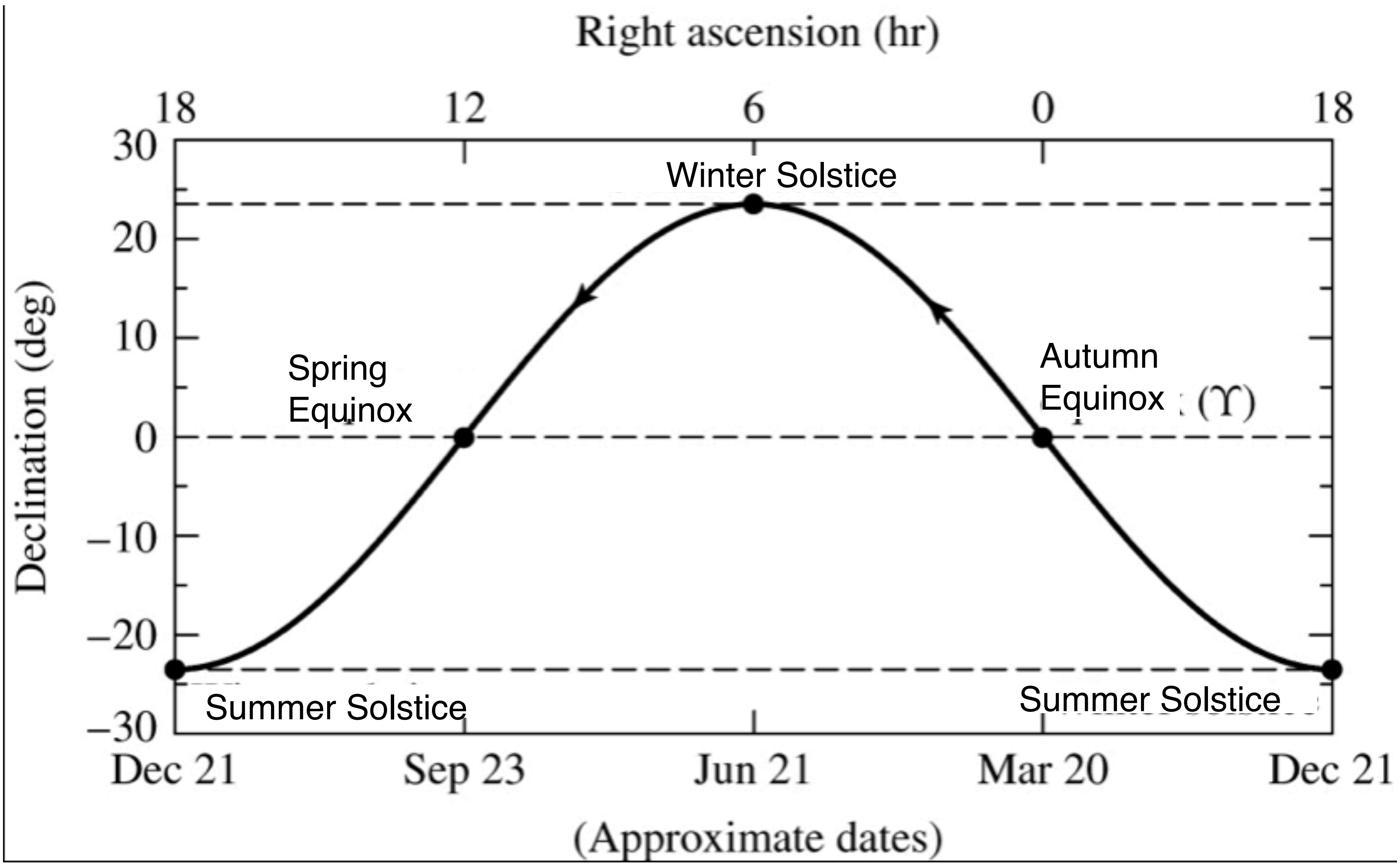


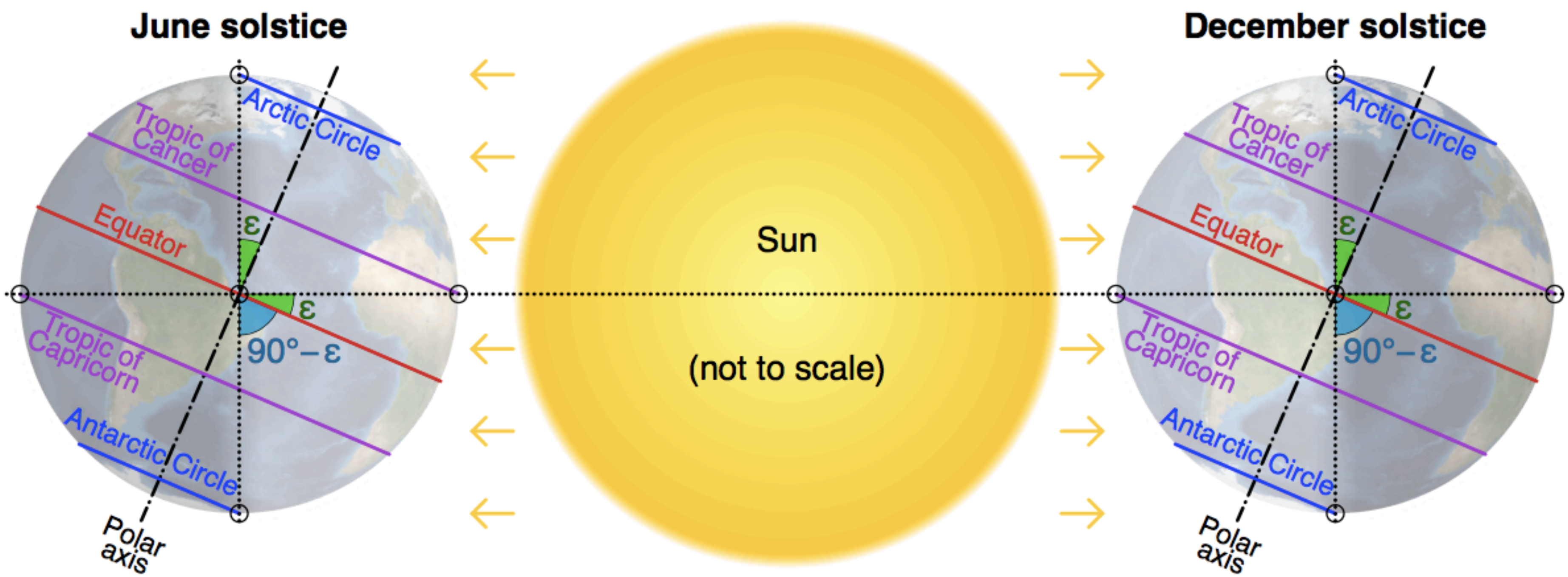
Right ascension (hr)
18
12
6
0
18
30
20
10
0
−10
−20
−30
Declination (deg)
June Solstice
September
Equinox
March
Equinox
(♈)
December Solstice
December Solstice
Dec 21
Sep 23
Jun 21
Mar 20
Dec 21
(Approximate dates)

Northern Hemisphere Seasons

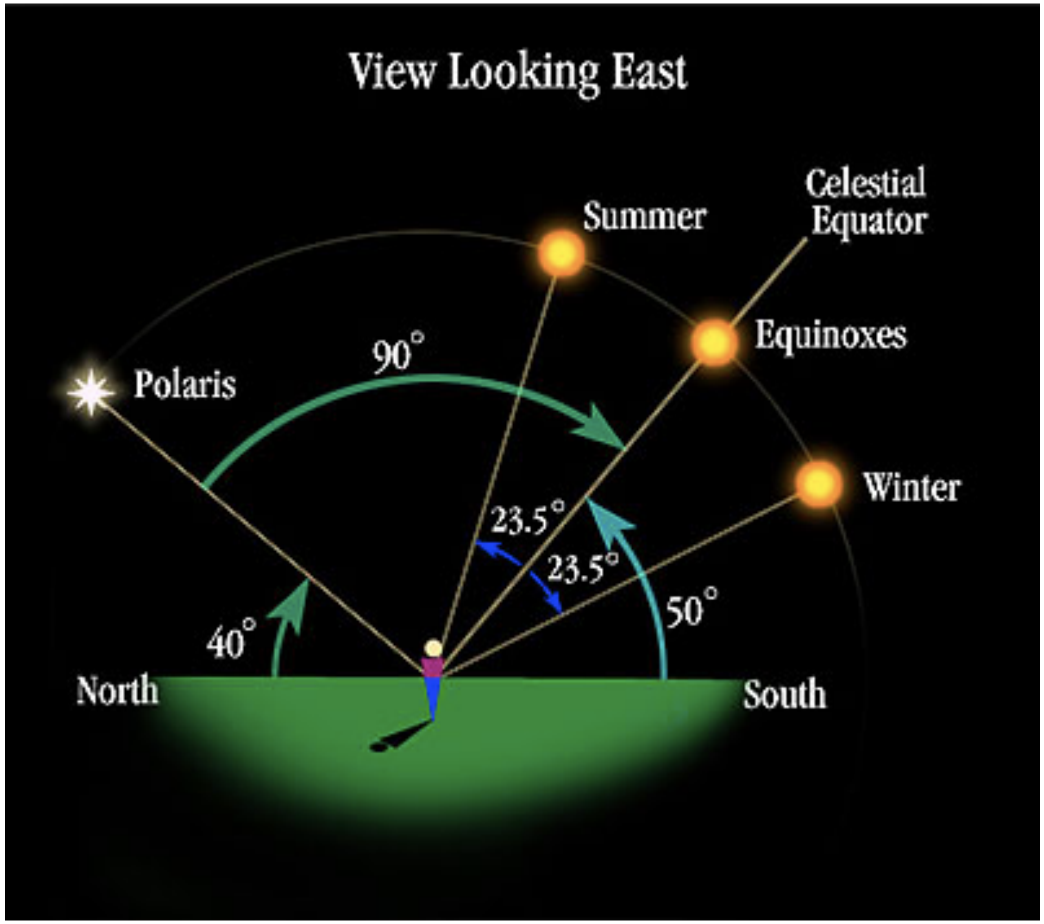


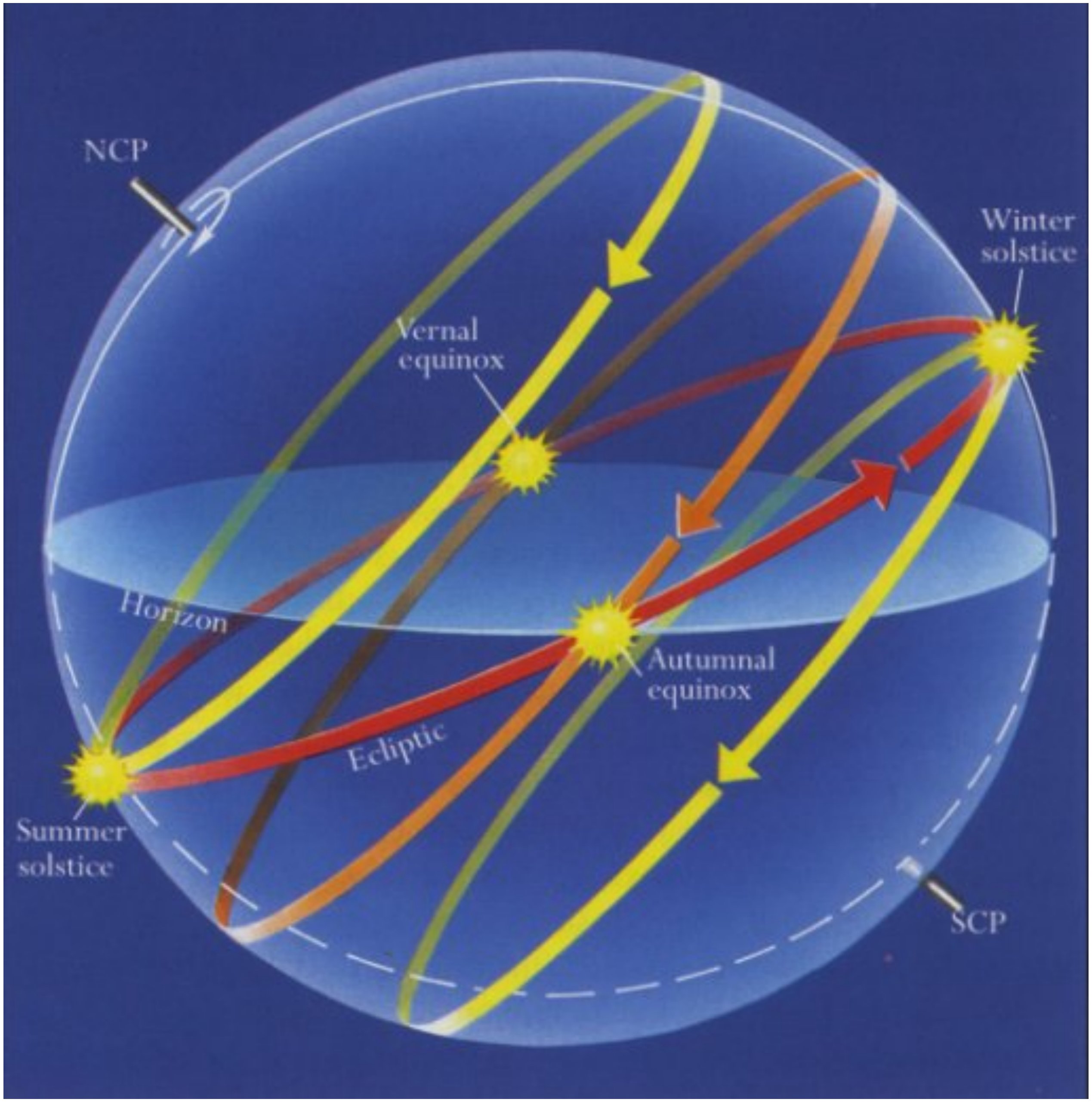
Southern Hemisphere Seasons

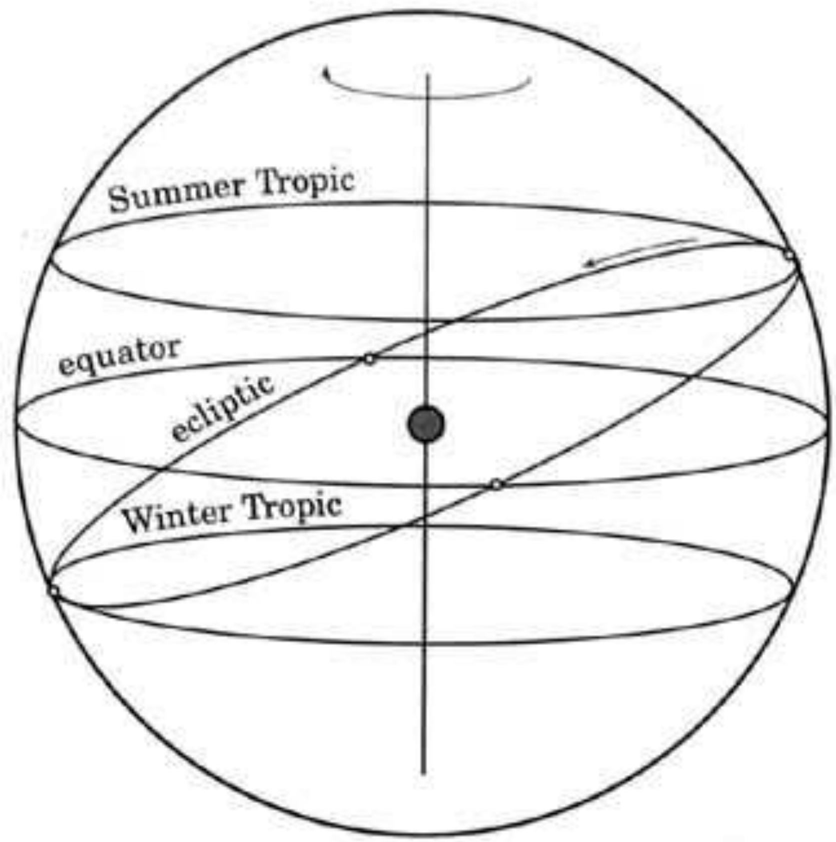




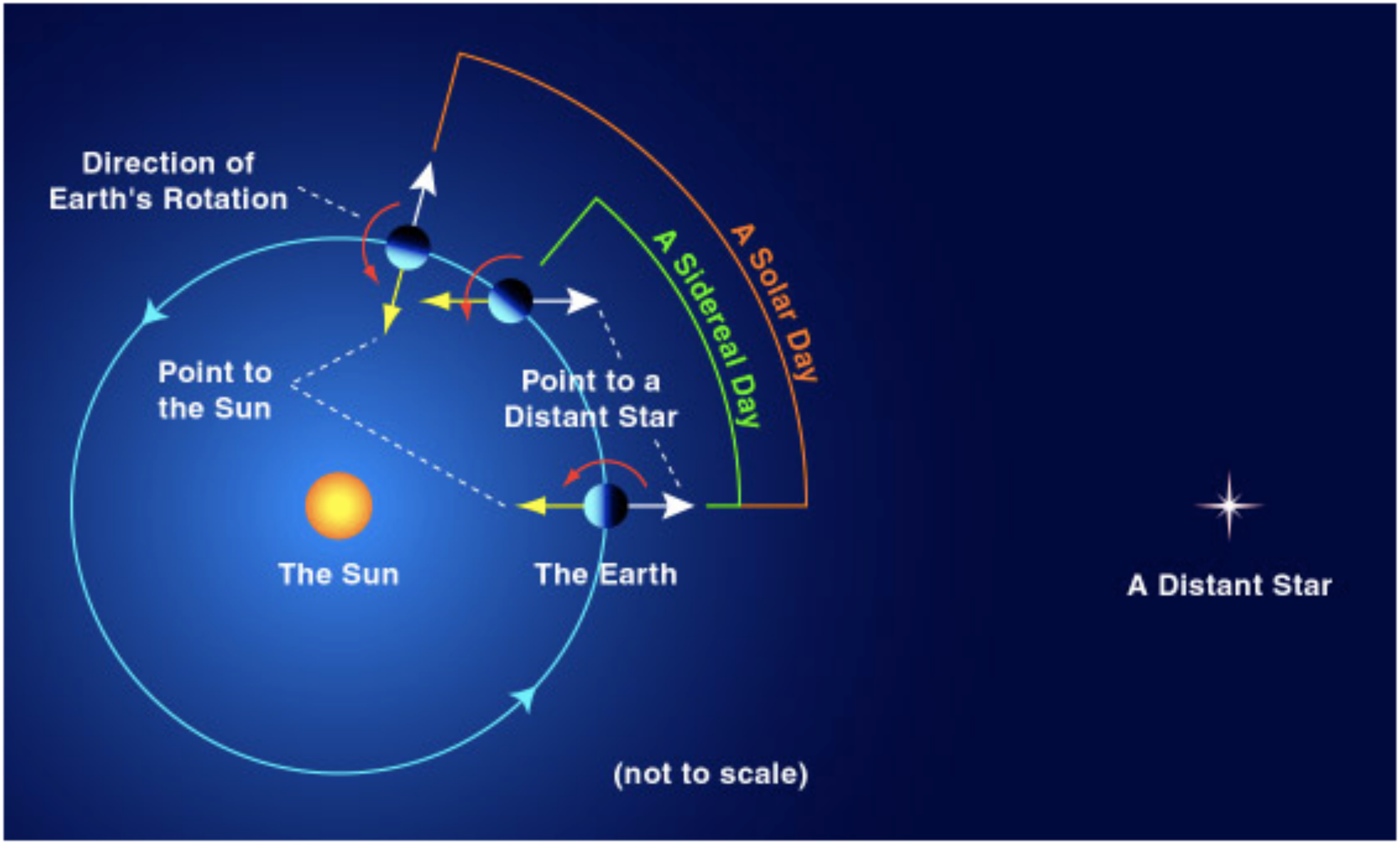
June solstice
December solstice
Sun
(not to scale)
Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
Antarctic Circle
Polar axis
ε
90° − ε
Arctic Circle
Tropic of Cancer
Equator
Tropic of Capricorn
Antarctic Circle
Polar axis
ε
90° − ε


View Looking East
Celestial Equator
Summer
Equinoxes
90°
Polaris
Winter
23.5°
23.5°
50°
40°
North
South


NCP
Winter solstice
Vernal equinox
Horizon
Autumnal equinox
Ecliptic
Summer solstice
SCP

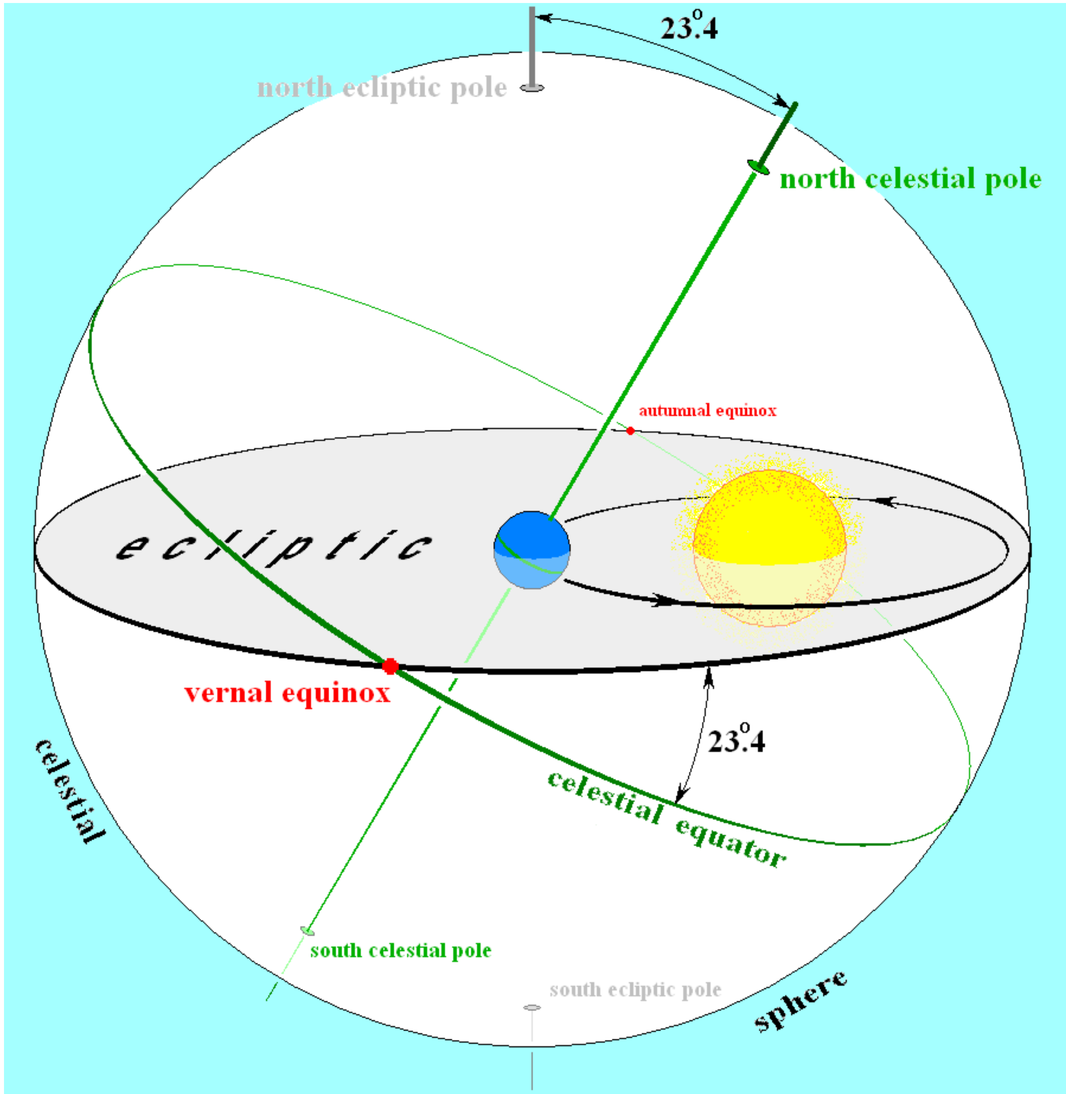


The ecliptic and tropic circles



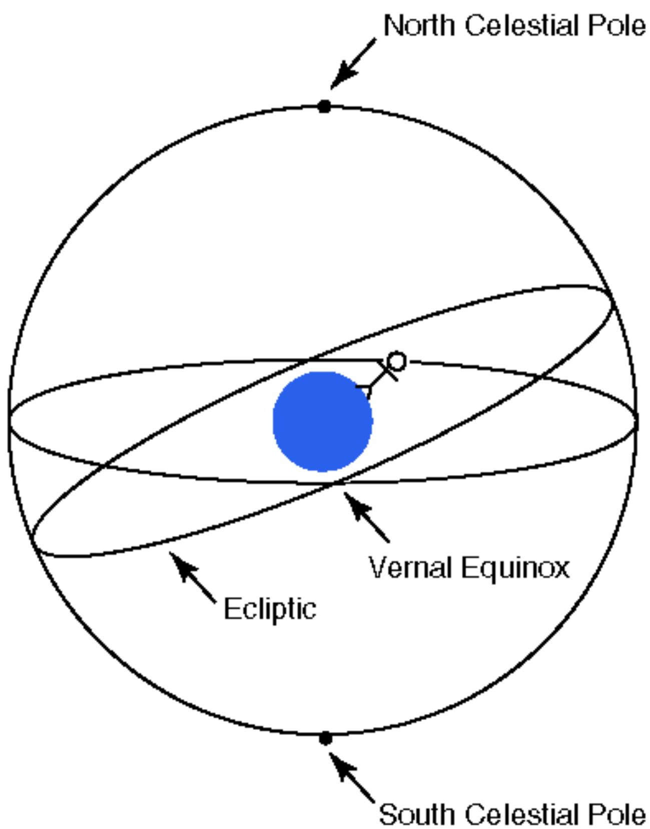
Direction of
Earth's Rotation
A Solar Day
A Sidereal Day
Point to
the Sun
Point to a
Distant Star
The Sun
The Earth
A Distant Star
(not to scale)

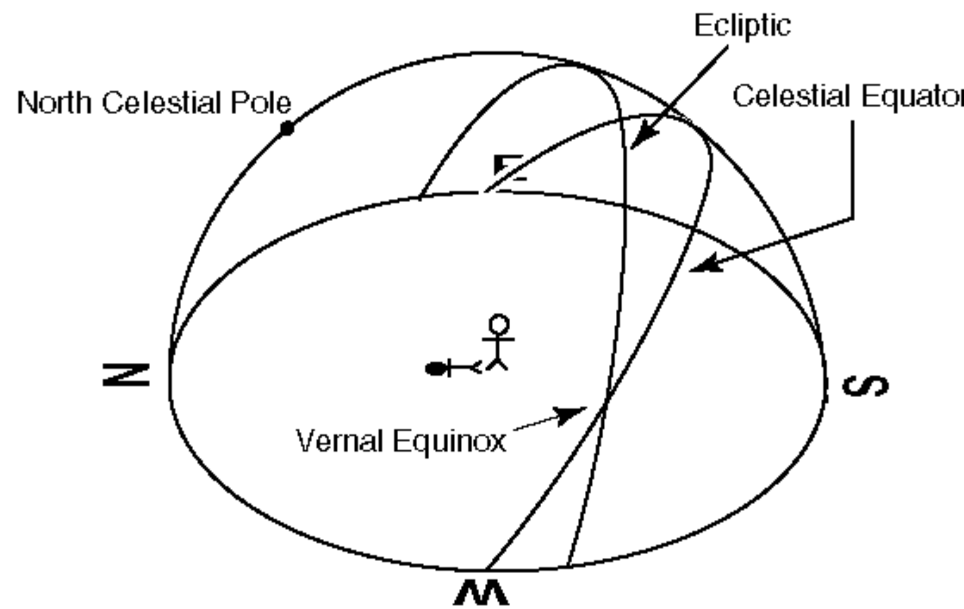
Ecliptic

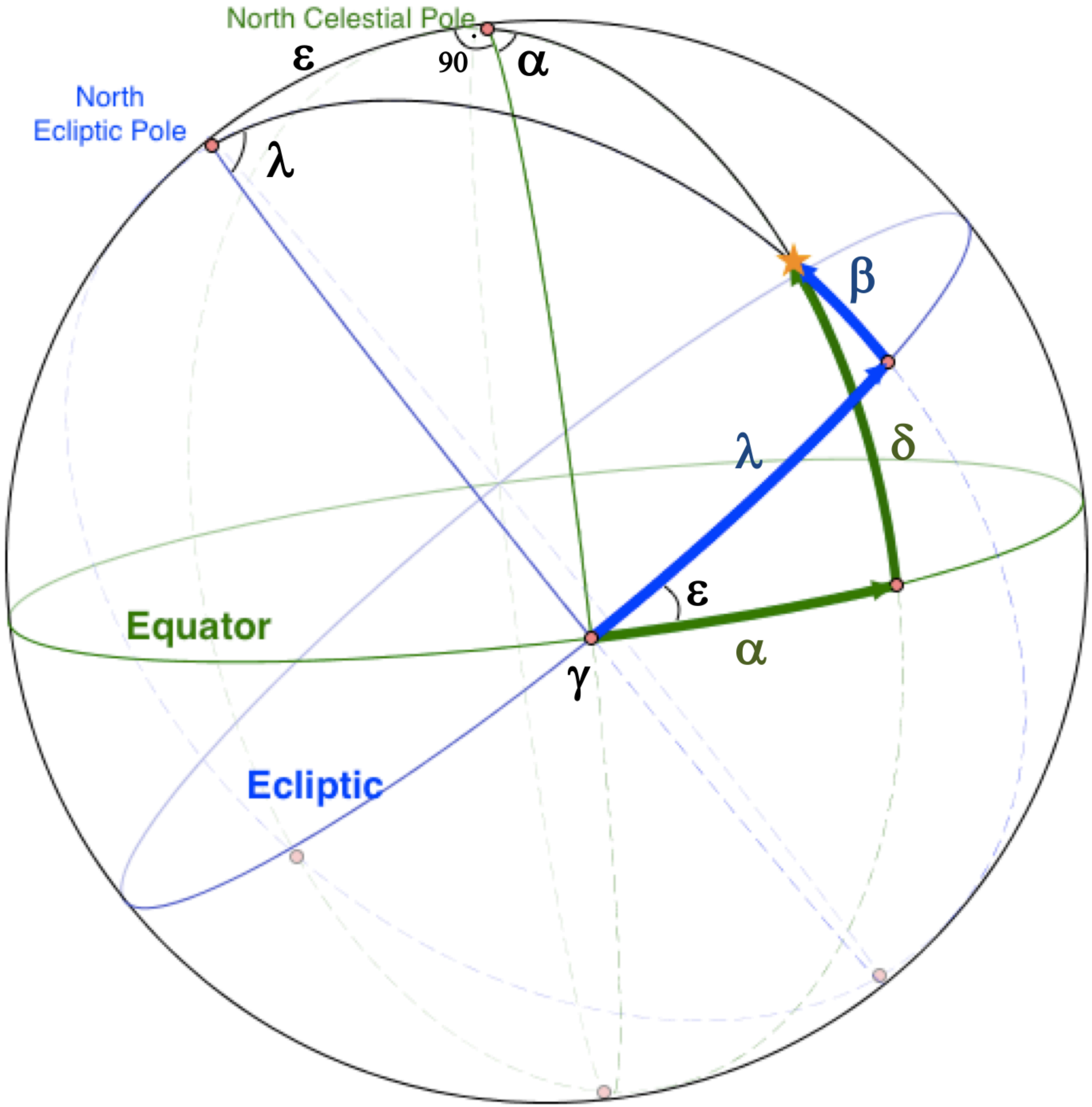


23°.4
north ecliptic pole
north celestial pole
autumnal equinox
ecliptic
vernal equinox
23°.4
celestial equator
celestial
sphere
south celestial pole
south ecliptic pole

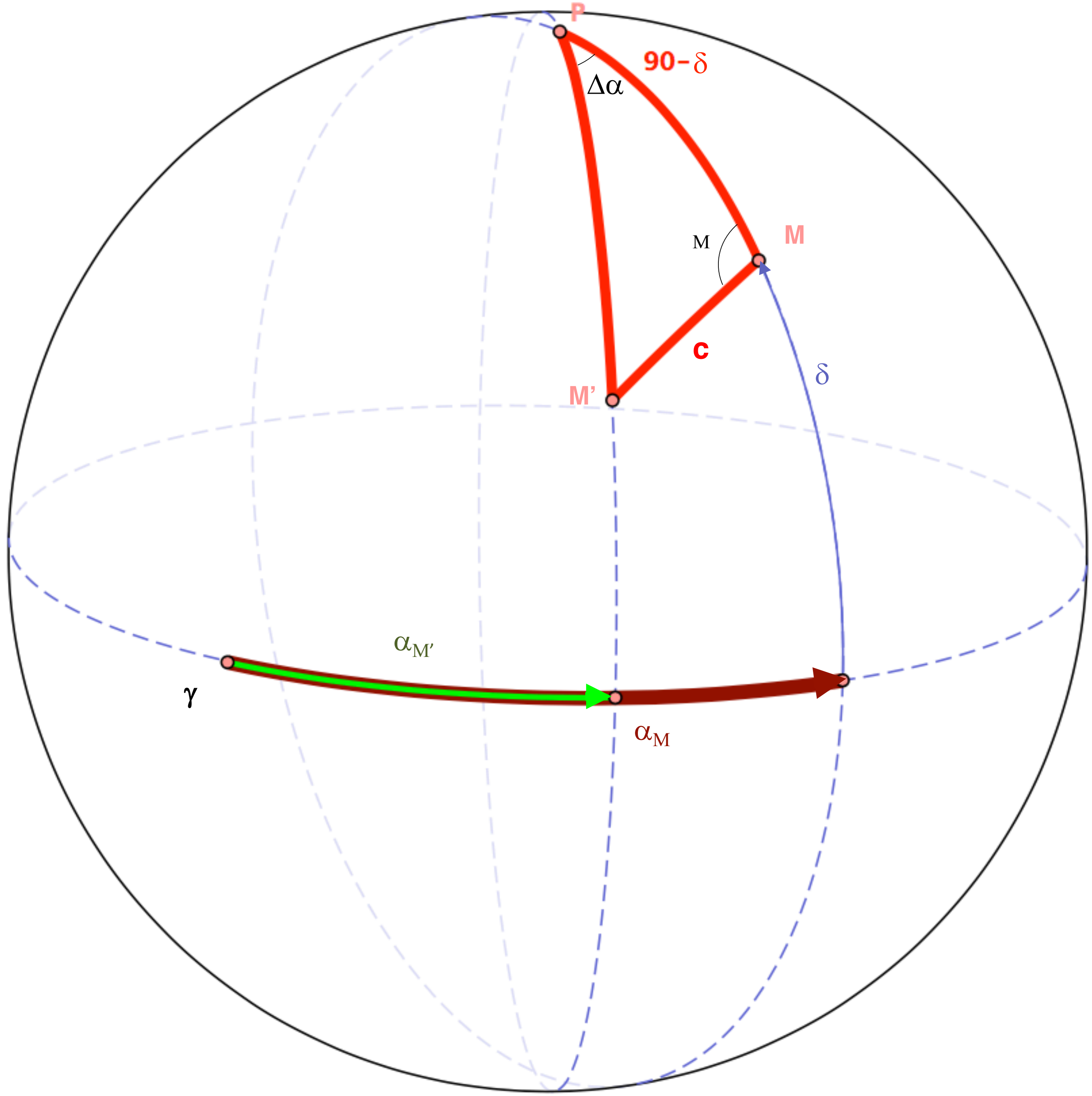
Ecliptic


North Celestial Pole
Vernal Equinox
Ecliptic
South Celestial Pole

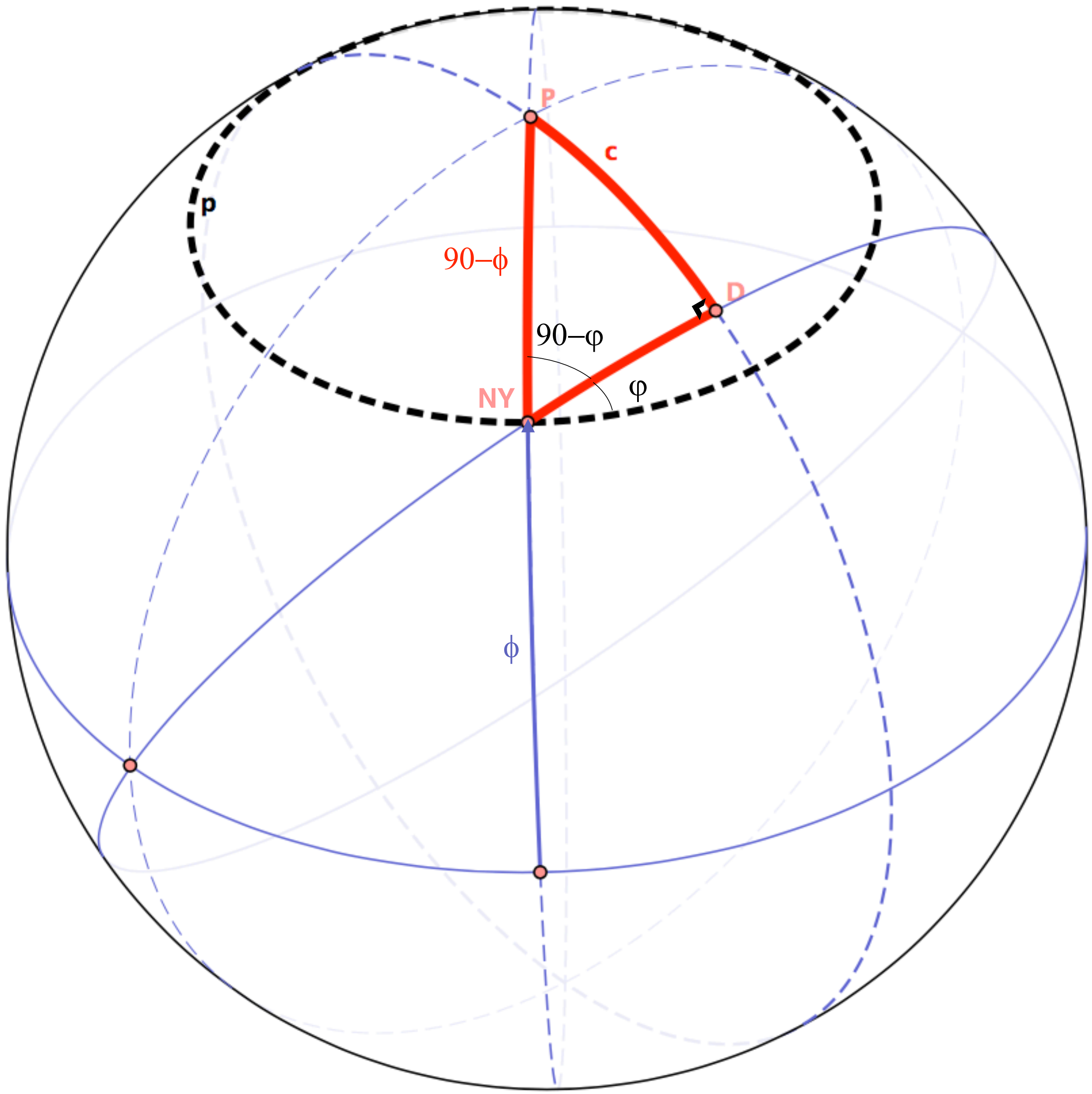

Ecliptic
Celestial Equator
North Celestial Pole
E
N
S
W
Vernal Equinox



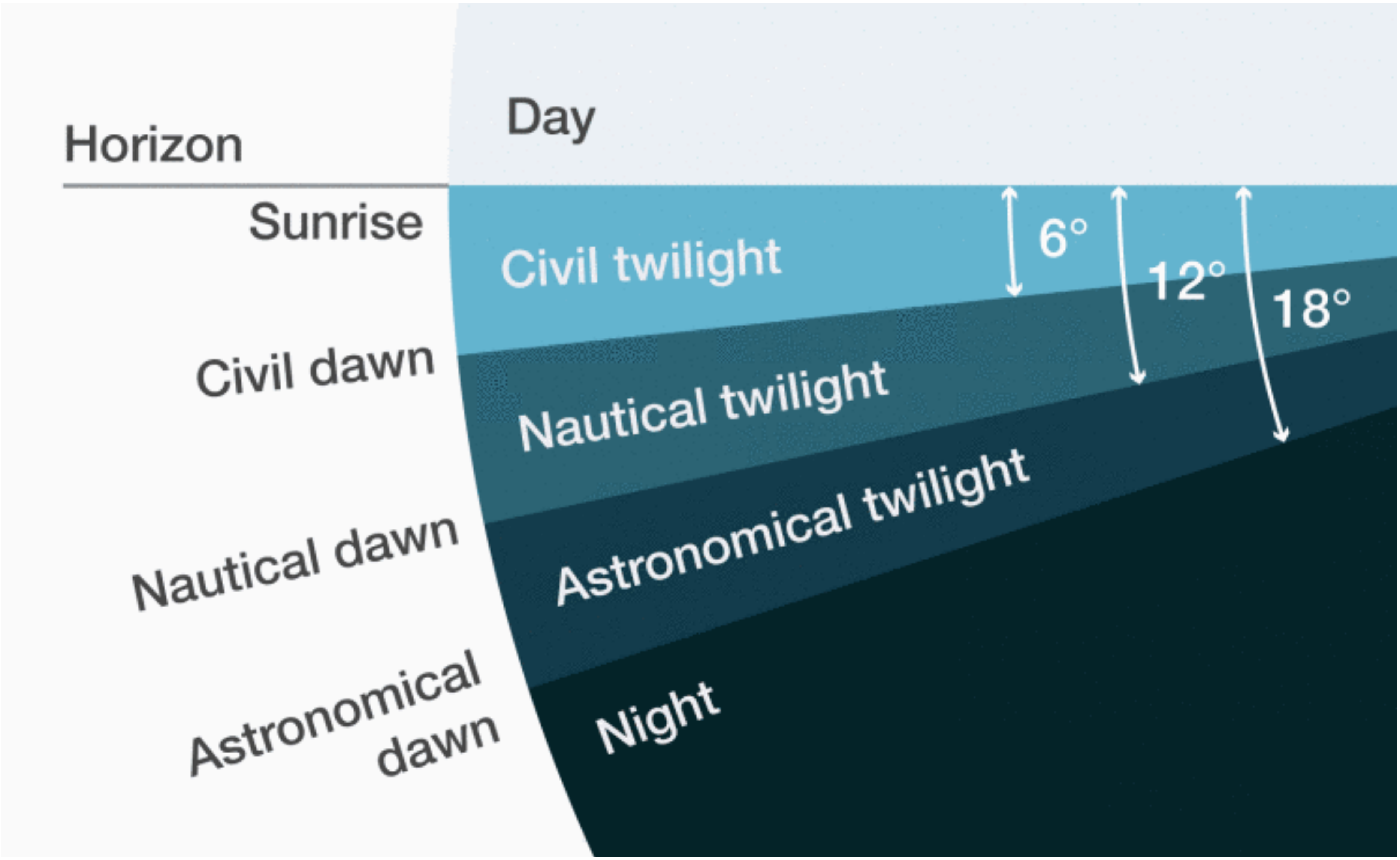
North Celestial Pole
ε
90
α
North
Ecliptic Pole
λ
β
λ
δ
ε
Equator
α
γ
Ecliptic



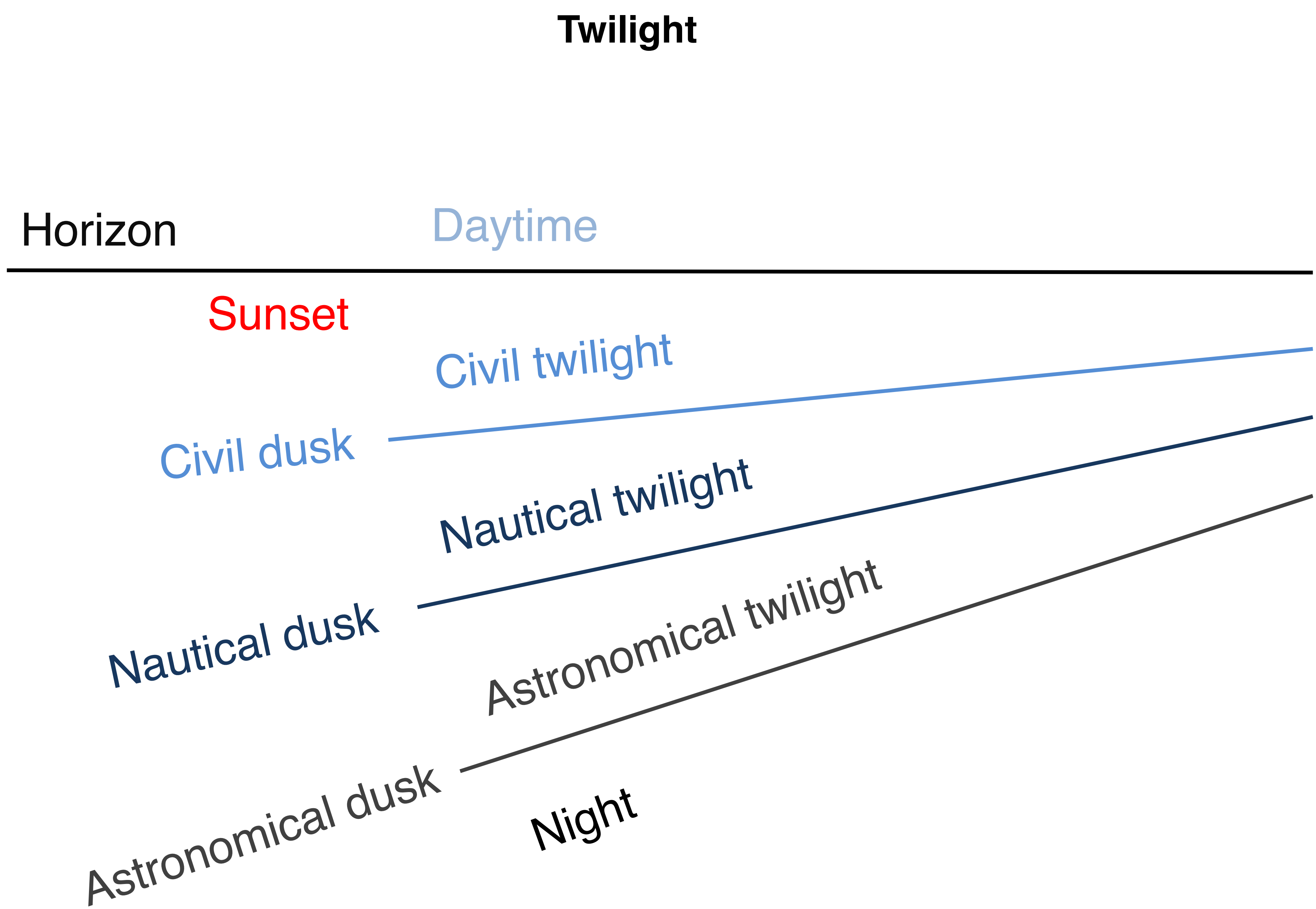
P
90-δ
Δα
M
M
c
δ
M'
$\alpha_{M'}$
γ
α_M

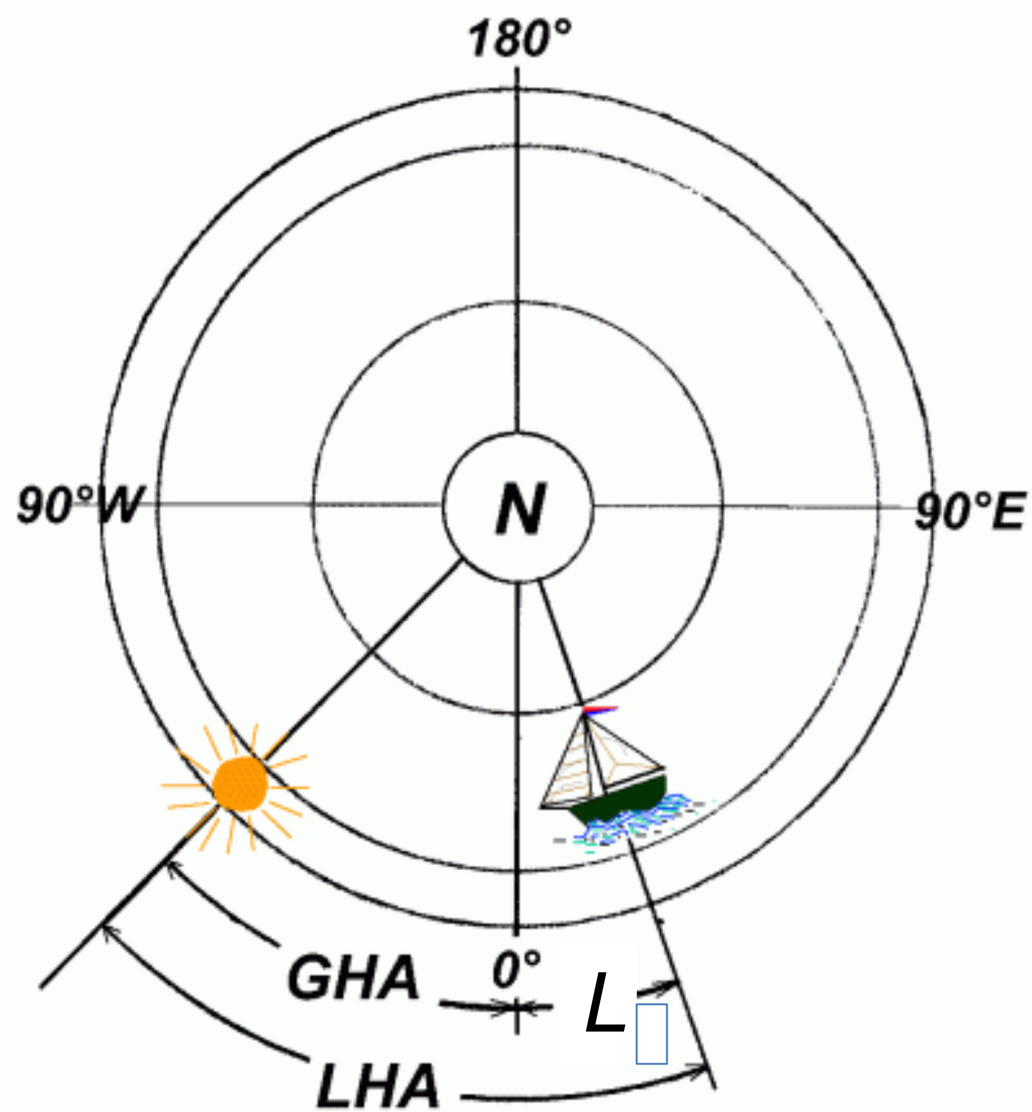

P
c
p
90−ϕ
D
90−φ
φ
NY
ϕ

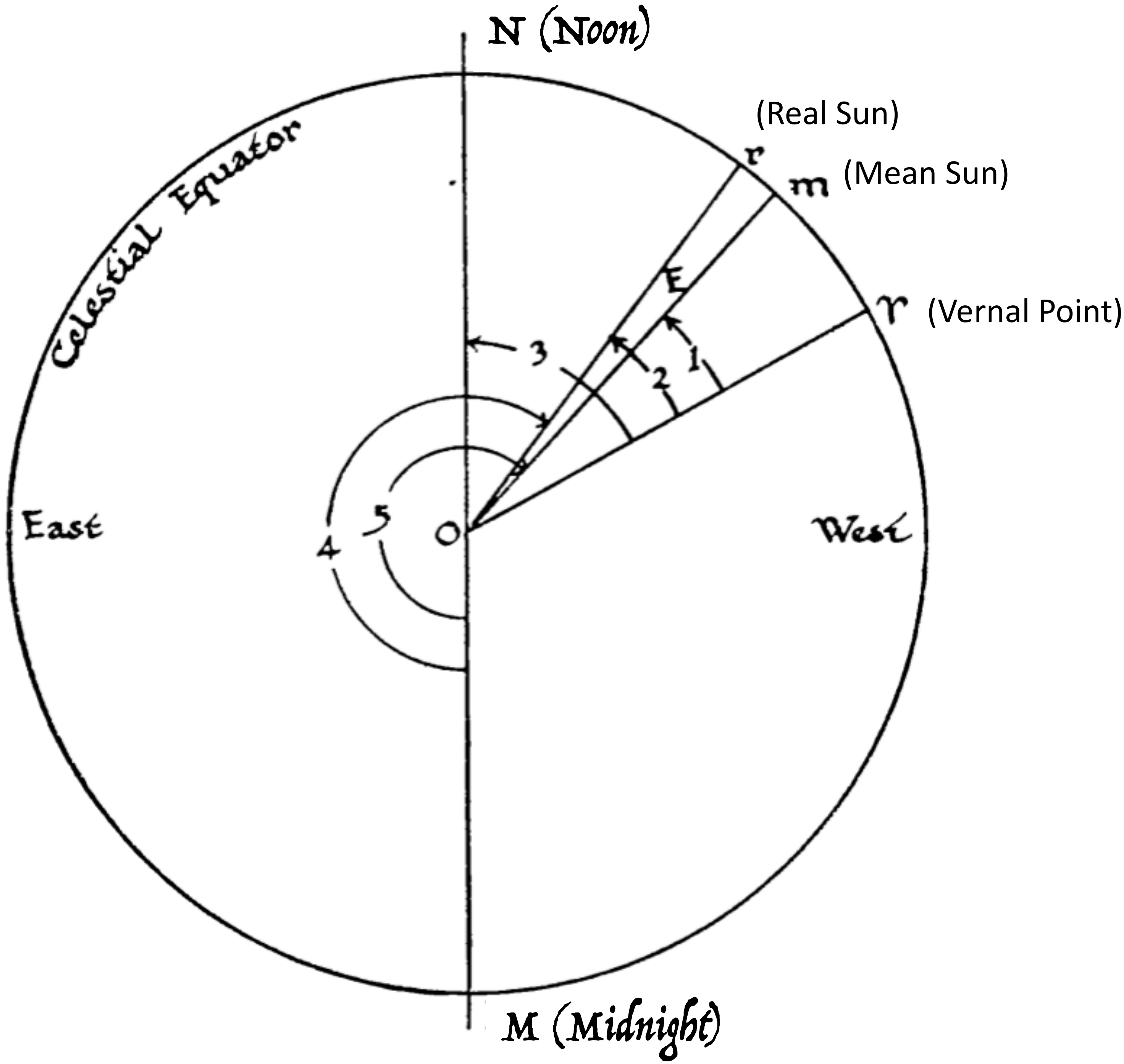
Twilight

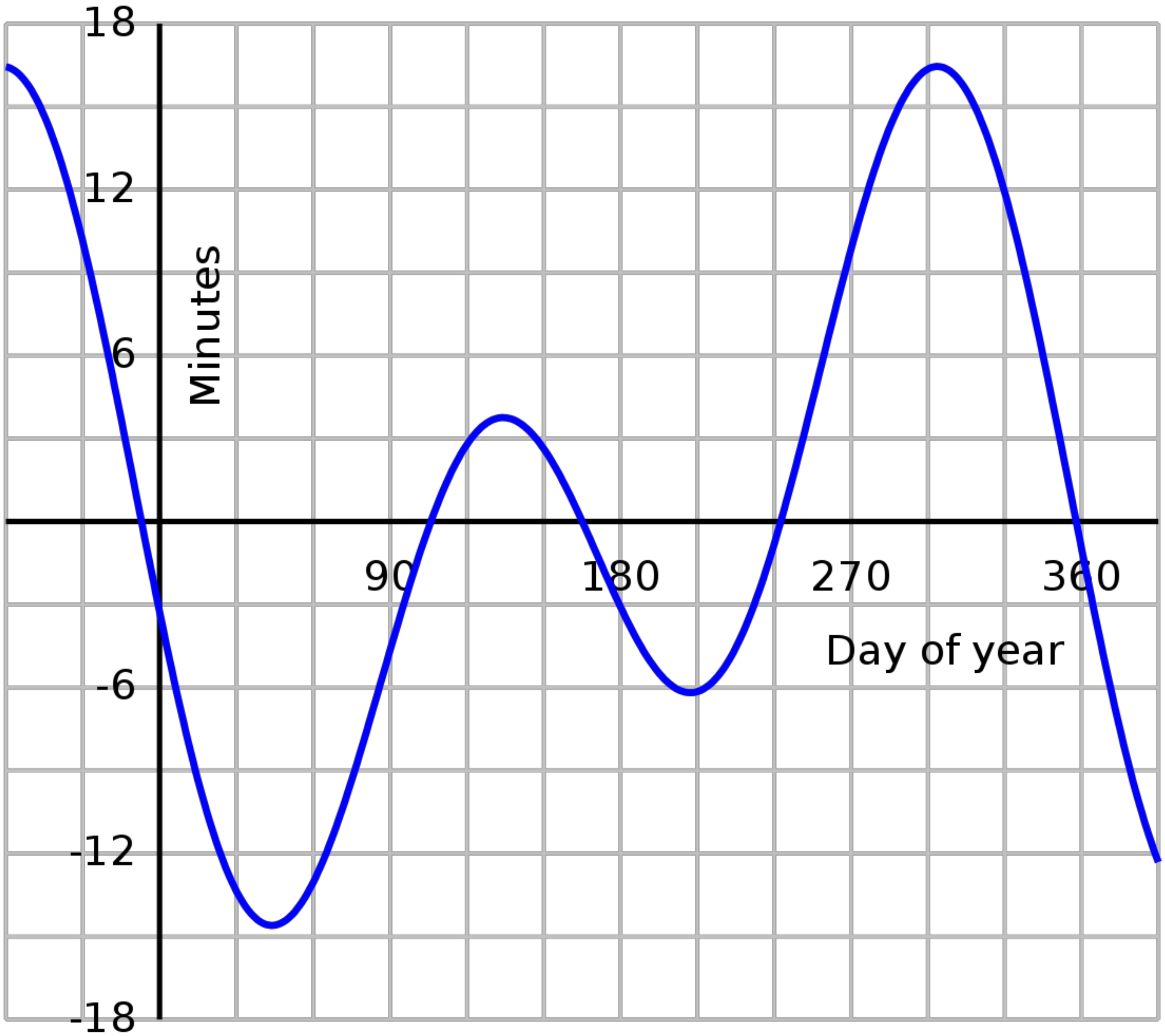


Horizon
Sunrise
Civil dawn
Nautical dawn
Astronomical dawn
Day
Civil twilight
Nautical twilight
Astronomical twilight
Night
6°
12°
18°

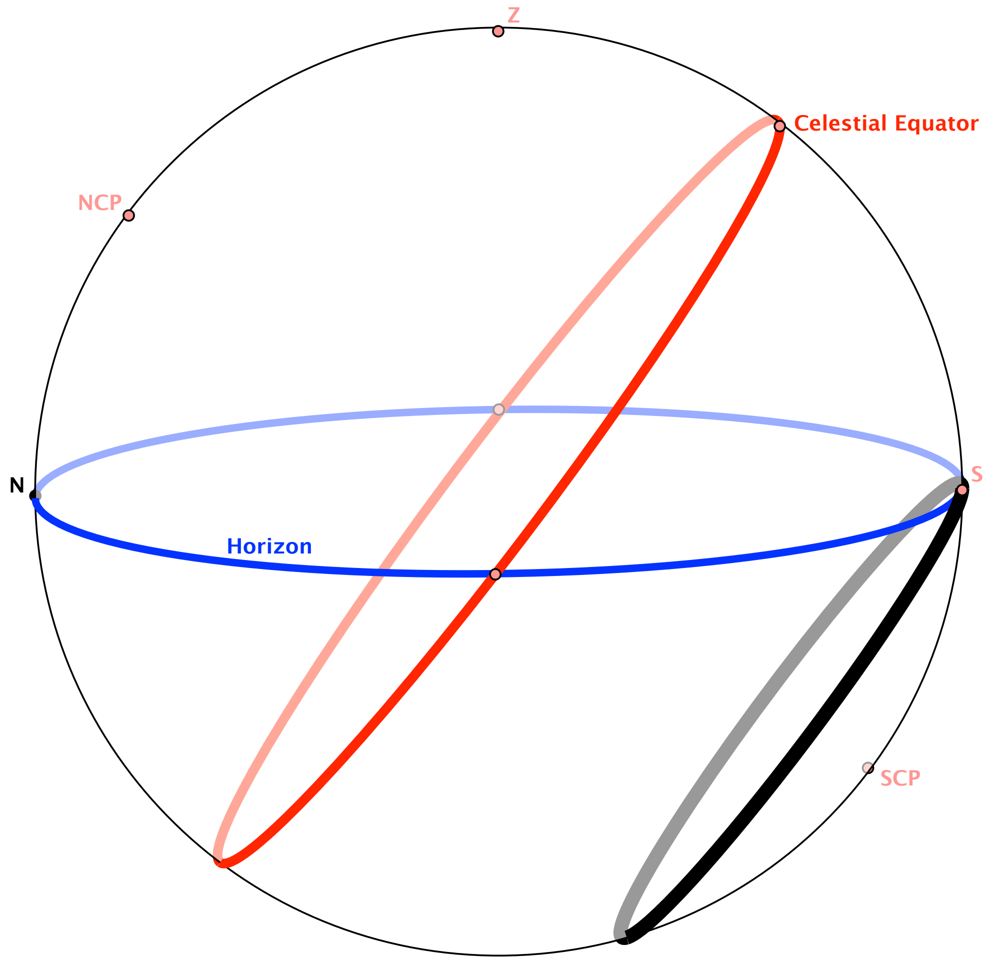

Twilight
Horizon
Daytime
Sunset
Civil twilight
Civil dusk
Nautical twilight
Nautical dusk
Astronomical twilight
Astronomical dusk
Night


180°
90°W
N
90°E
GHA
0°
L
LHA

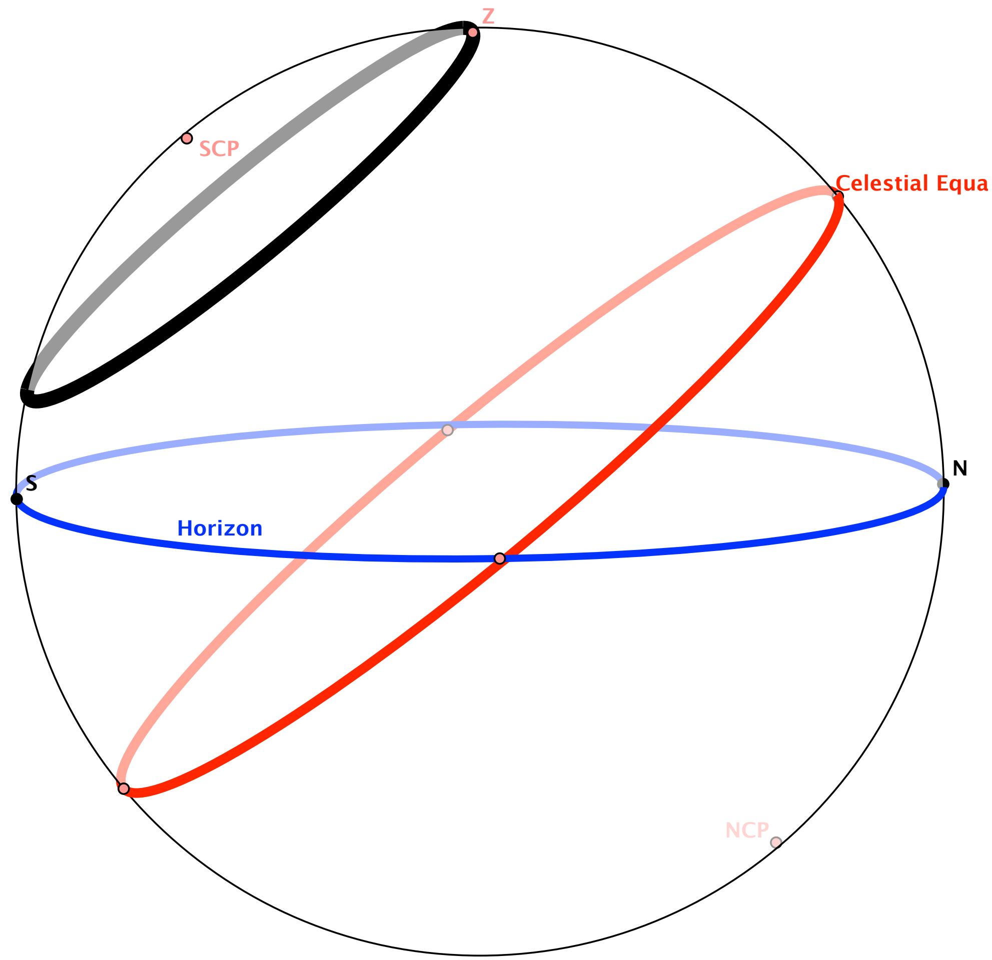

N (Noon)
(Real Sun)
r
m
(Mean Sun)
♈
(Vernal Point)
Celestial Equator
E
3
2
1
5
4
O
East
West
M (Midnight)



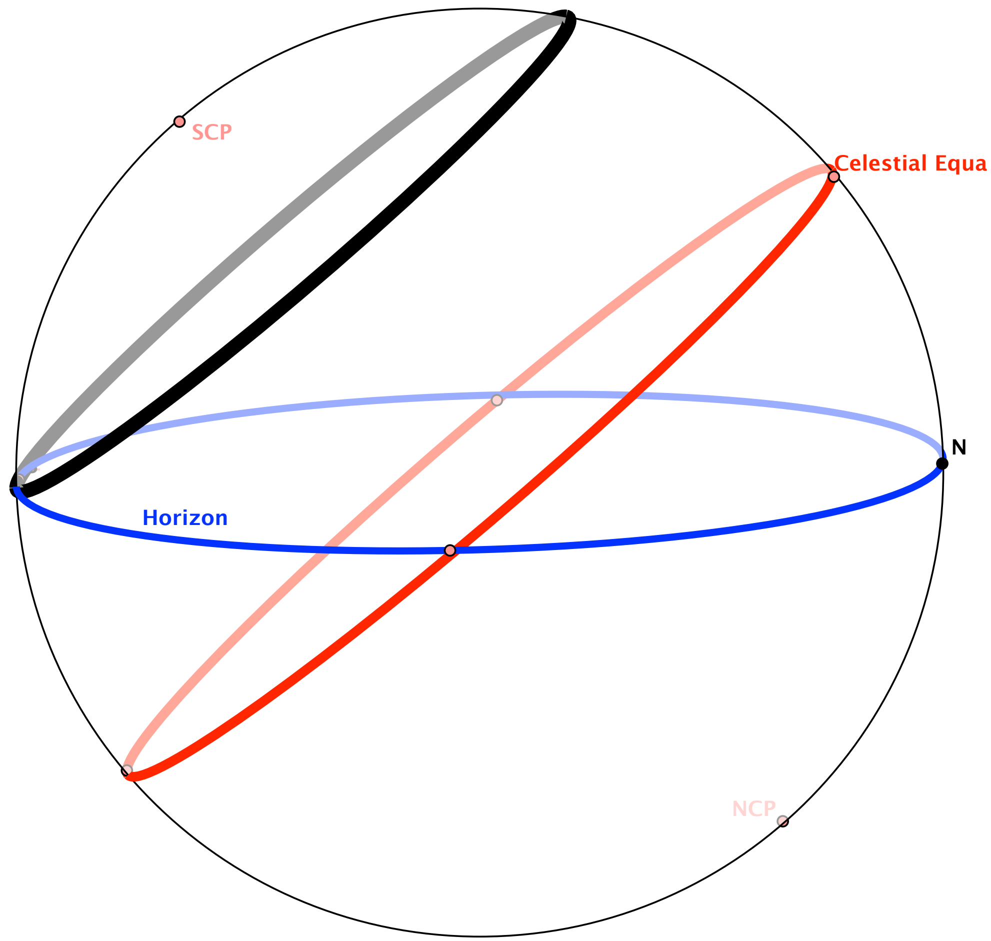
18
12
6
-6
-12
-18
Minutes
90
180
270
360
Day of year

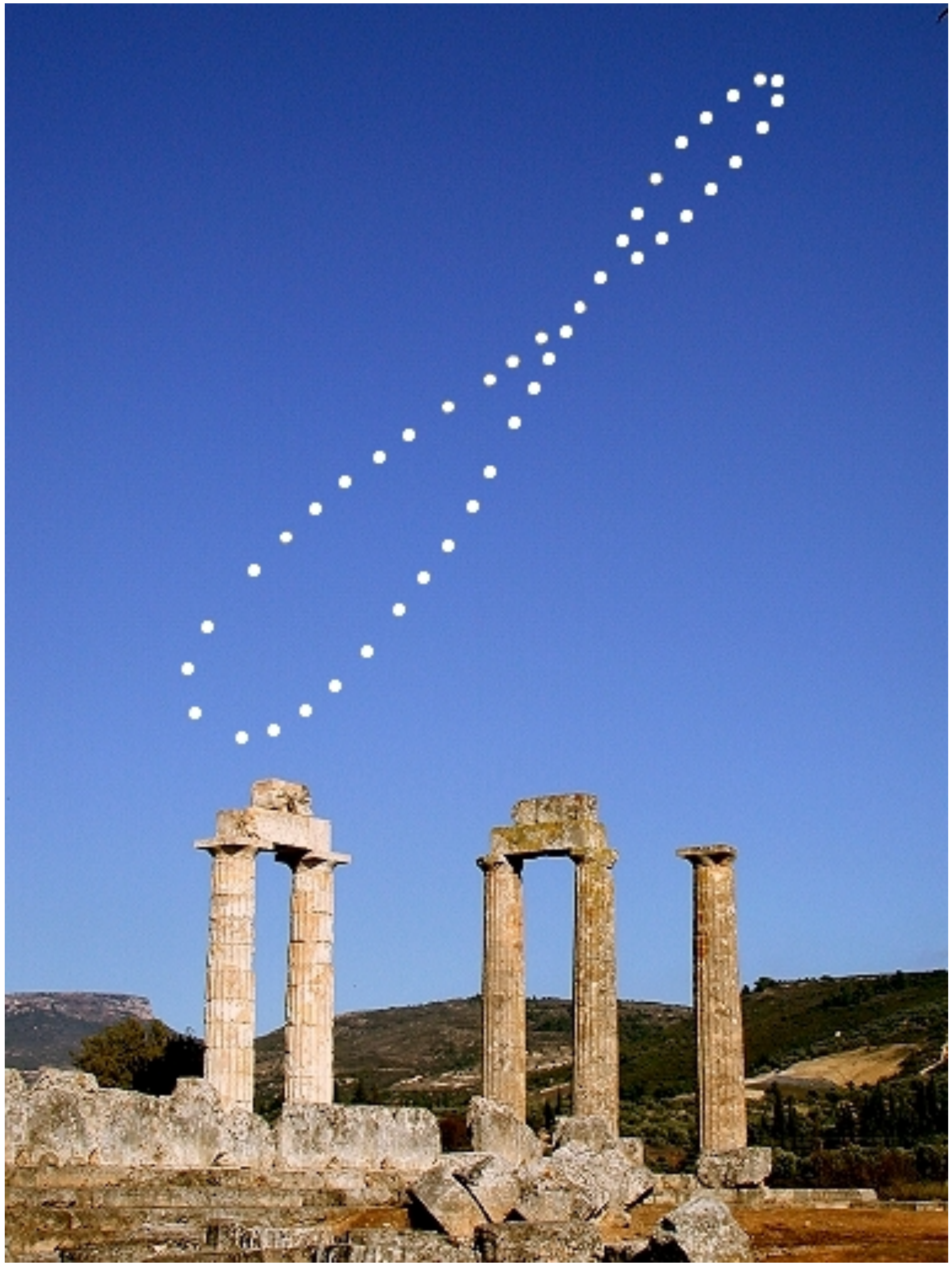


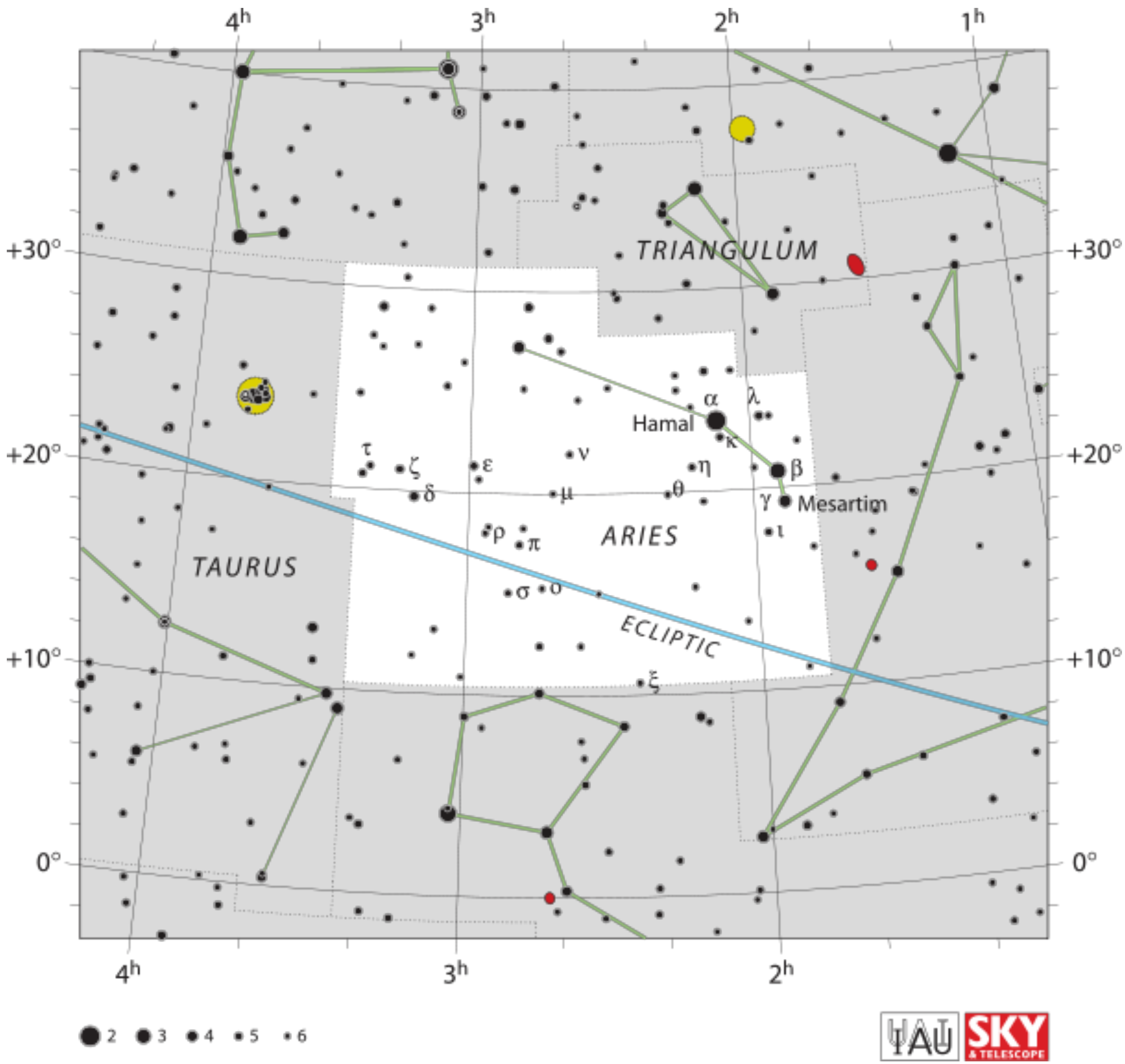
Z
Celestial Equator
NCP
N
S
Horizon
SCP



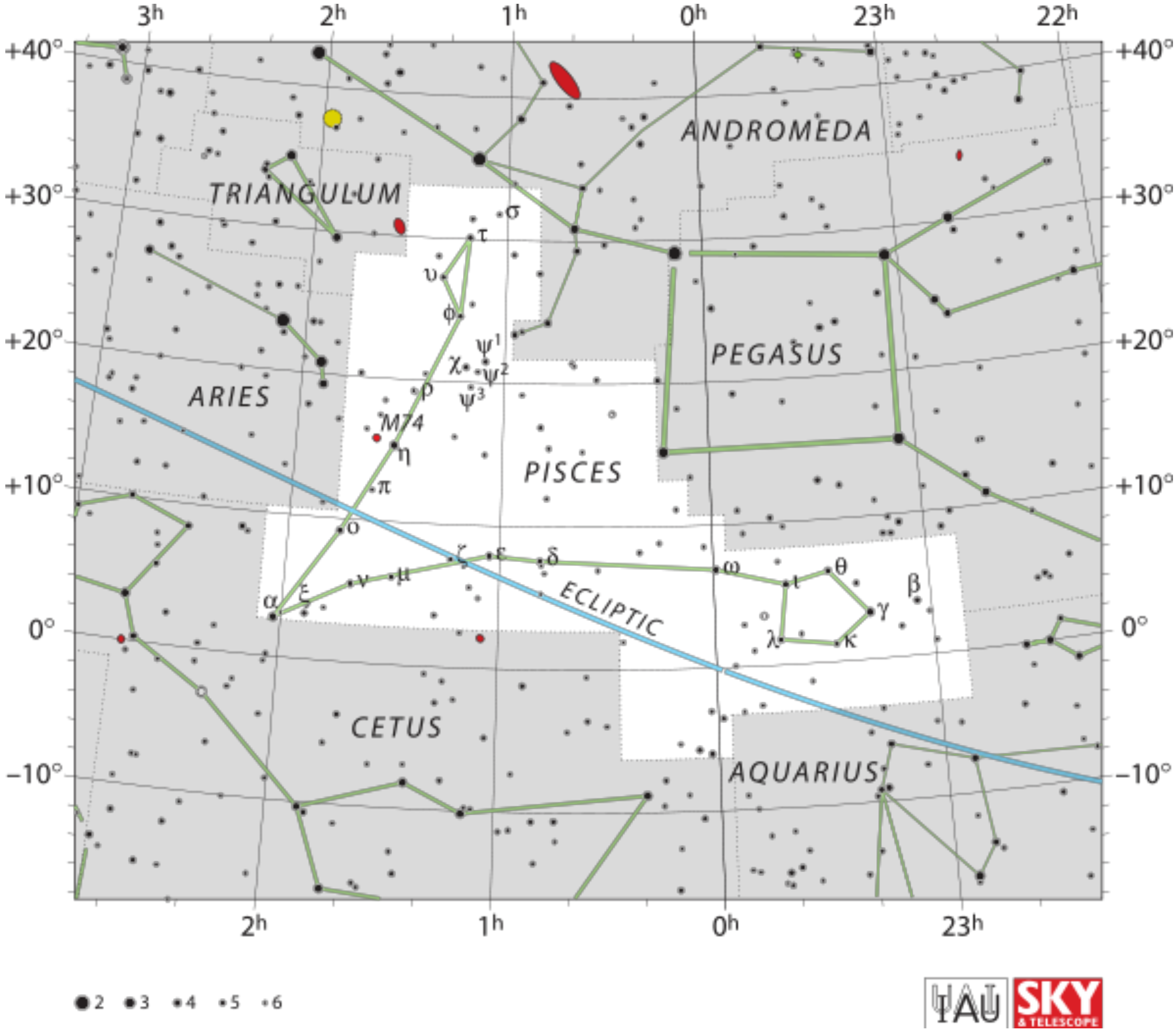
Z
SCP
Celestial Equa
N
S
Horizon
NCP

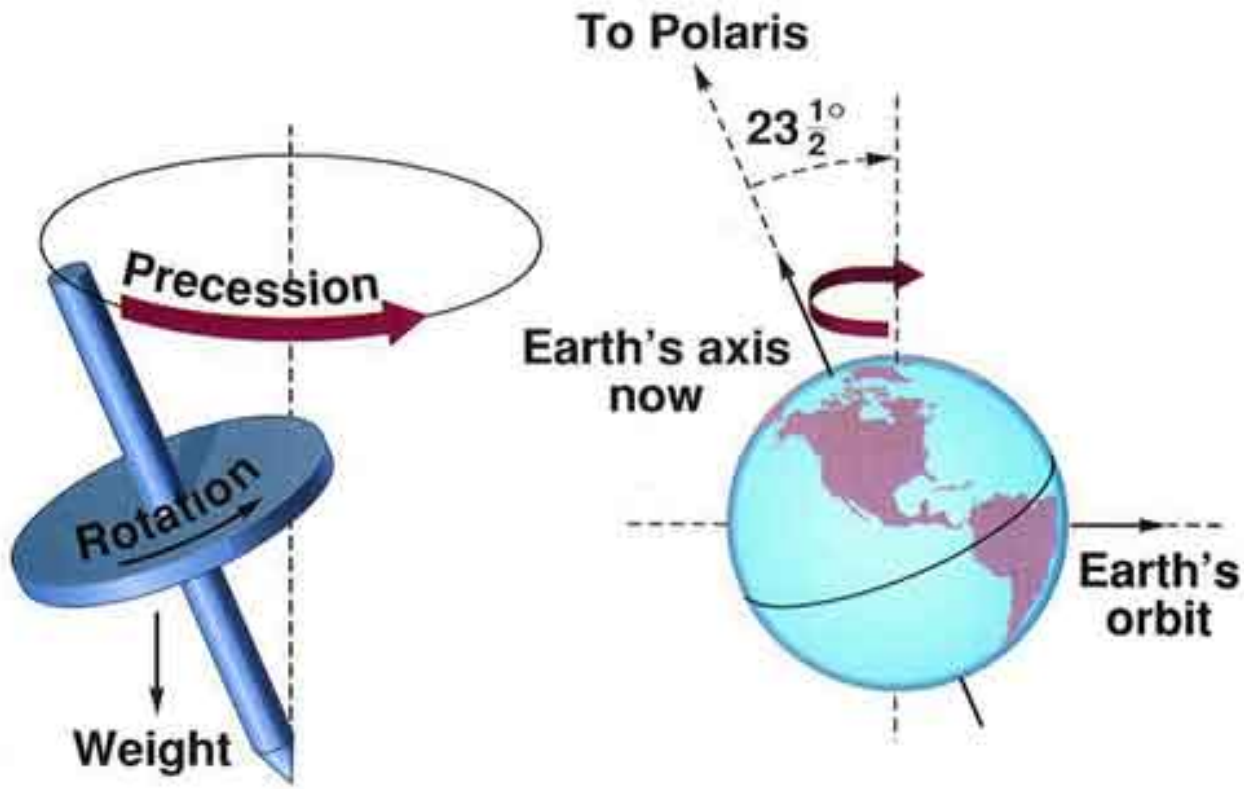

SCP
Celestial Equa
N
Horizon
NCP



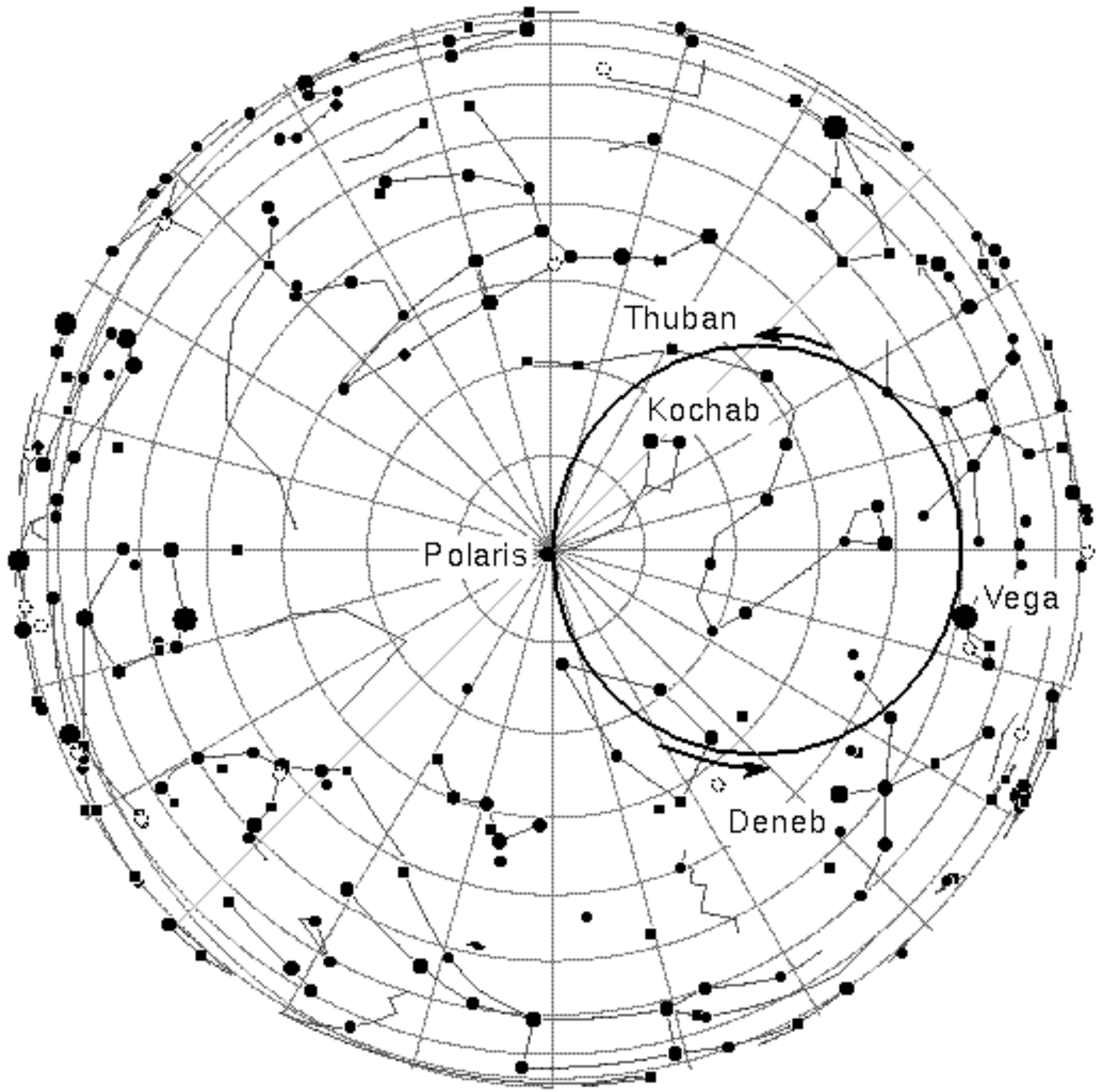


4h
3h
2h
1h
+30°
+20°
+10°
0°
TRIANGULUM
TAURUS
ARIES
ECLIPTIC
Hamal
Mesartim
α
β
γ
δ
ε
ζ
η
θ
ι
κ
λ
μ
ν
ξ
ο
π
ρ
σ
τ
2
3
4
5
6
IAU
SKY & TELESCOPE

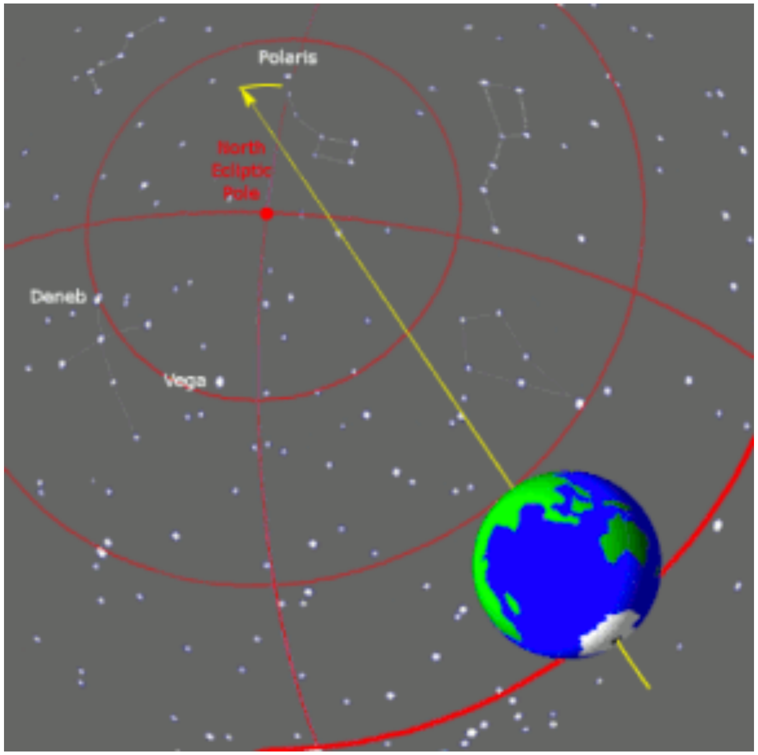

3h
2h
1h
0h
23h
22h
+40°
+30°
+20°
+10°
0°
−10°
ANDROMEDA
TRIANGULUM
ARIES
PEGASUS
PISCES
CETUS
AQUARIUS
ECLIPTIC
M74
σ
τ
υ
φ
ψ1
ψ2
ψ3
χ
ρ
η
π
ο
ζ
ε
δ
ω
ι
θ
β
γ
κ
λ
α
ξ
ν
μ
2
3
4
5
6
IAU
SKY & TELESCOPE



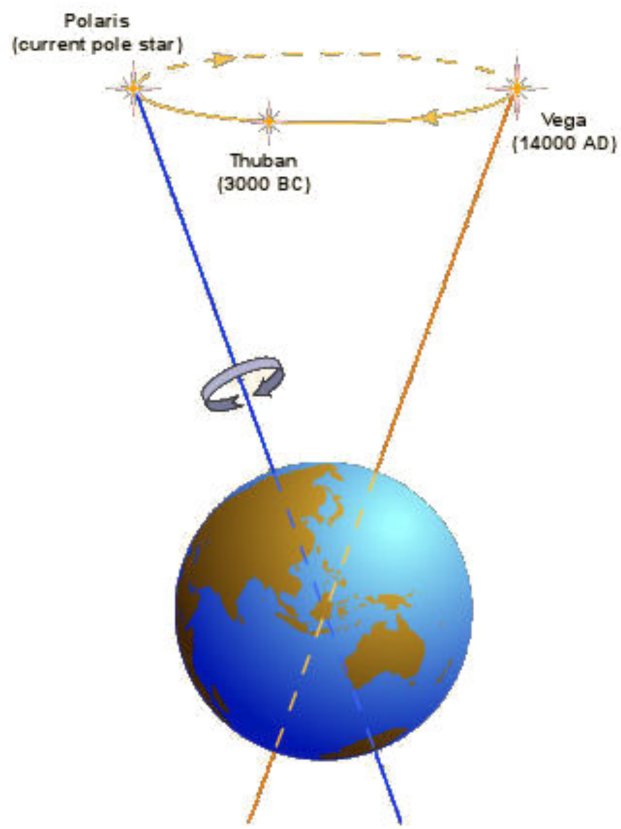
Precession
Rotation
Weight
To Polaris
$23\frac{1}{2}°$
Earth's axis now
Earth's orbit

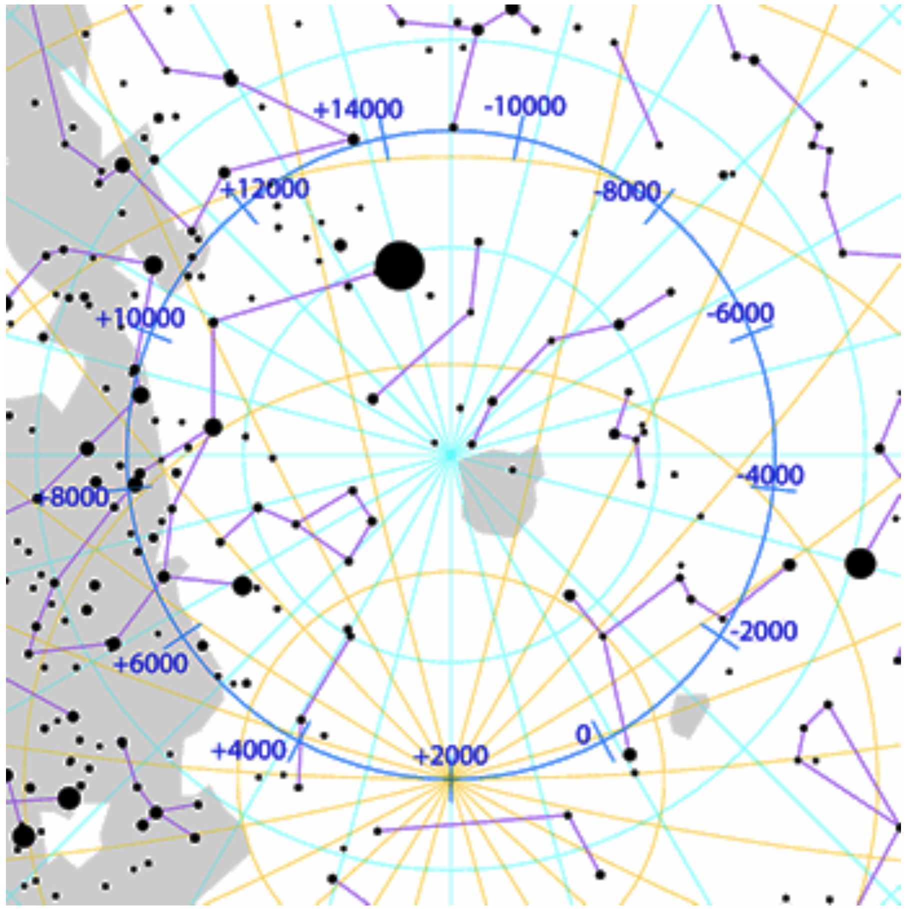


Thuban
Kochab
Polaris
Vega
Deneb

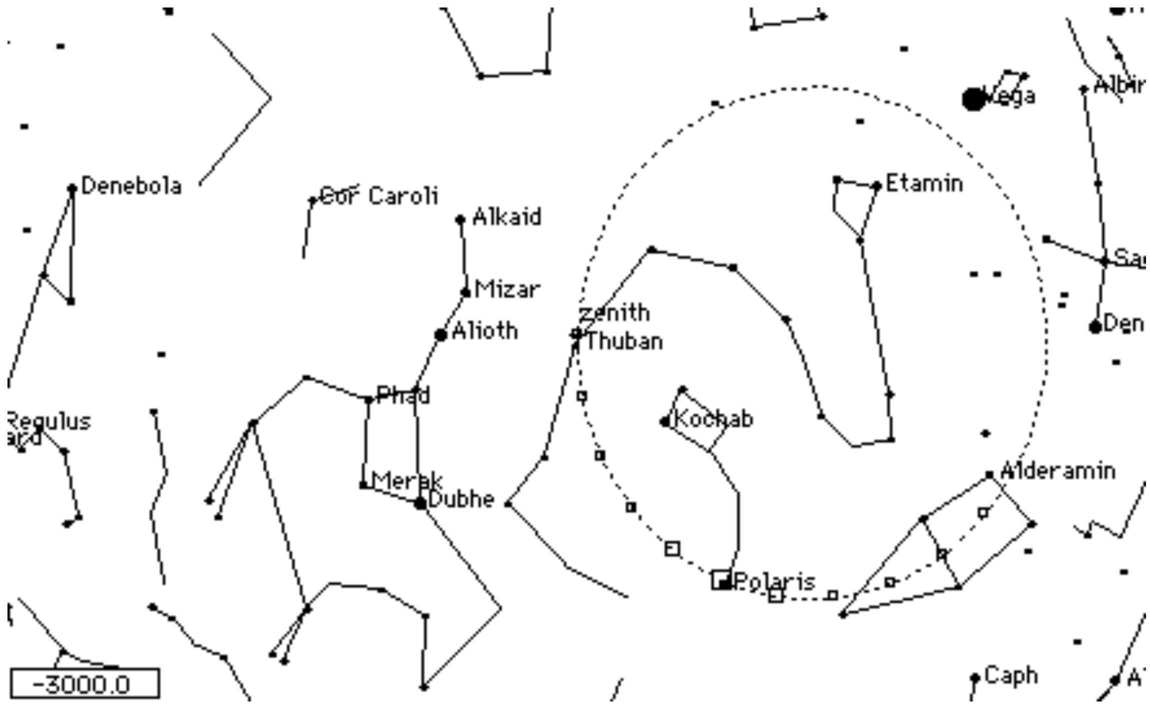


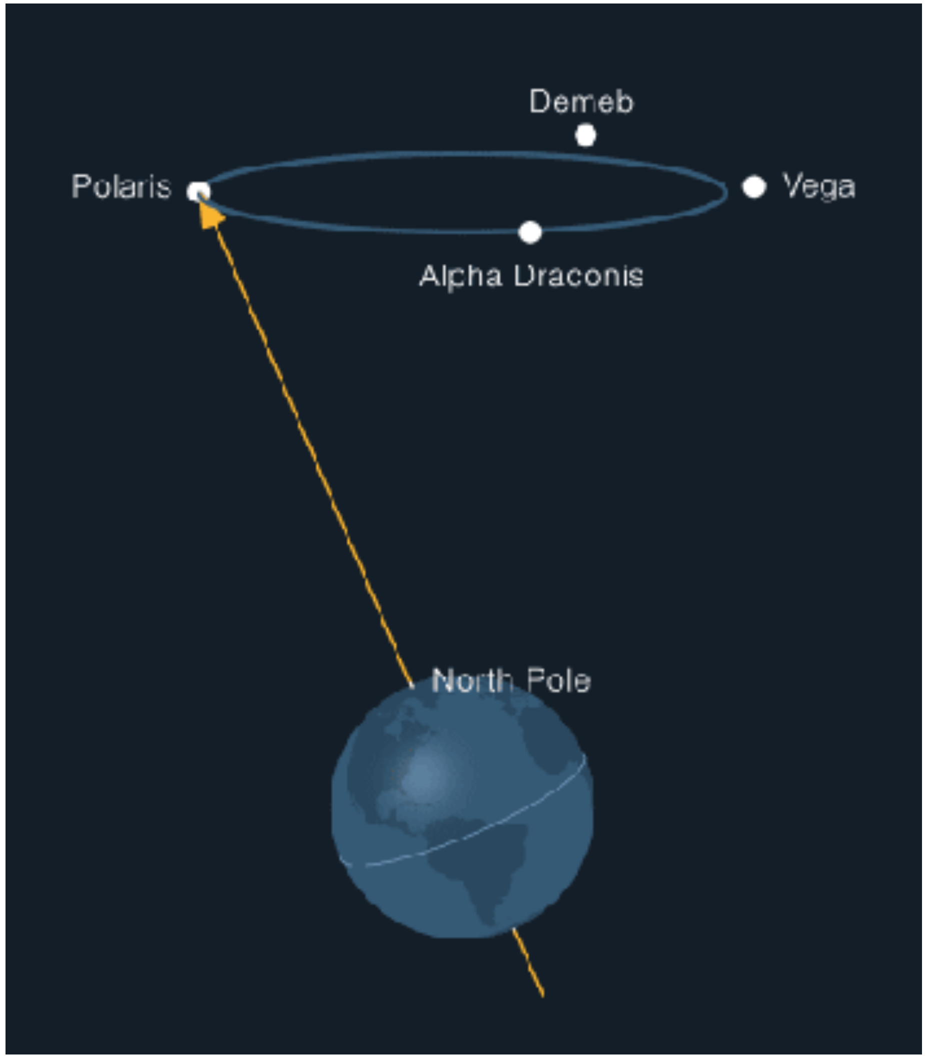
Polaris
North
Ecliptic
Pole
Deneb
Vega

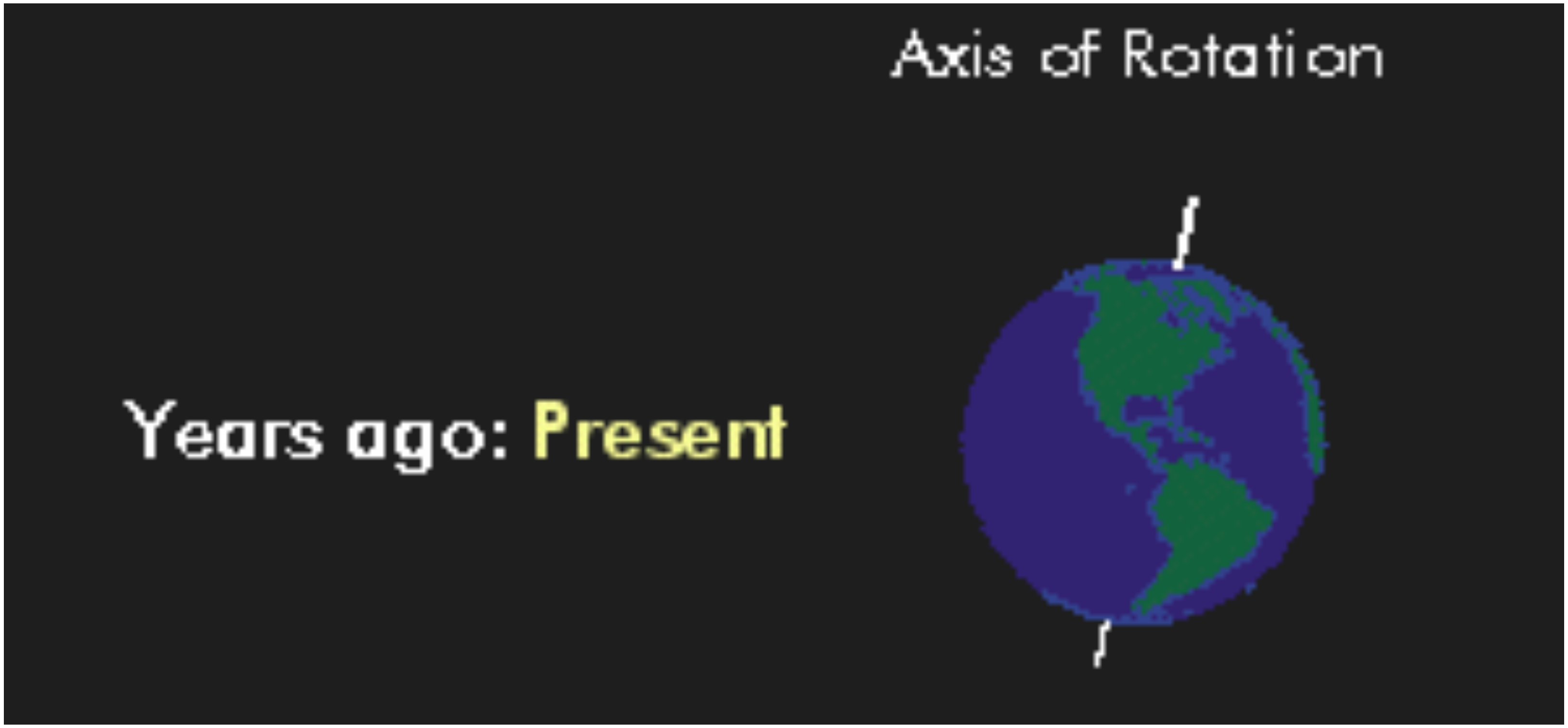

Polaris
(current pole star)
Thuban
(3000 BC)
Vega
(14000 AD)

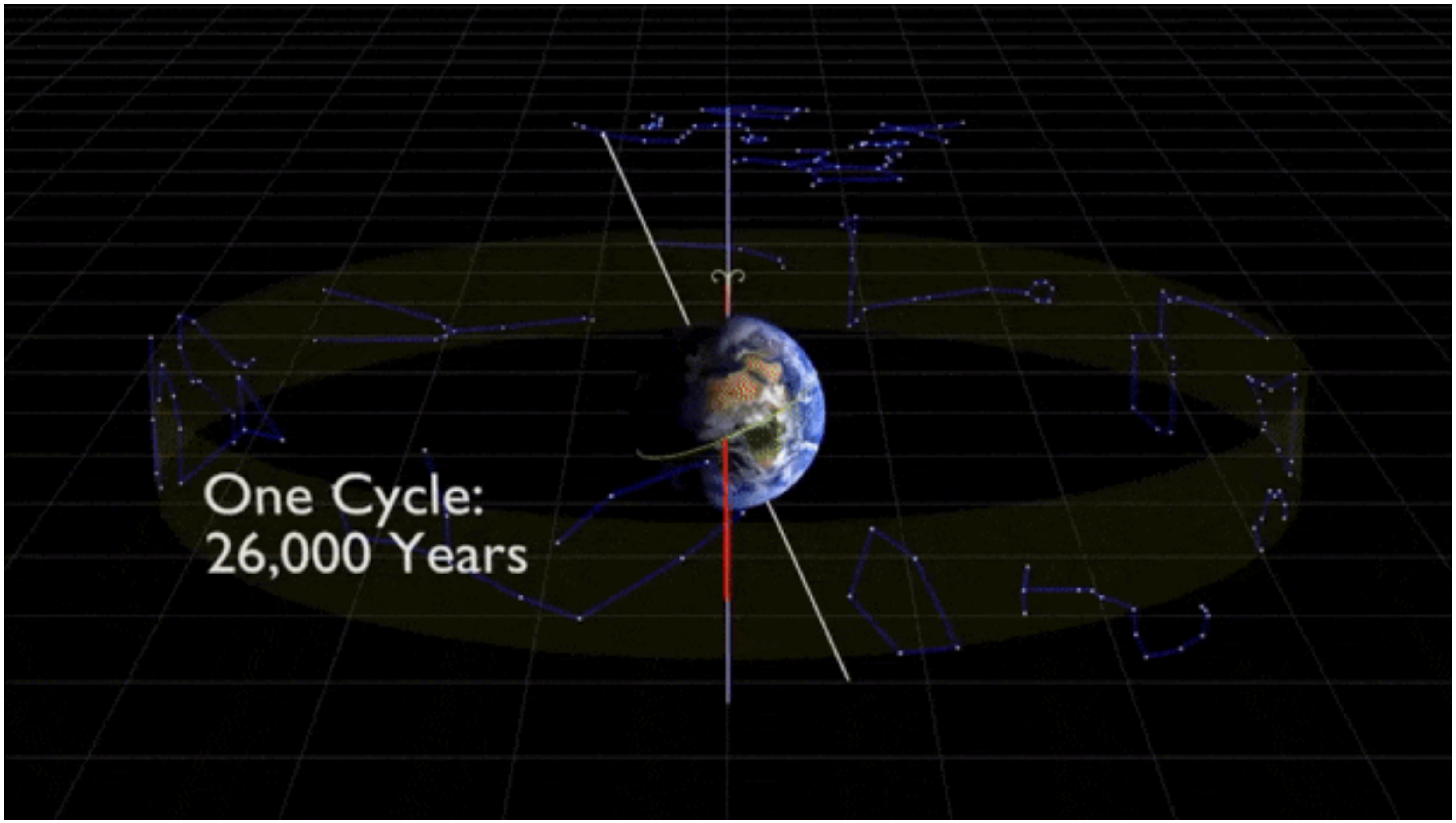


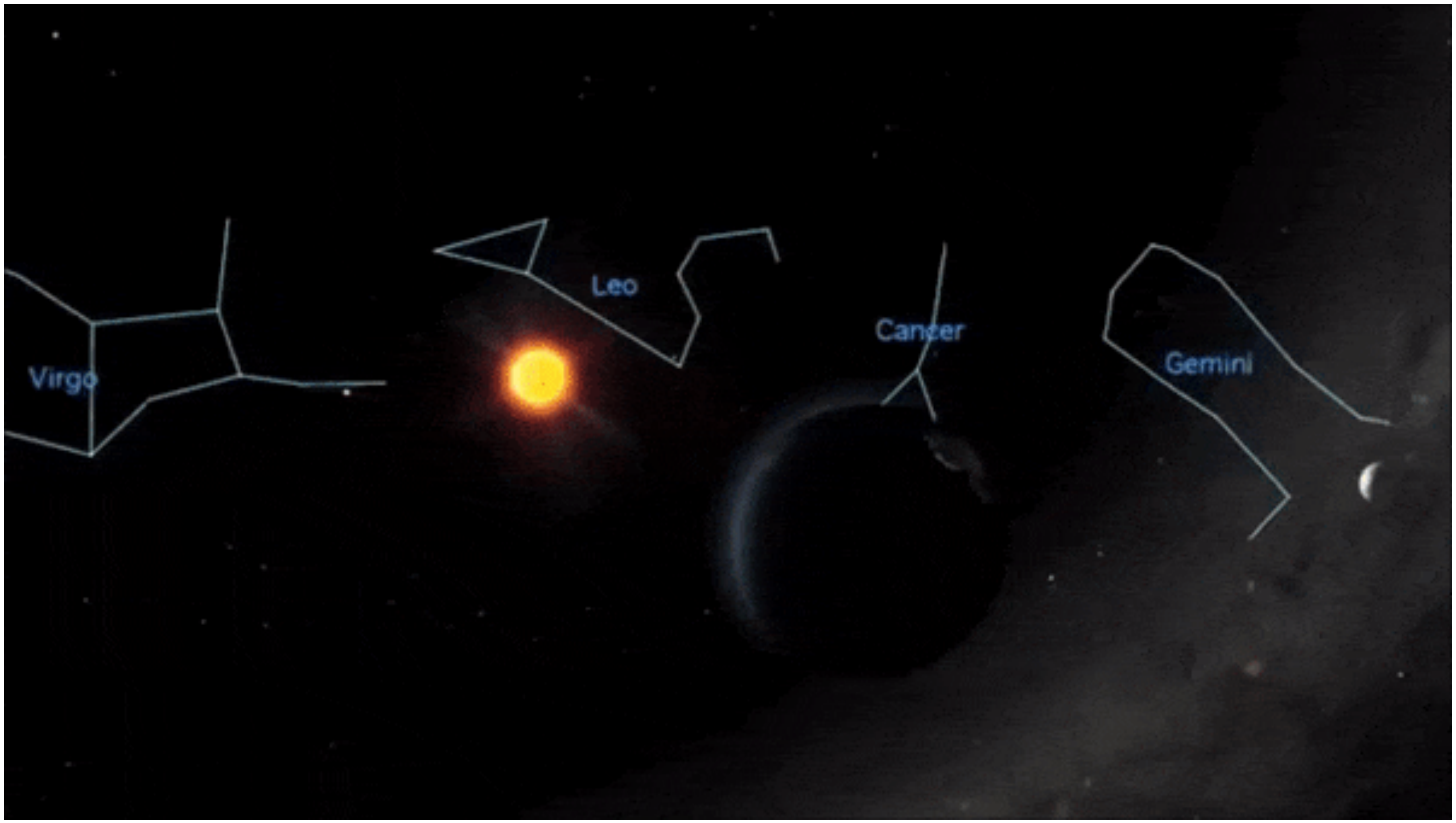
+14000
-10000
+12000
-8000
+10000
-6000
-4000
+8000
-2000
+6000
0
+4000
+2000

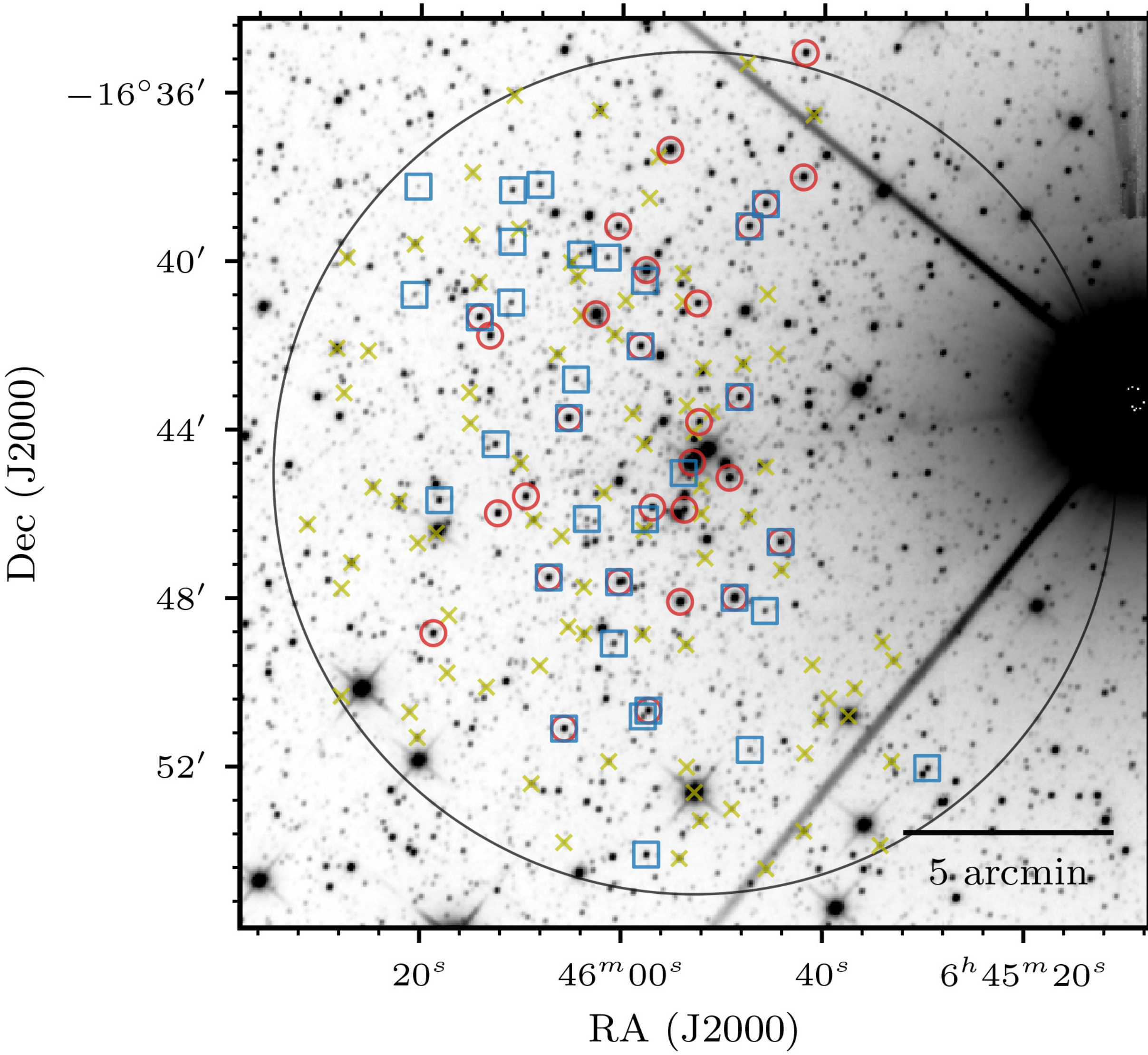

Vega
Denebola
Cor Caroli
Alkaid
Etamin
Mizar
Zenith
Alioth
Thuban
Phad
Regulus
Kochab
Merak
Dubhe
Alderamin
Polaris
Caph
-3000.0


Demeb
Polaris
Vega
Alpha Draconis
North Pole

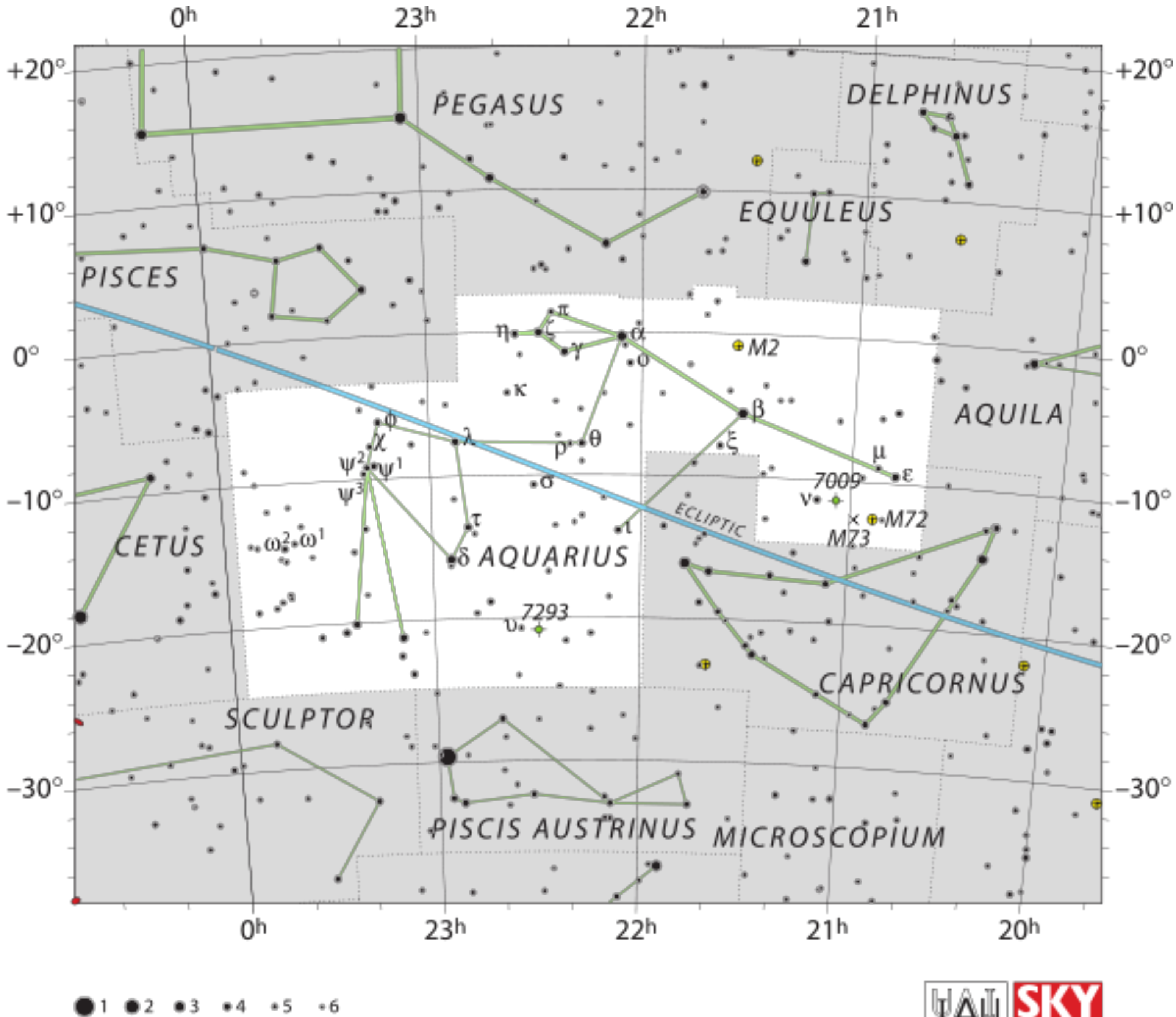

Axis of Rotation
Years ago: Present

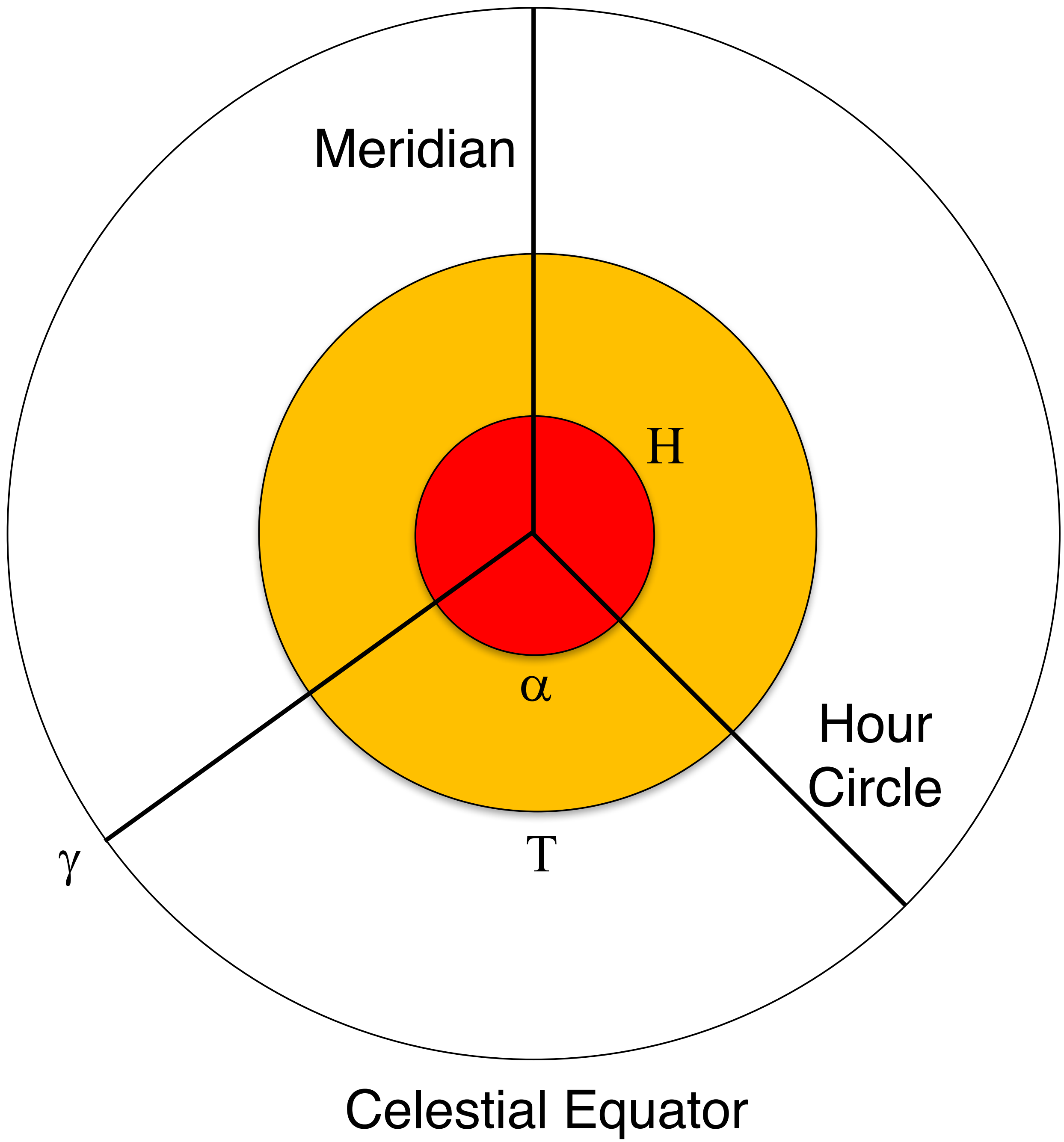

One Cycle:
26,000 Years

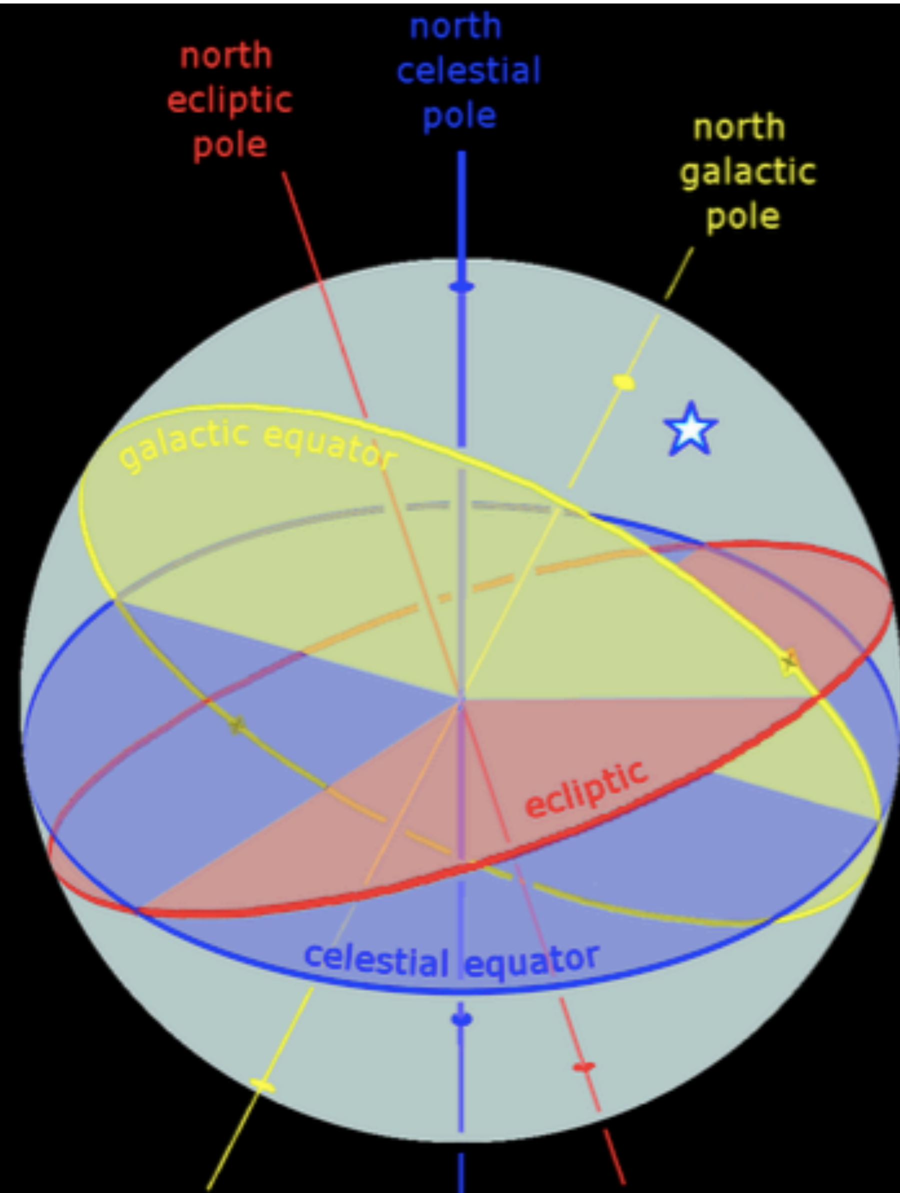

Virgo
Leo
Cancer
Gemini



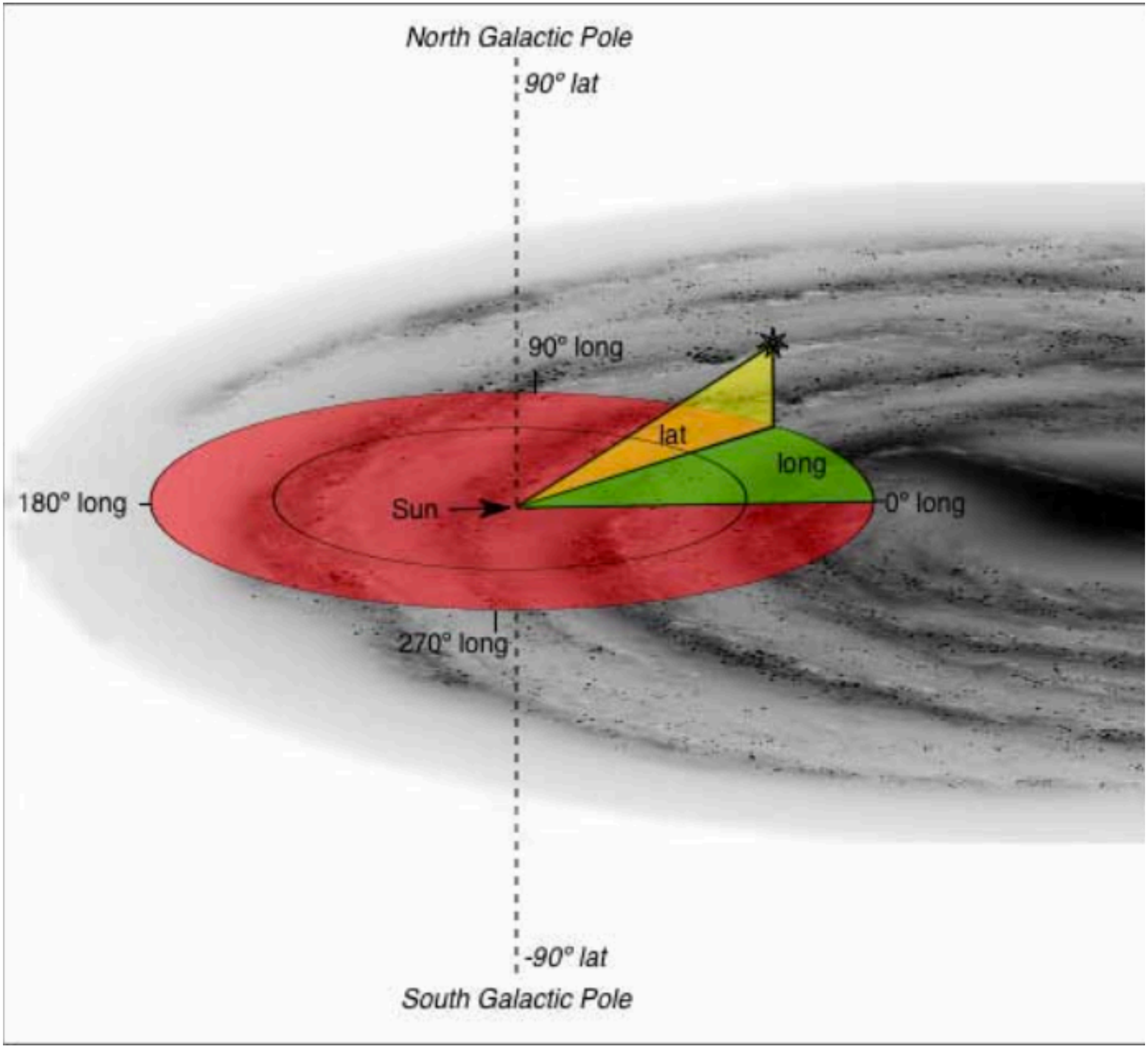
$-16°36'$
$40'$
$44'$
$48'$
$52'$
Dec (J2000)
20^s
46^m00^s
40^s
$6^h45^m20^s$
RA (J2000)
5 arcmin

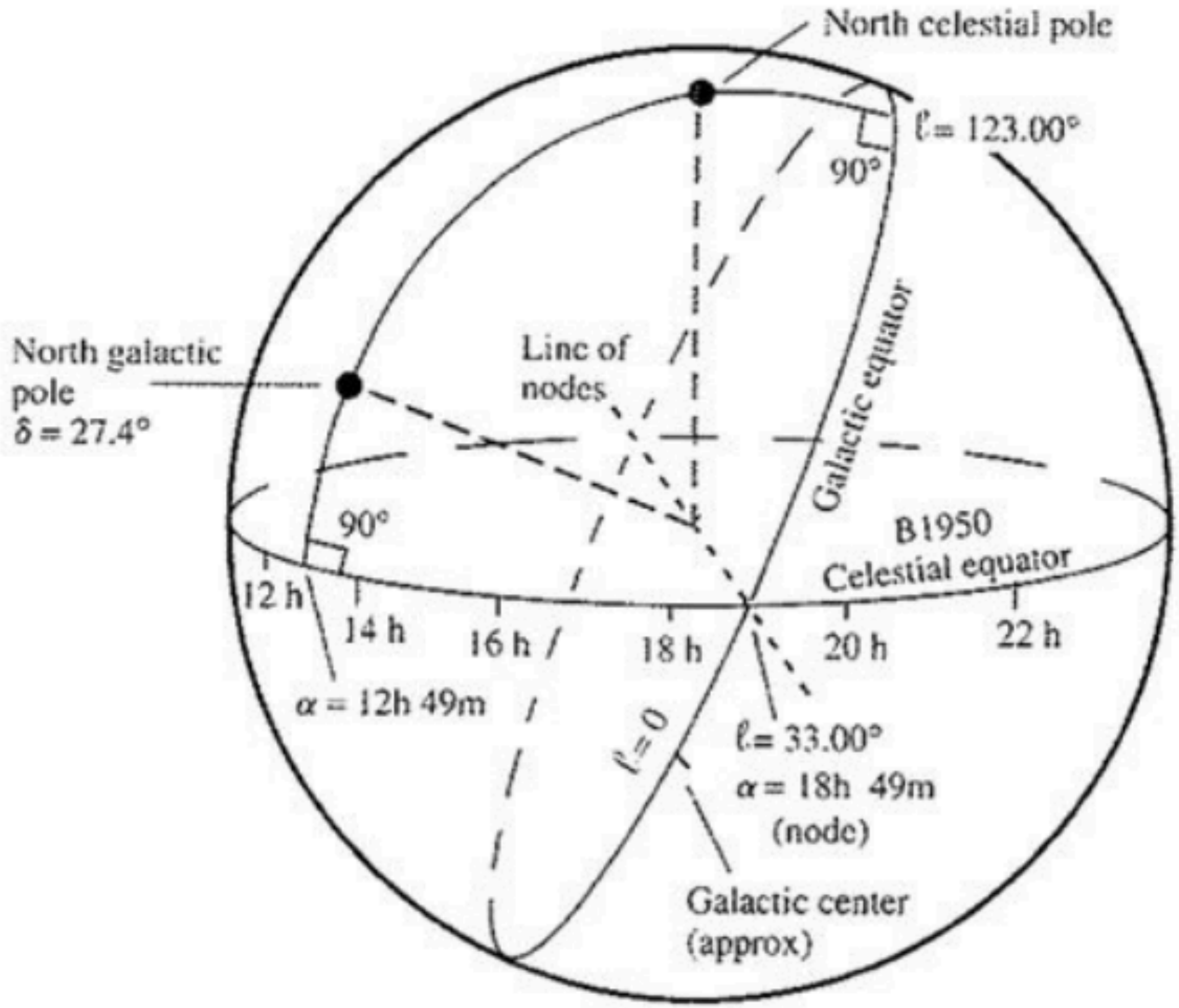

0h 23h 22h 21h
+20° +10° 0° −10° −20° −30°
PEGASUS
DELPHINUS
EQUULEUS
PISCES
AQUILA
CETUS
AQUARIUS
SCULPTOR
CAPRICORNUS
PISCIS AUSTRINUS
MICROSCOPIUM
ECLIPTIC
M2
7009
M72
M73
7293
0h 23h 22h 21h 20h
1 2 3 4 5 6

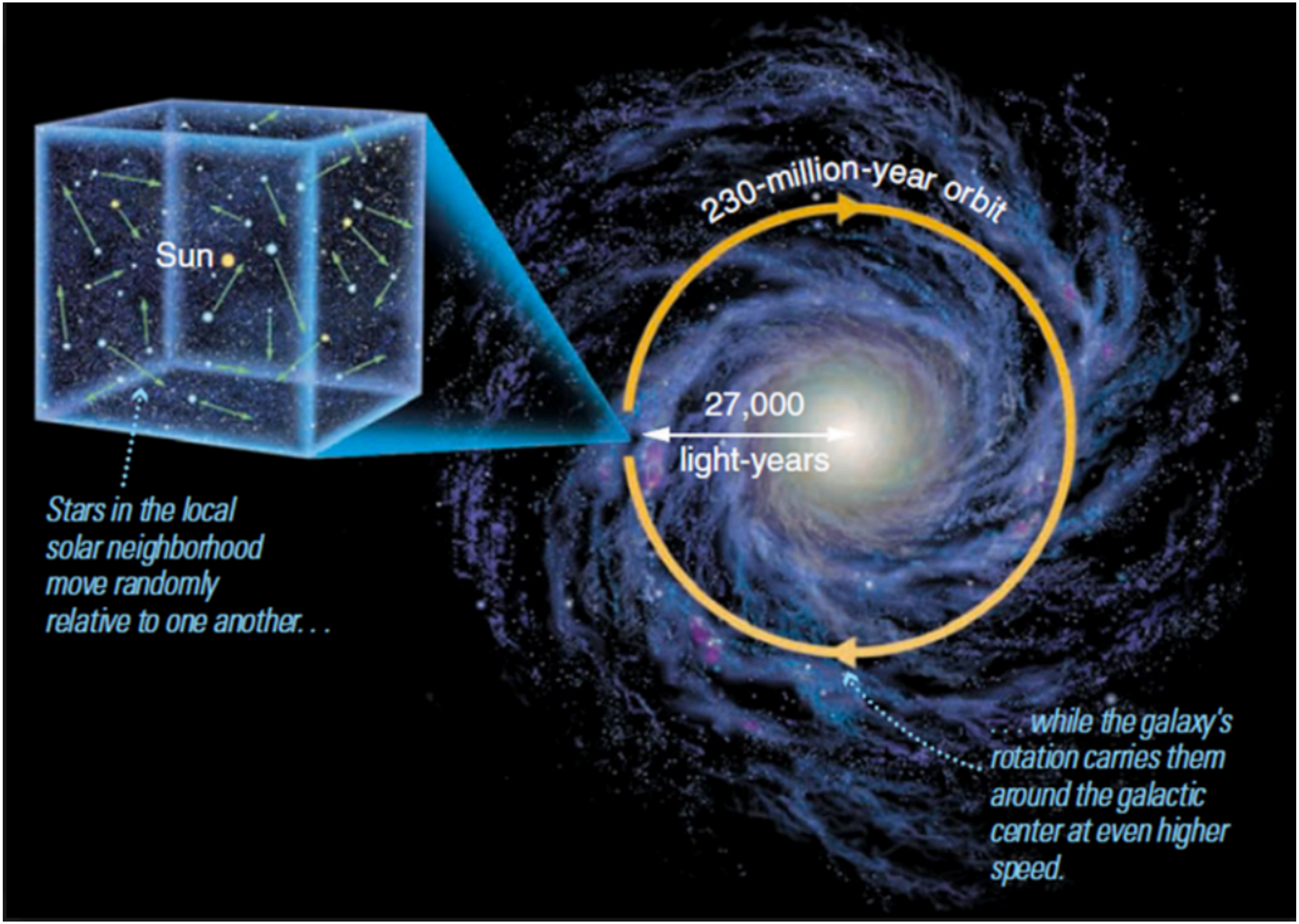

Meridian
H
α
Hour Circle
γ
T
Celestial Equator

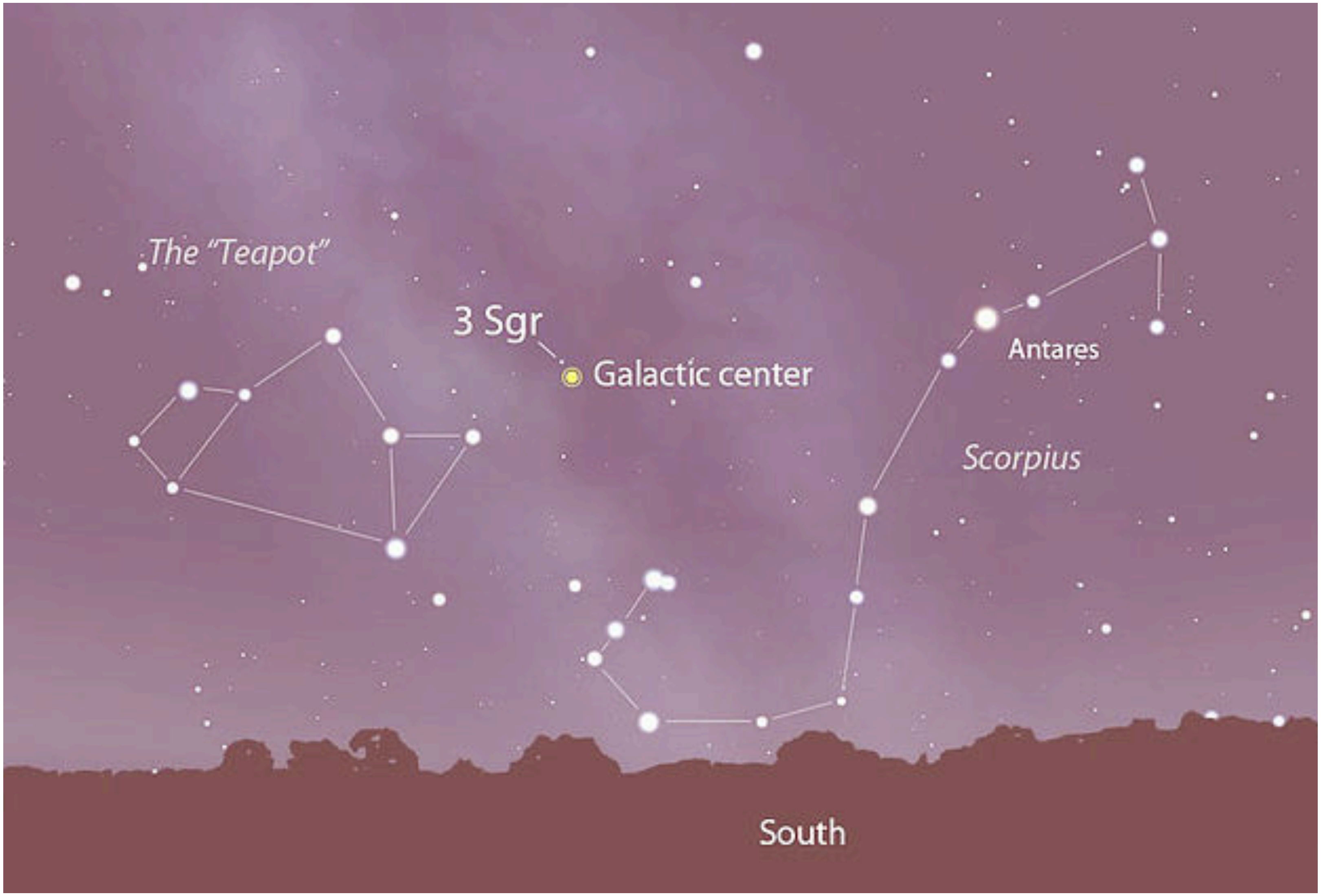


https://commons.wikimedia.org/w/index.php?curid=20028939


North Galactic Pole
90° lat
90° long
lat
long
180° long
Sun
0° long
270° long
-90° lat
South Galactic Pole

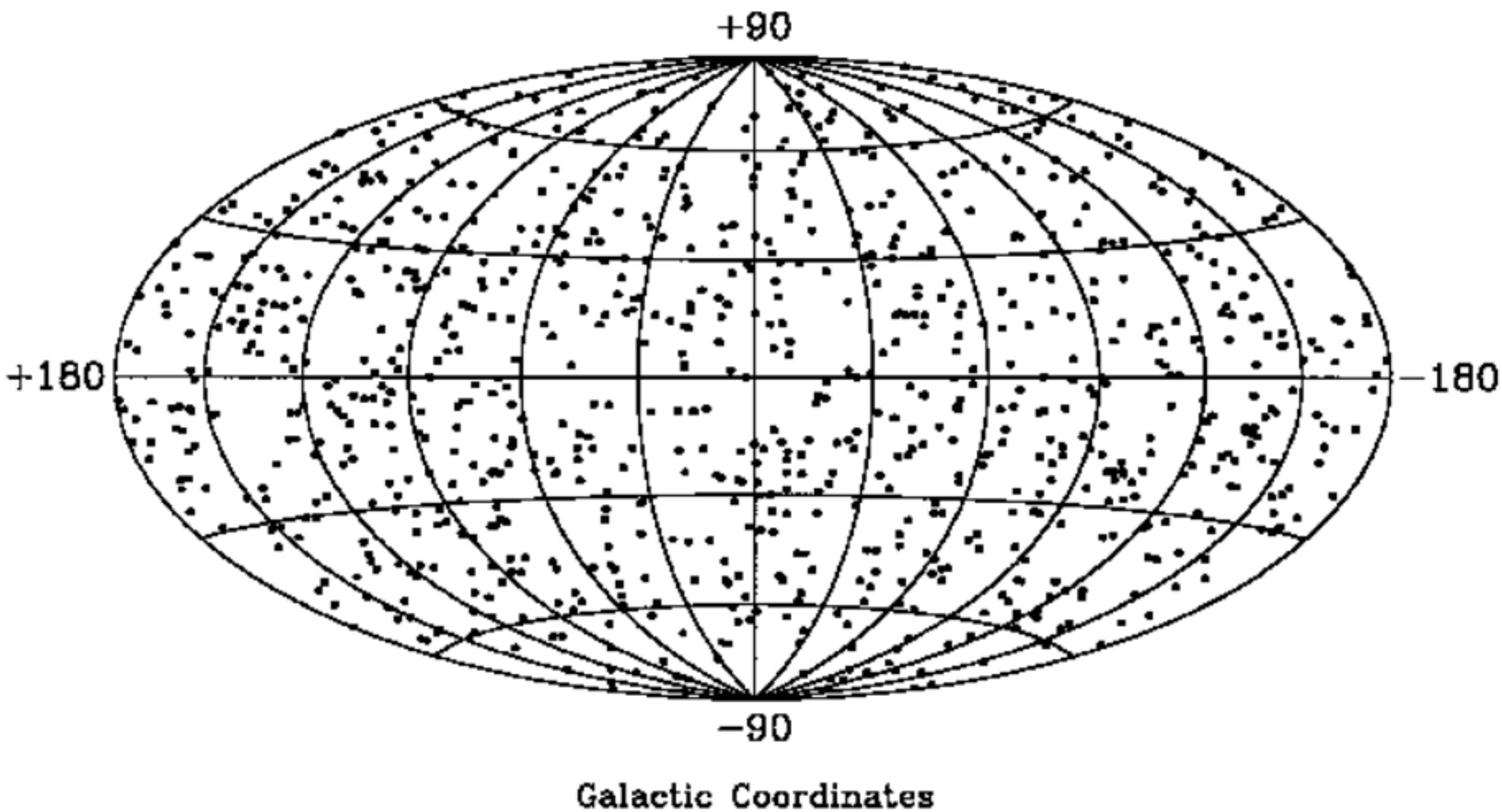

North celestial pole
ℓ = 123.00°
90°
North galactic pole
δ = 27.4°
Line of nodes
Galactic equator
90°
B1950
Celestial equator
12 h
14 h
16 h
18 h
20 h
22 h
α = 12h 49m
ℓ = 0
ℓ = 33.00°
α = 18h 49m
(node)
Galactic center
(approx)

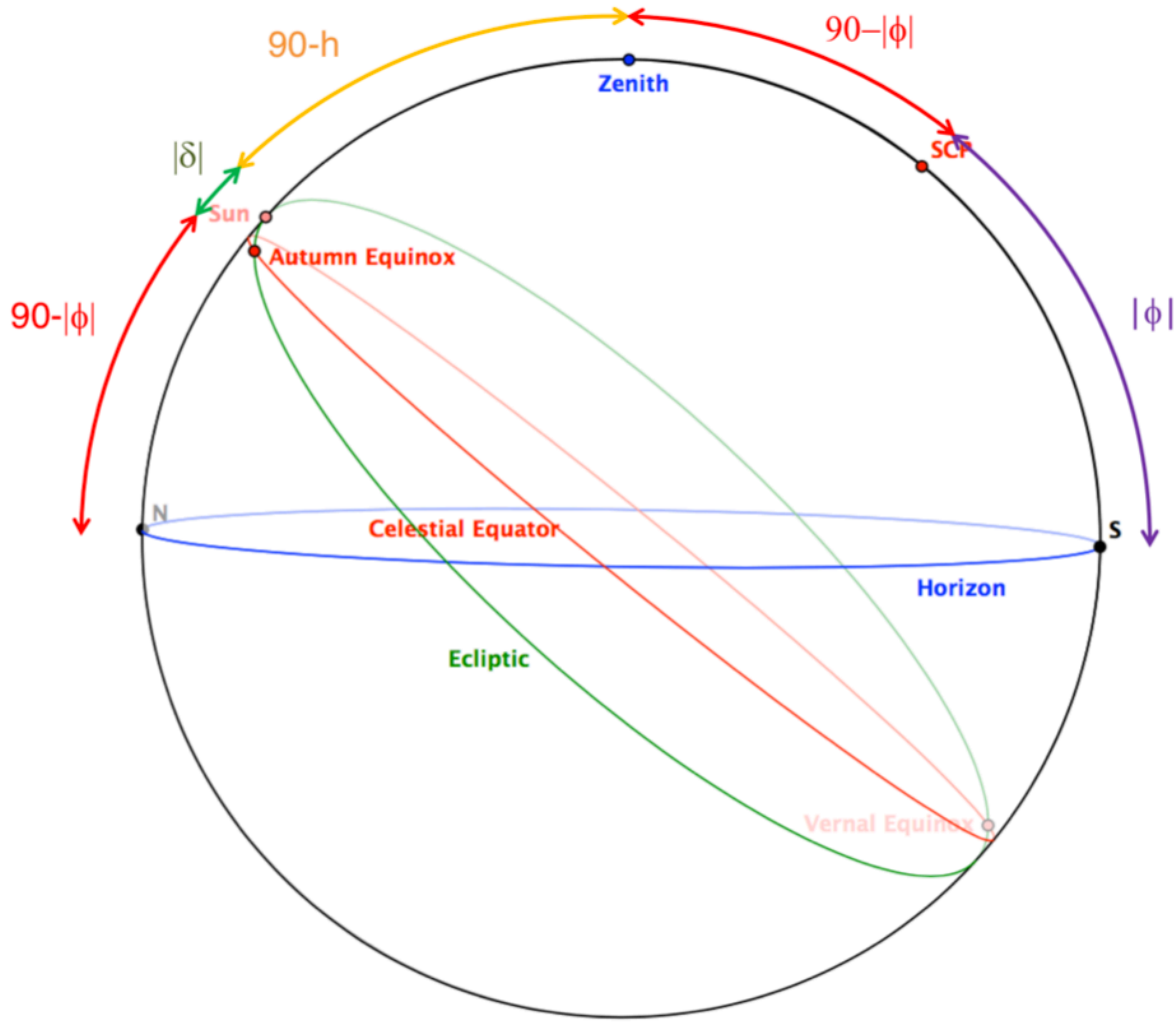

230-million-year orbit
Sun
27,000
light-years
Stars in the local solar neighborhood move randomly relative to one another. . .
. . . while the galaxy's rotation carries them around the galactic center at even higher speed.



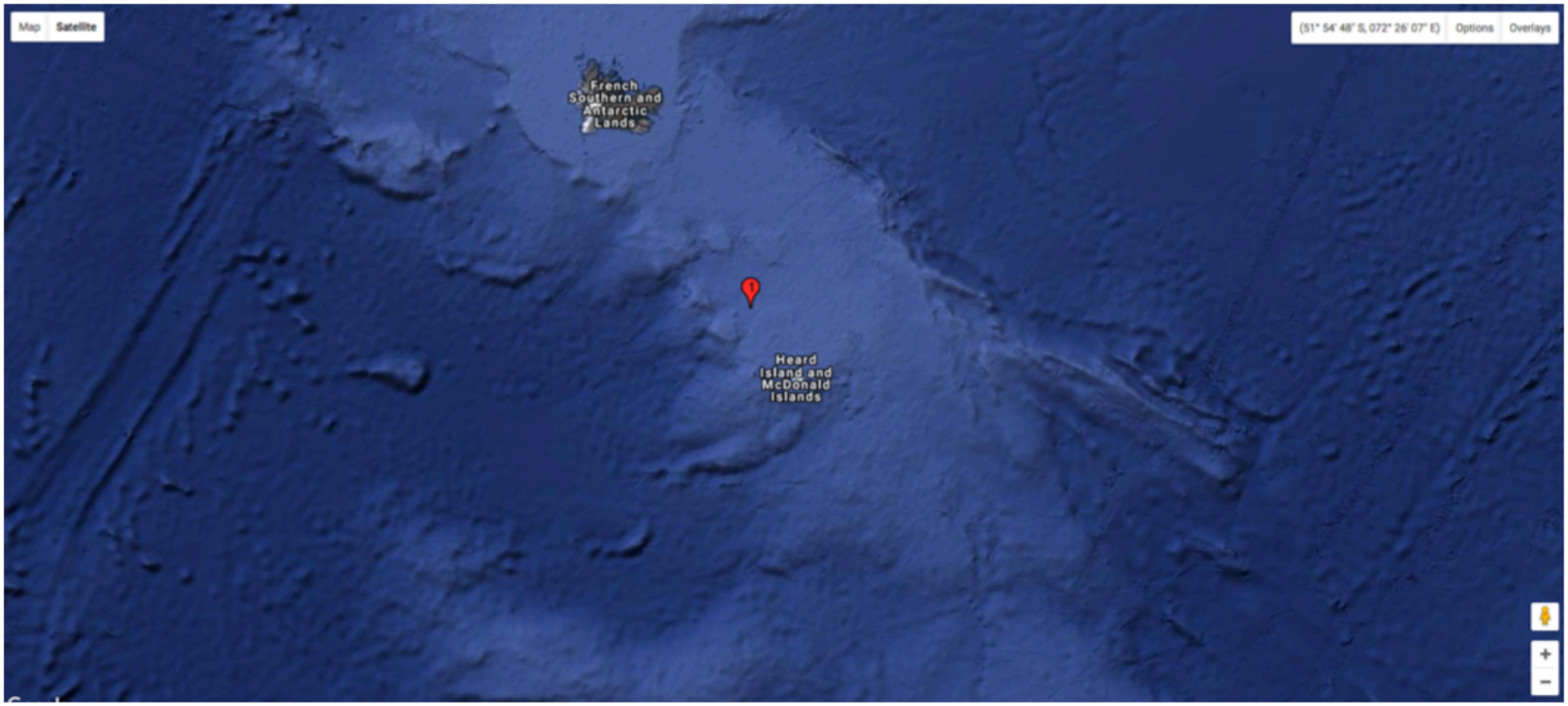
The "Teapot"
3 Sgr
Galactic center
Antares
Scorpius
South

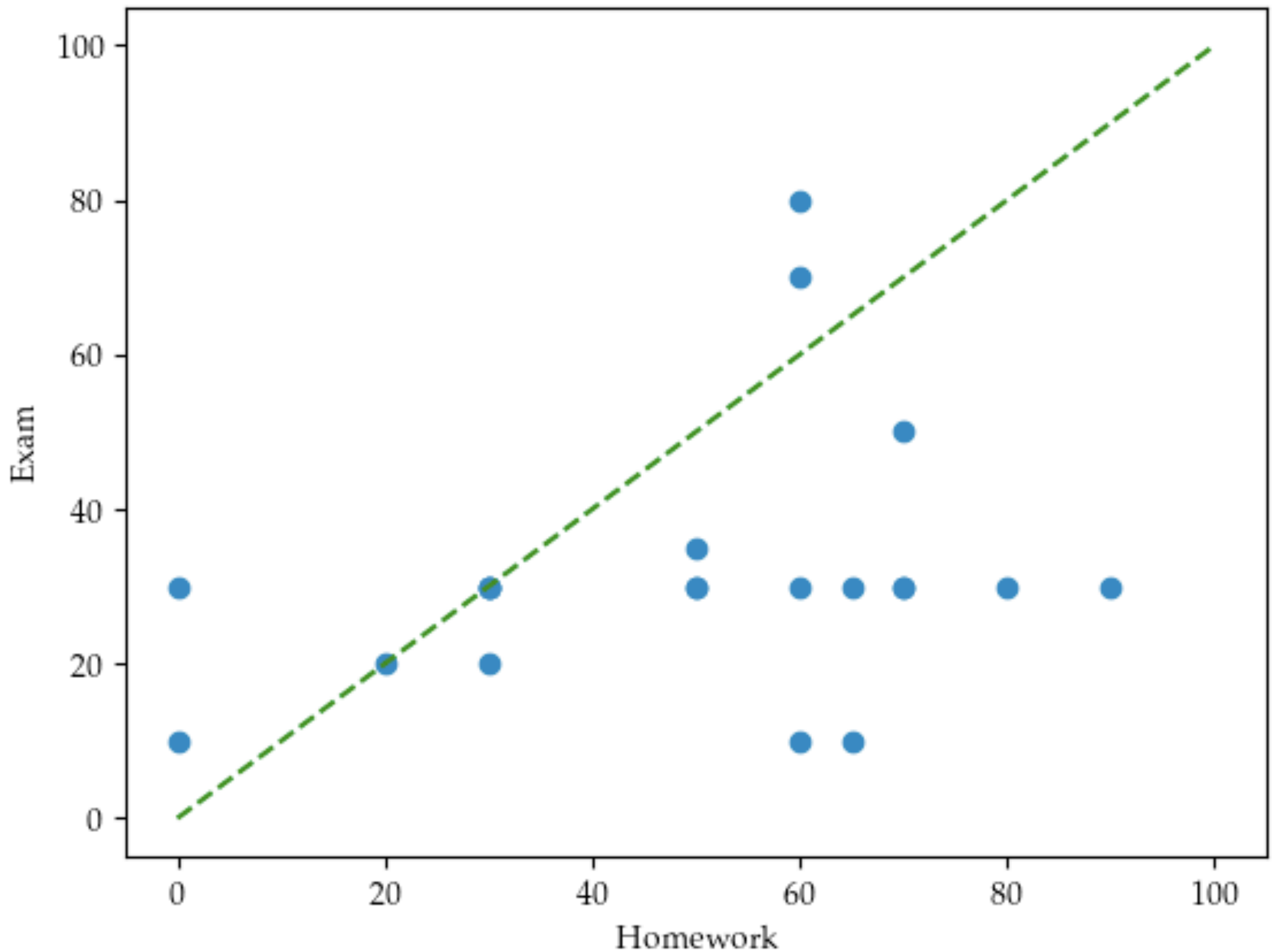
921 BATSE Gamma-Ray Bursts

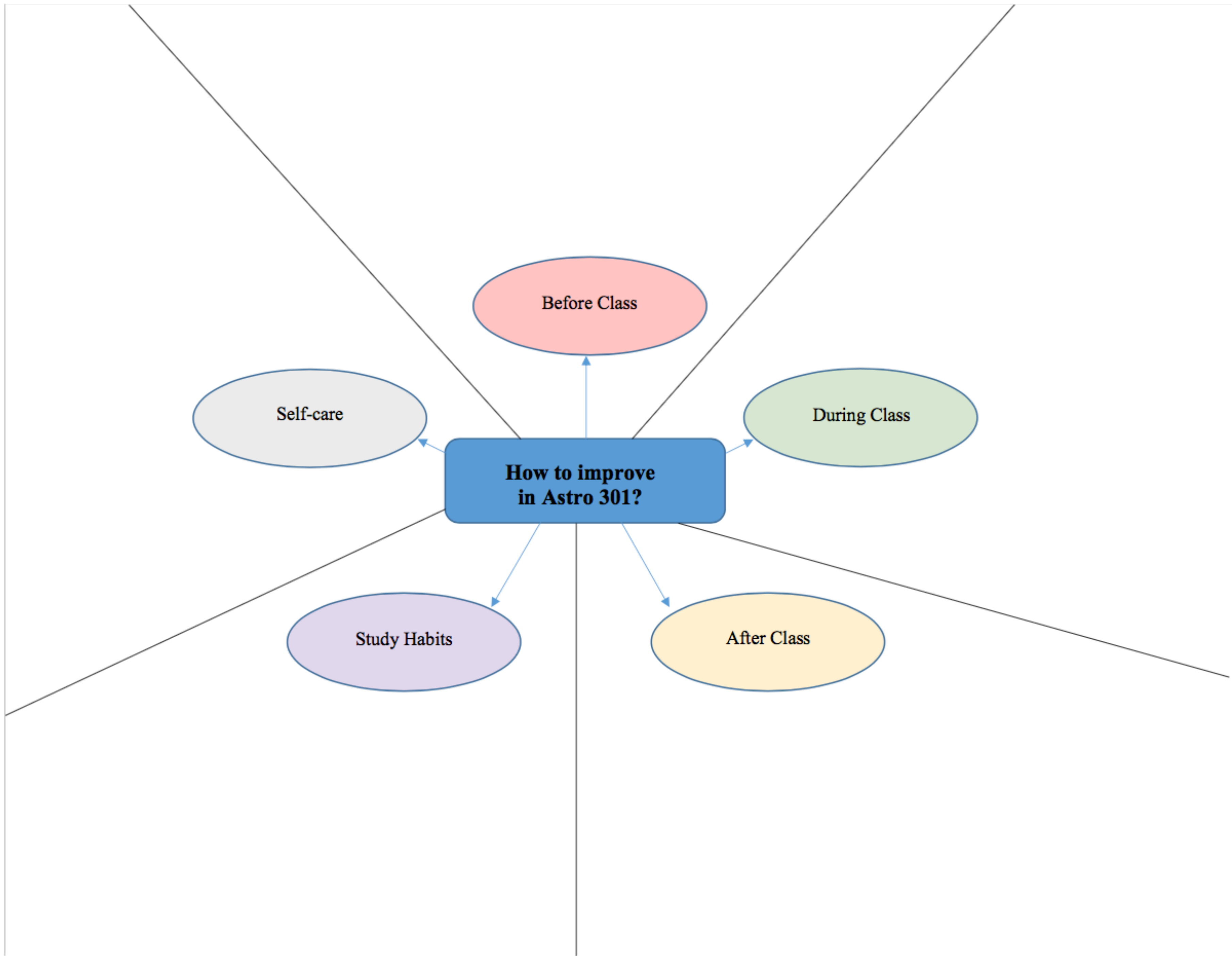


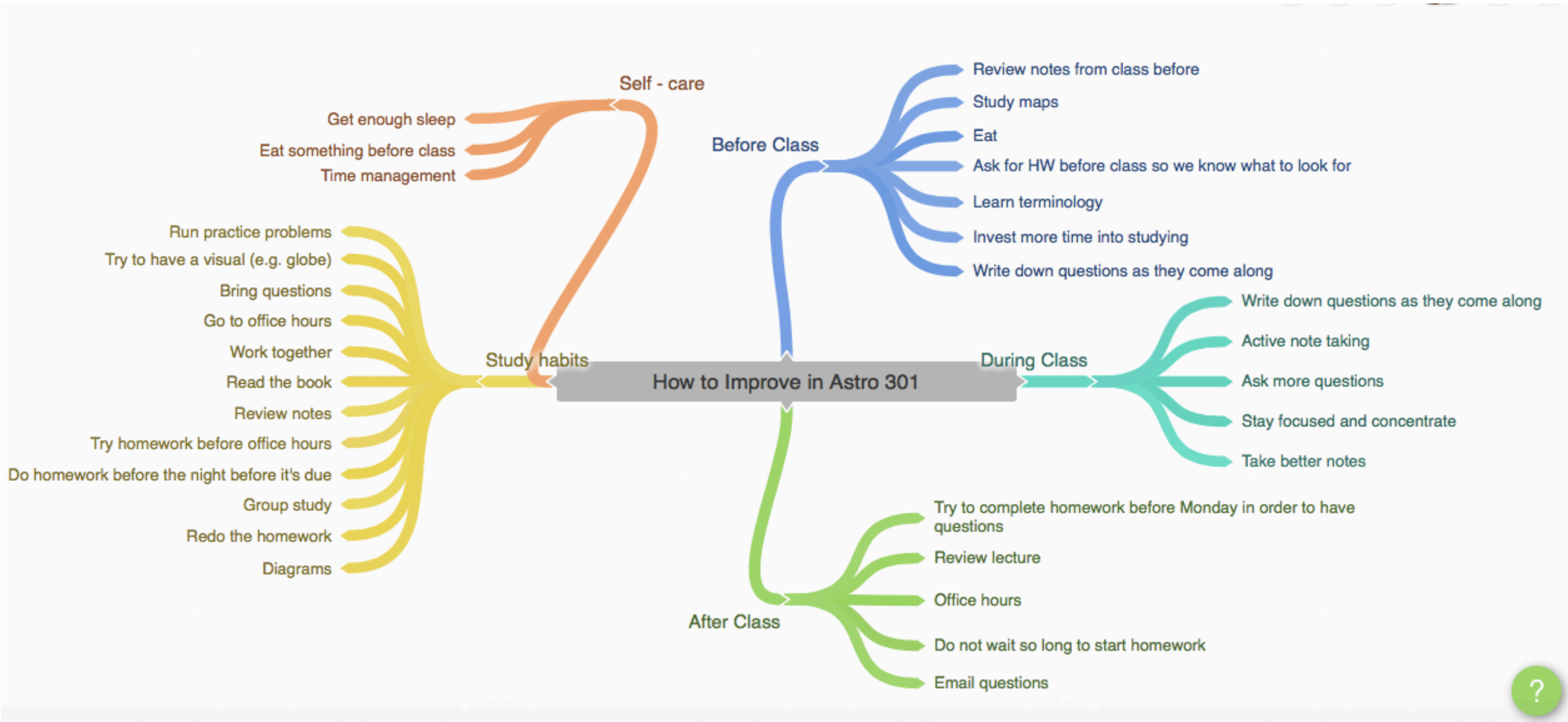


90-h
90–|ϕ|
Zenith
|δ|
SCP
Sun
Autumn Equinox
90-|ϕ|
|ϕ|
N
Celestial Equator
S
Horizon
Ecliptic
Vernal Equinox

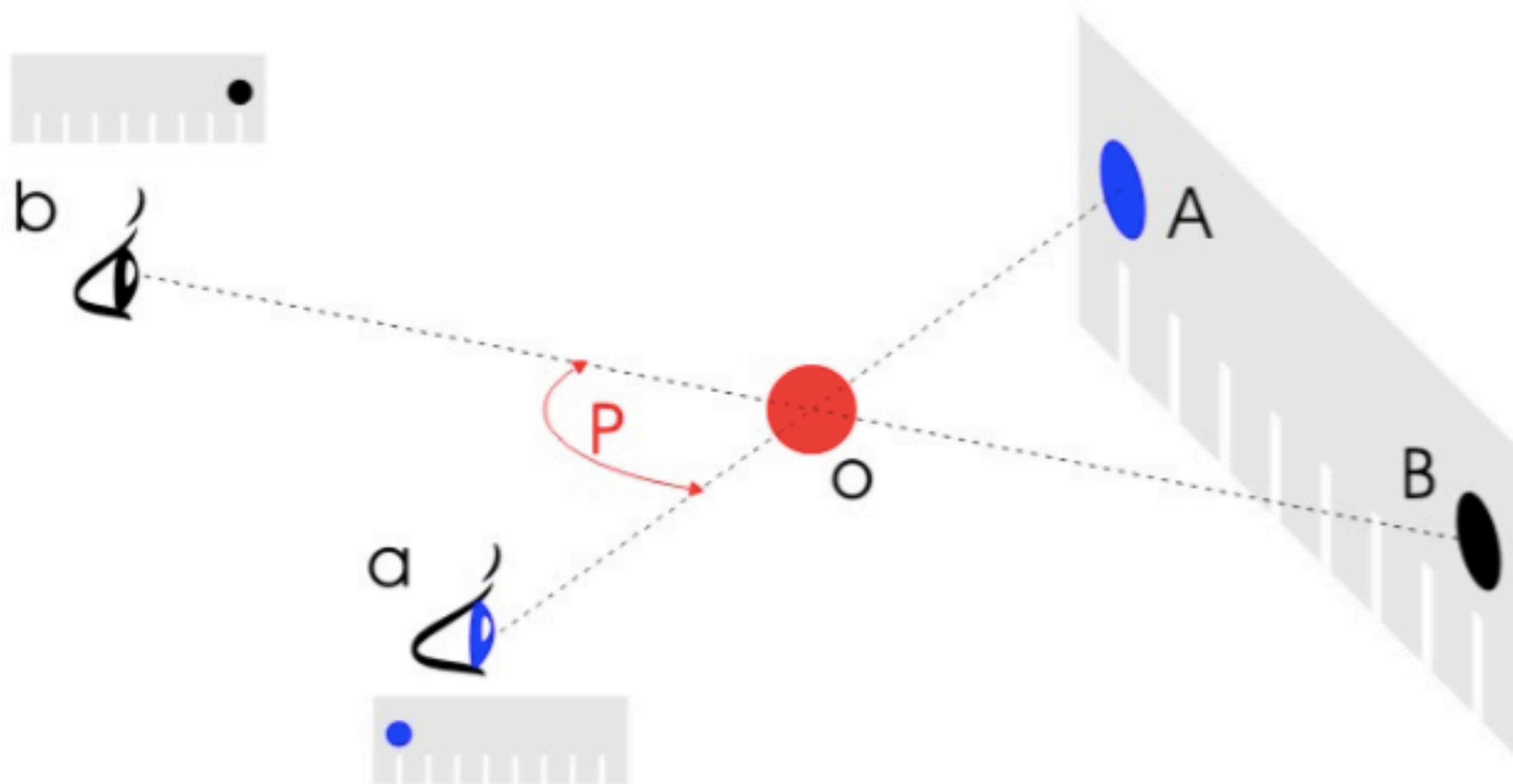

Map
Satellite
(51° 54' 48" S, 072° 26' 07" E)
Options
Overlays
French Southern and Antarctic Lands
1
Heard Island and McDonald Islands
+
−


100
80
60
40
20
0
Exam
0
20
40
60
80
100
Homework

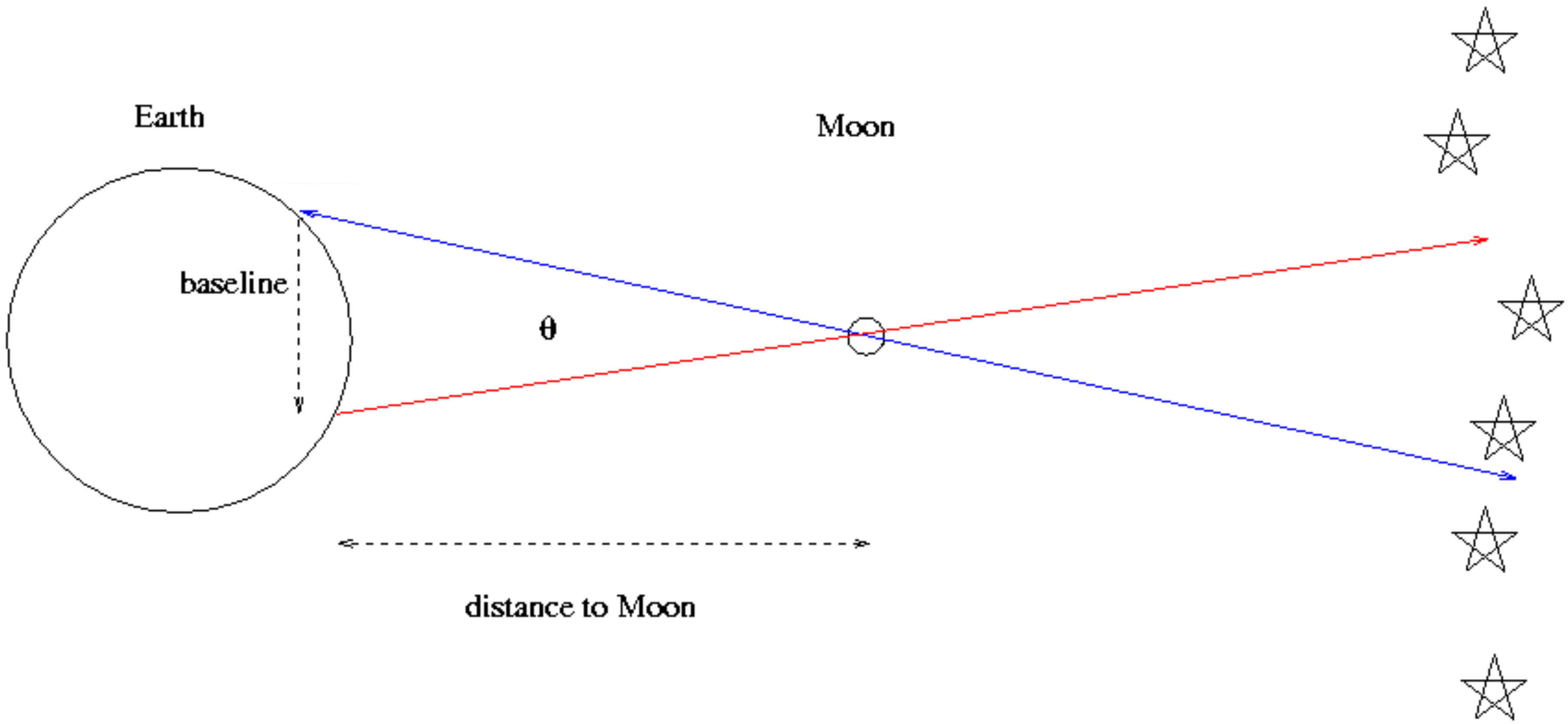

Before Class
Self-care
During Class
How to improve
in Astro 301?
Study Habits
After Class


How to Improve in Astro 301
Self - care
Get enough sleep
Eat something before class
Time management
Study habits
Run practice problems
Try to have a visual (e.g. globe)
Bring questions
Go to office hours
Work together
Read the book
Review notes
Try homework before office hours
Do homework before the night before it's due
Group study
Redo the homework
Diagrams
Before Class
Review notes from class before
Study maps
Eat
Ask for HW before class so we know what to look for
Learn terminology
Invest more time into studying
Write down questions as they come along
During Class
Write down questions as they come along
Active note taking
Ask more questions
Stay focused and concentrate
Take better notes
After Class
Try to complete homework before Monday in order to have questions
Review lecture
Office hours
Do not wait so long to start homework
Email questions

Parallax



Motion Parallax


Earth
Moon
baseline
θ
distance to Moon

Lunar Parallax

Lunar Parallax Demonstration Project - Update 2004 October 28

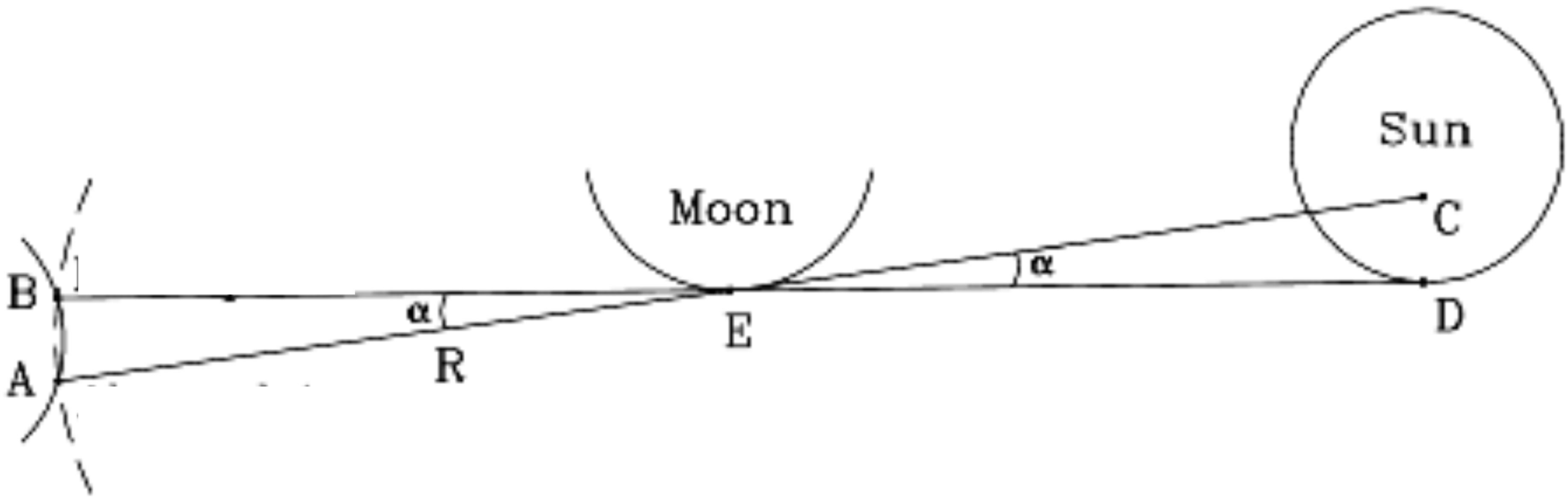
http://www.DigitalSky.org.uk/lunar_parallax.html

Upper Moon - Gerardo Addiego
Lower-left-hand Moon - Pete Cleary
Background stars, lower-right-hand Moon and image composition - Pete Lawrence

Pete Lawrence, Selsey, UK

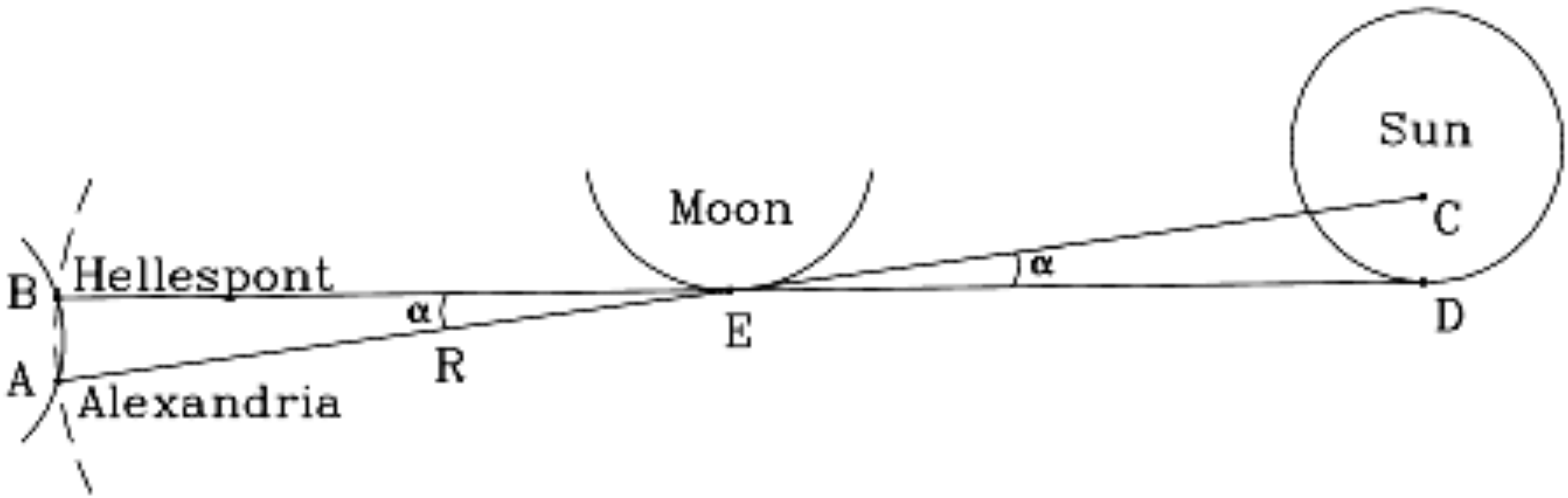
Location A

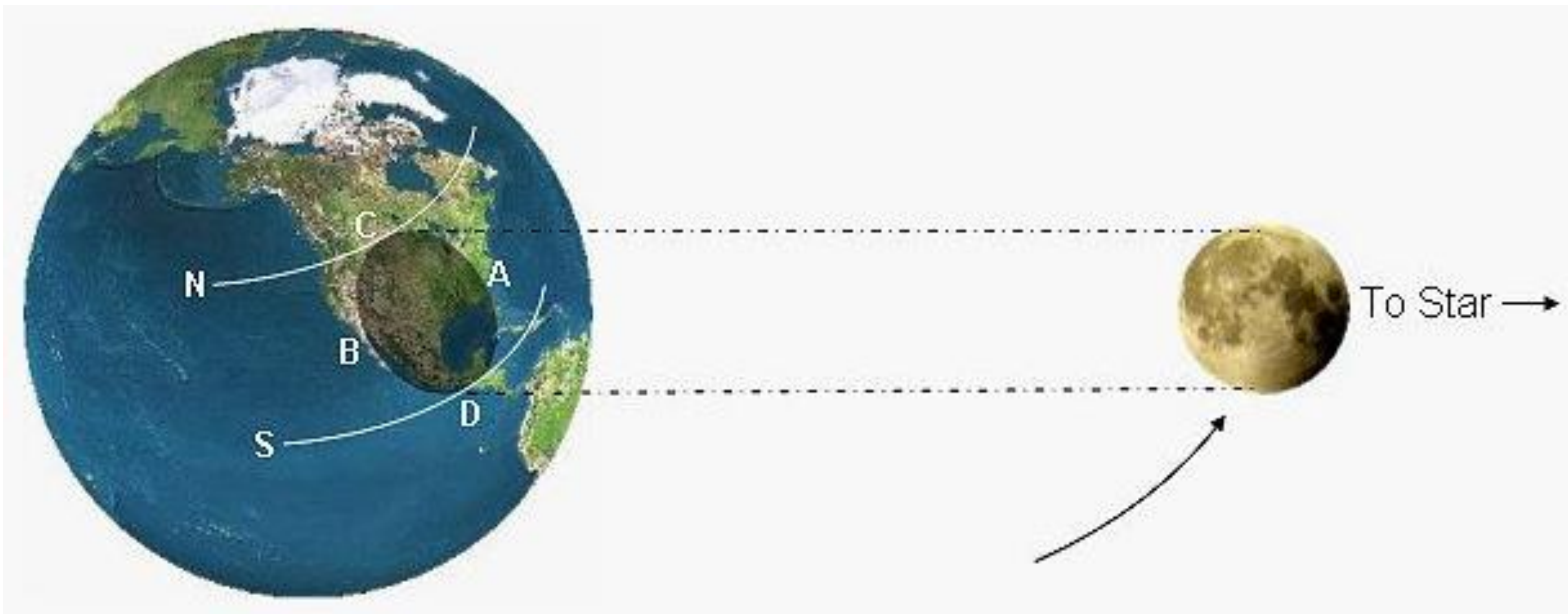
Location B



Location A

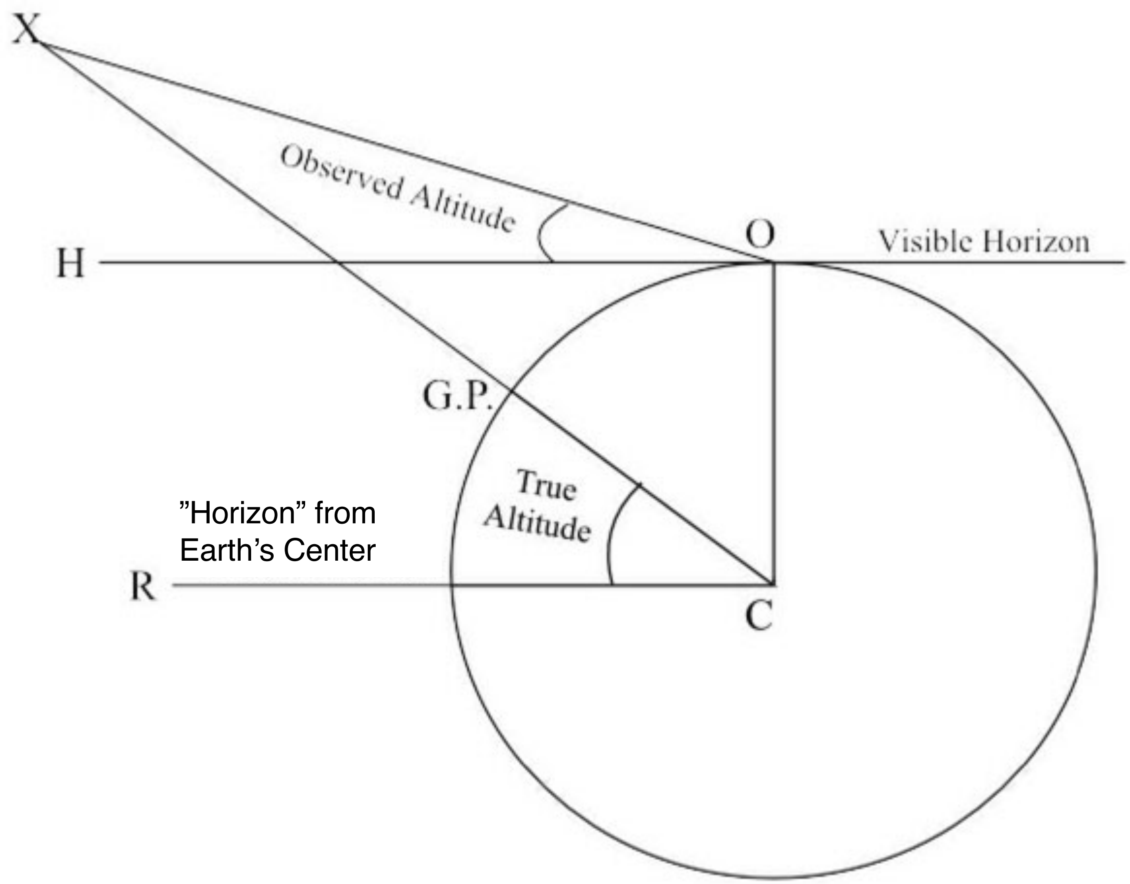
Location B



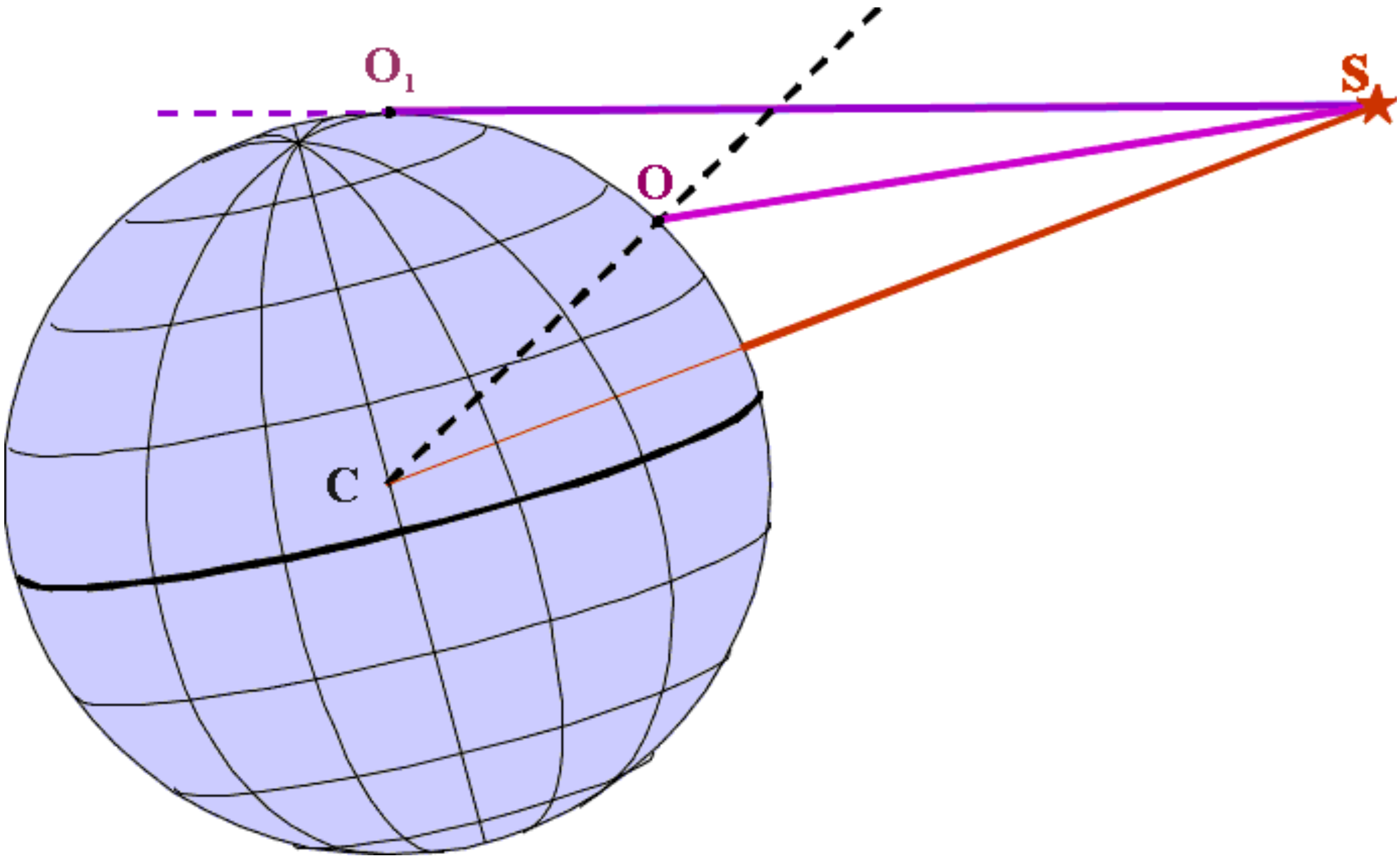


C
N
A
B
D
S
To Star

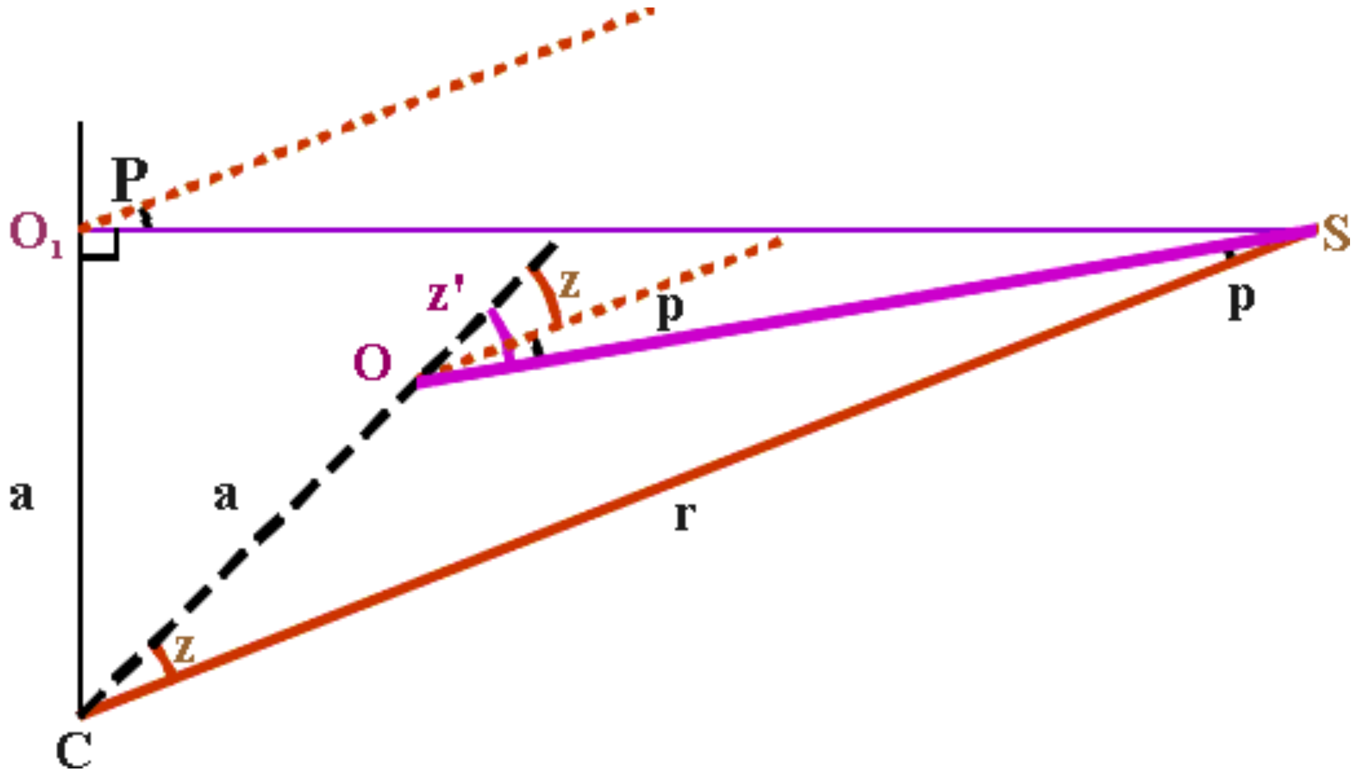
Geocentric Parallax

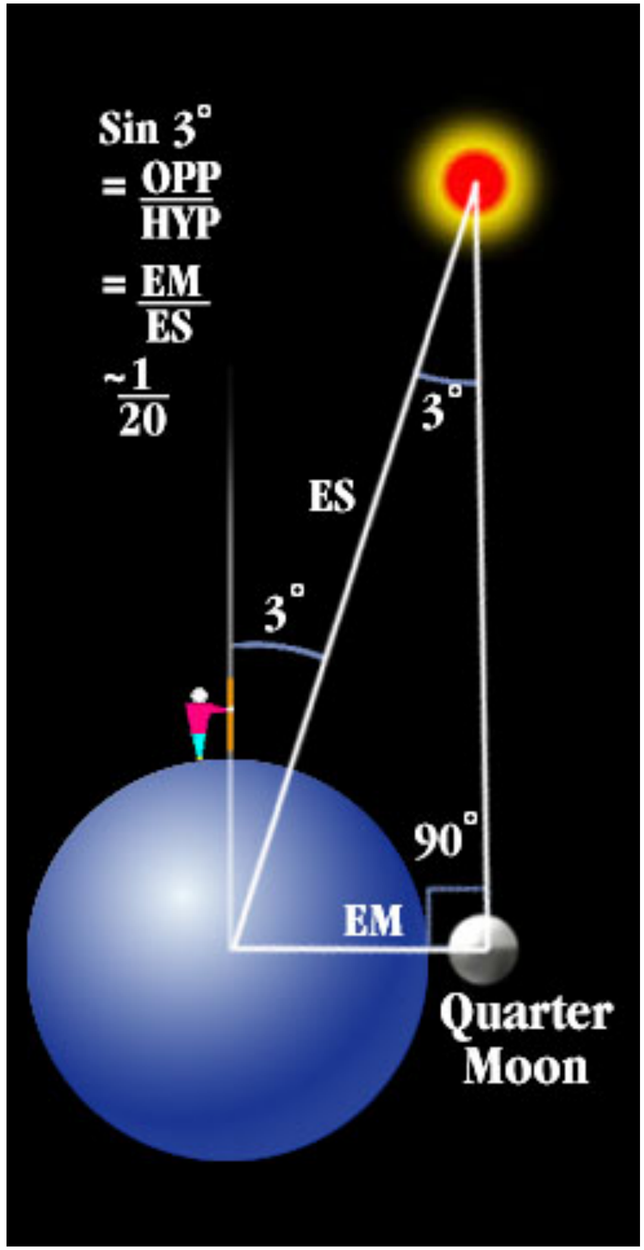


Geocentric Parallax



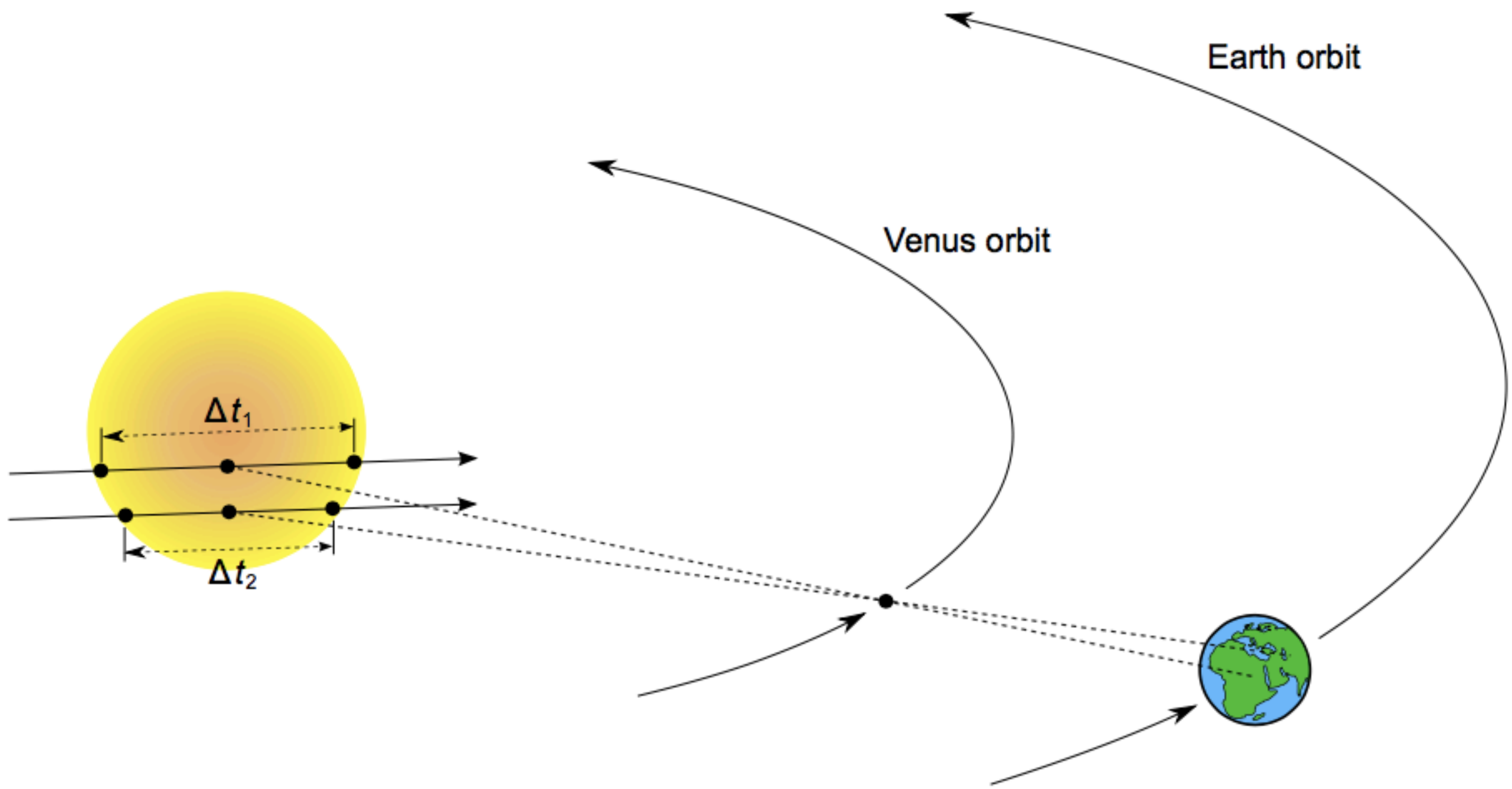
Geocentric Parallax





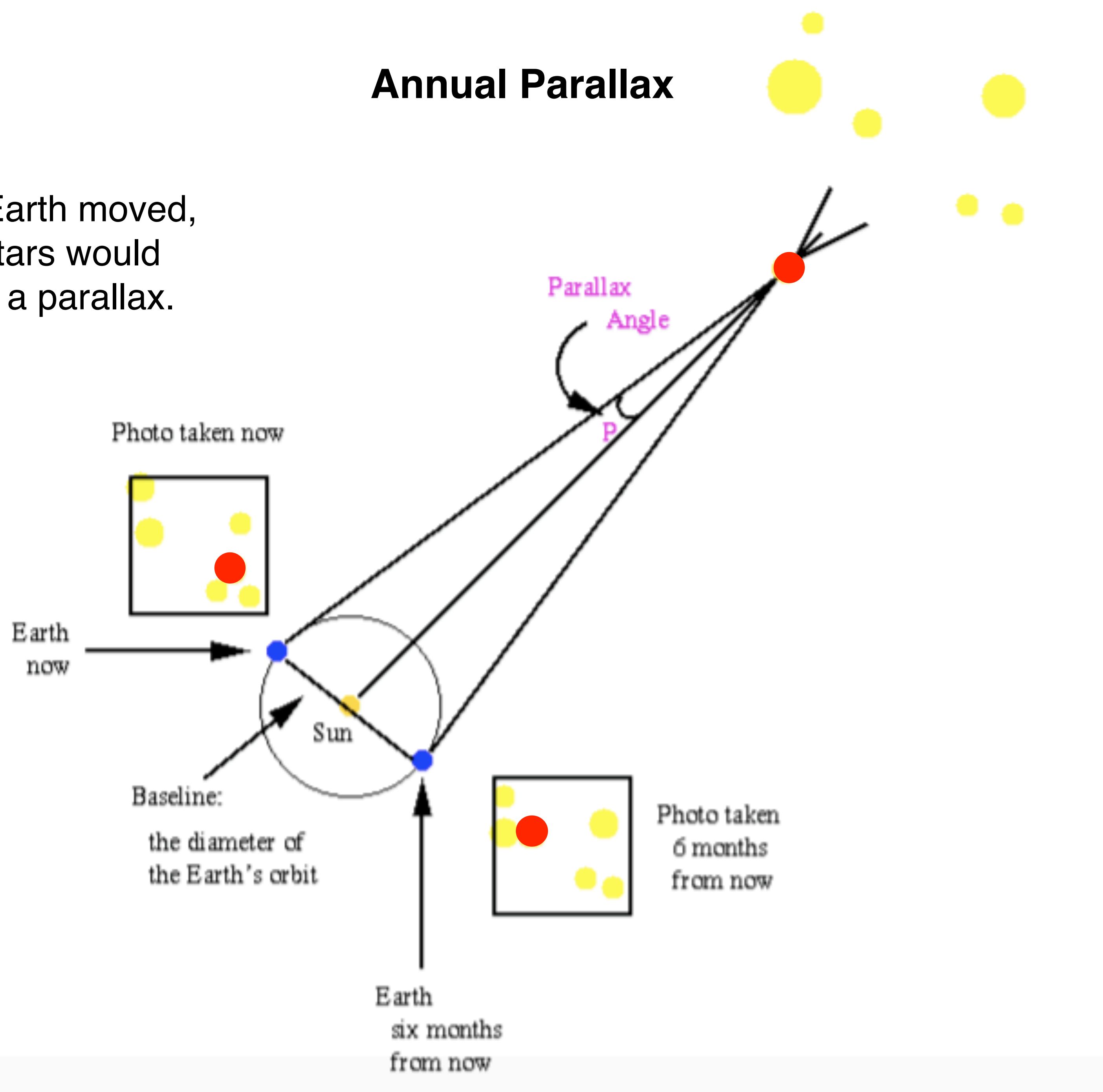
Sin 3°
= OPP/HYP
= EM/ES
~1/20
3°
ES
3°
90°
EM
Quarter Moon

Distance to the Sun

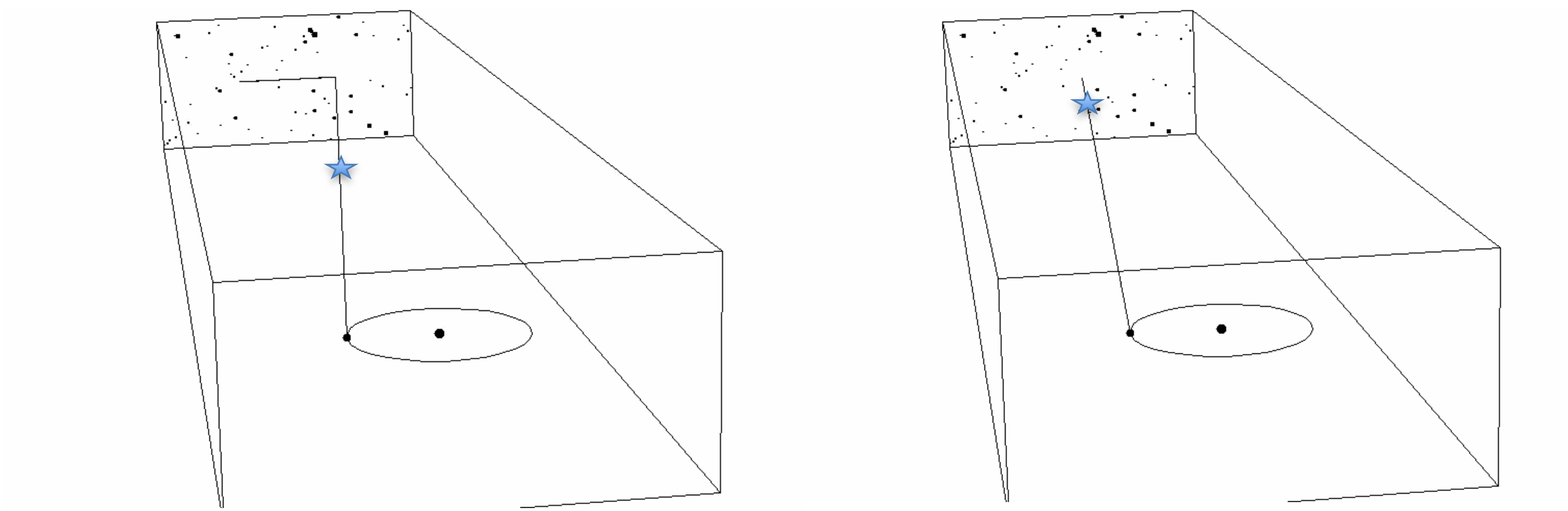


Annual Parallax

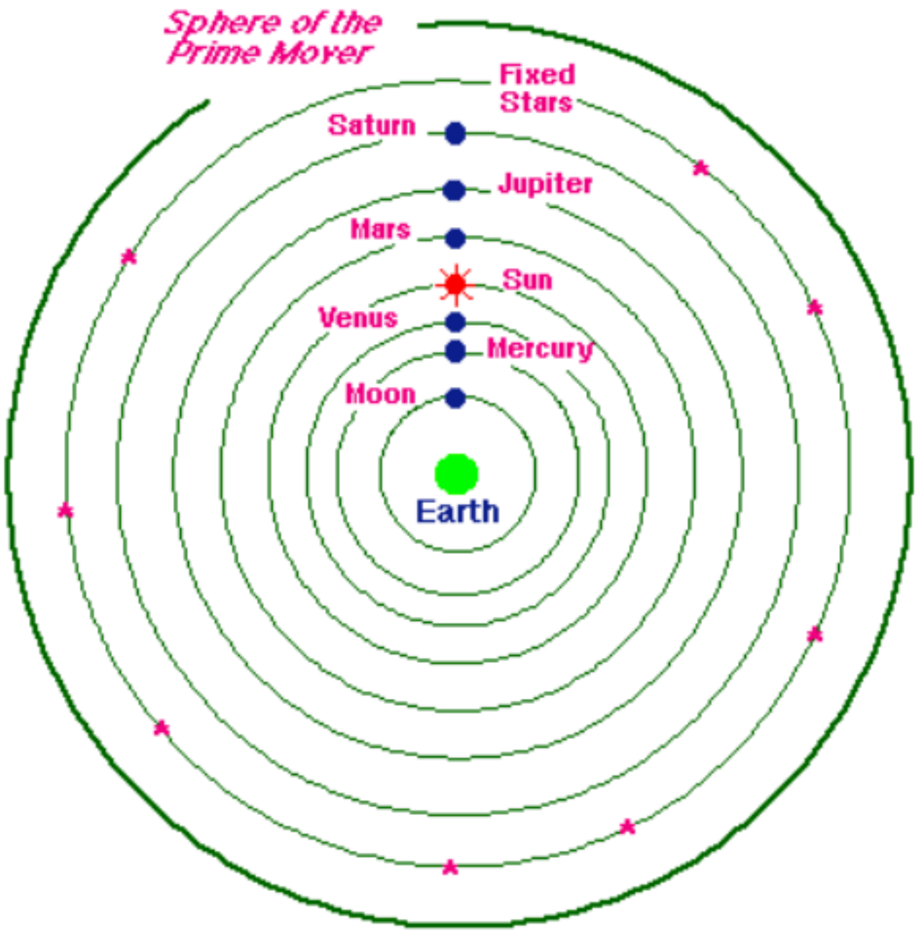
If the Earth moved,
the stars would
show a parallax.



Annual Parallax



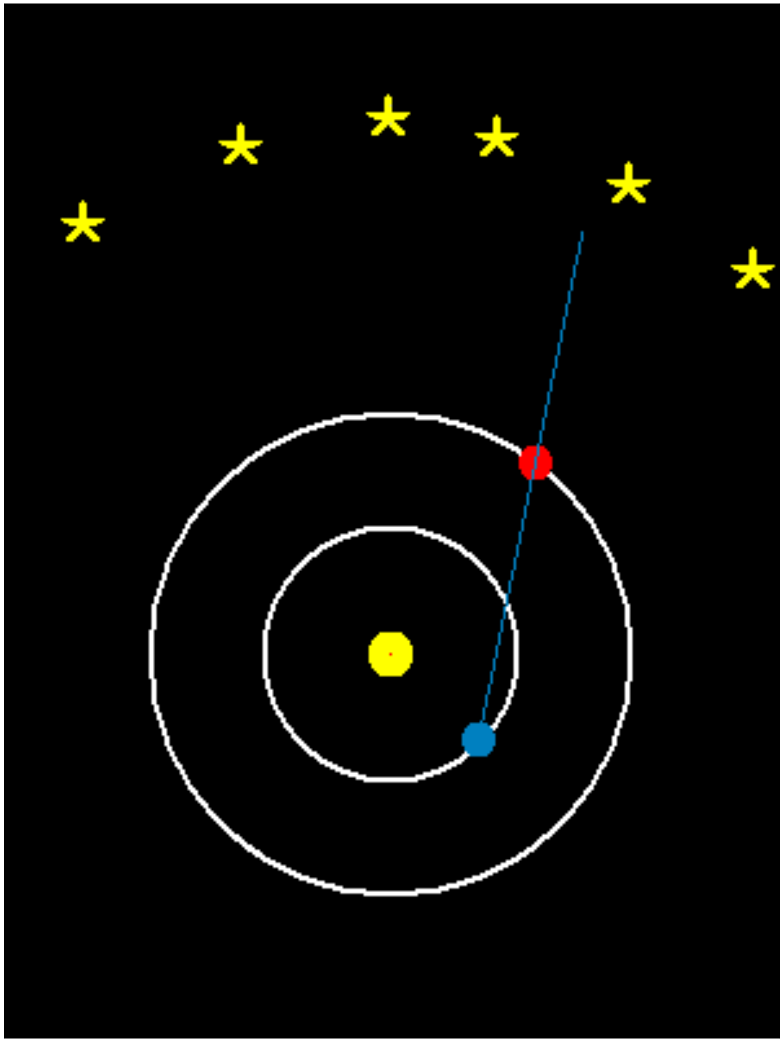
Geocentrism

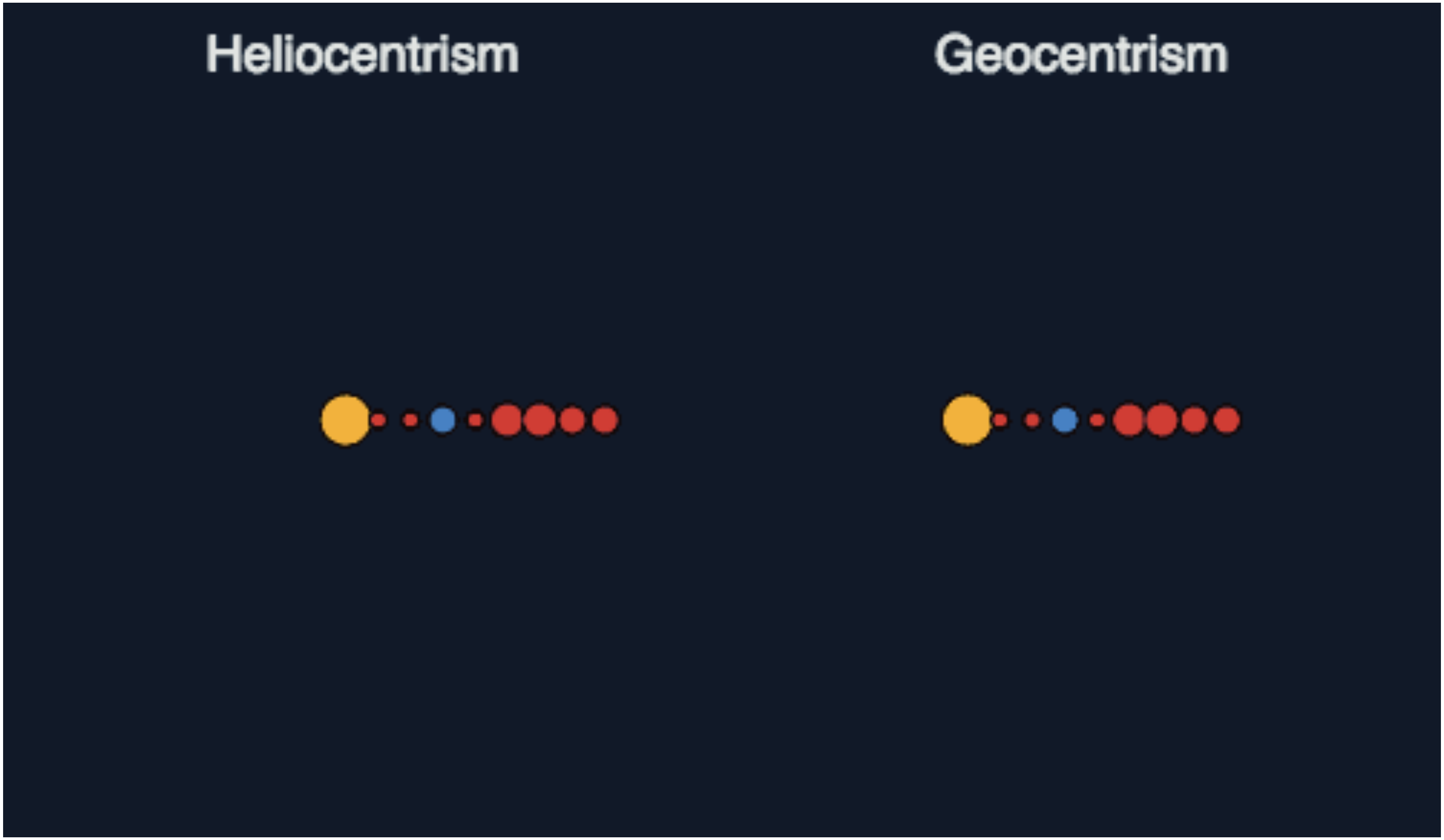


Aristotle's Universe

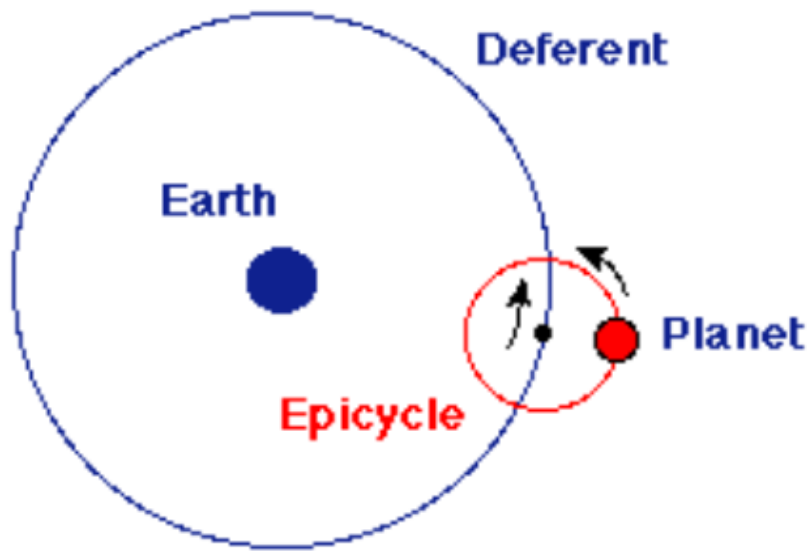
Retrograde Motion

Retrograde Motion




Heliocentrism
Geocentrism

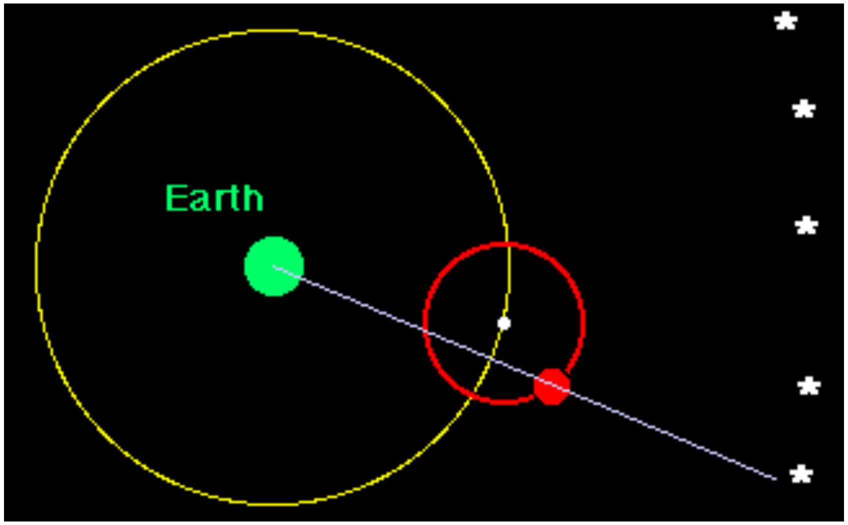
An ingenious idea: Epicycles



Two circles!

The planet executes an orbit (epicycle) around a point
This point executes an orbit (deferent) around Earth

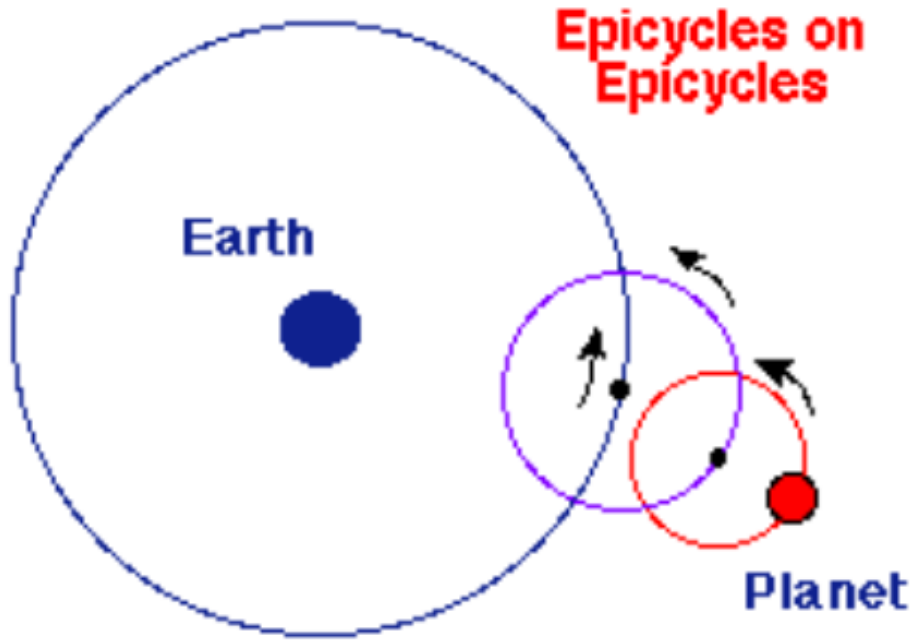
An ingenious idea: Epicycles



Two circles!

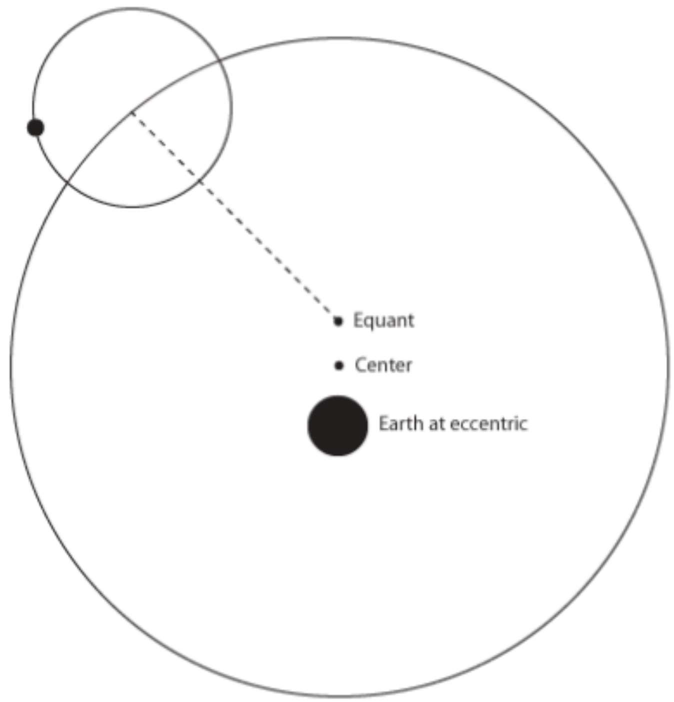
The planet executes an orbit (epicycle) around a point
This point executes an orbit (deferent) around Earth

Sophistications



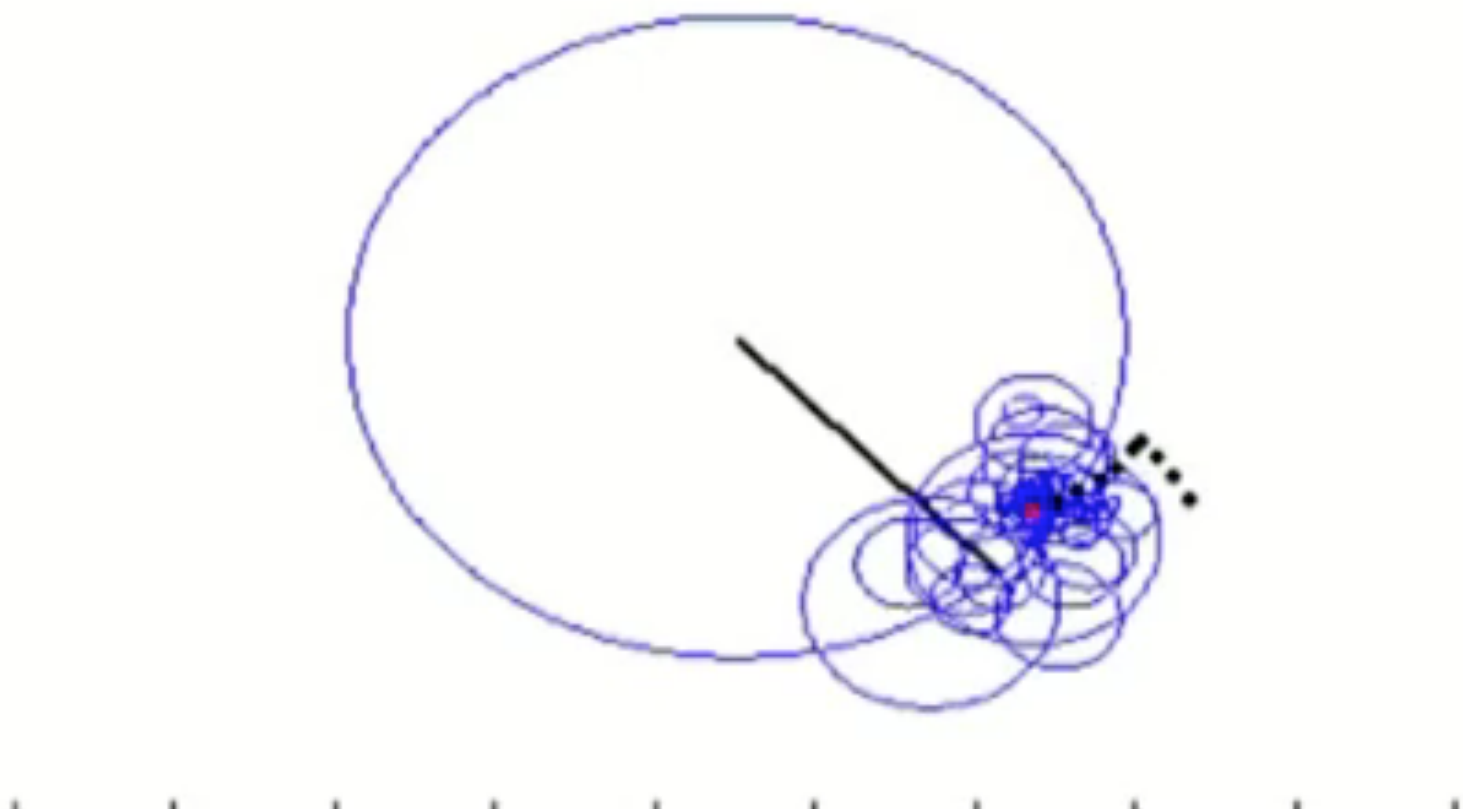
Sometimes more epicycles were needed
to accurately predict the position of the planets

Sophistications: The **Equant**



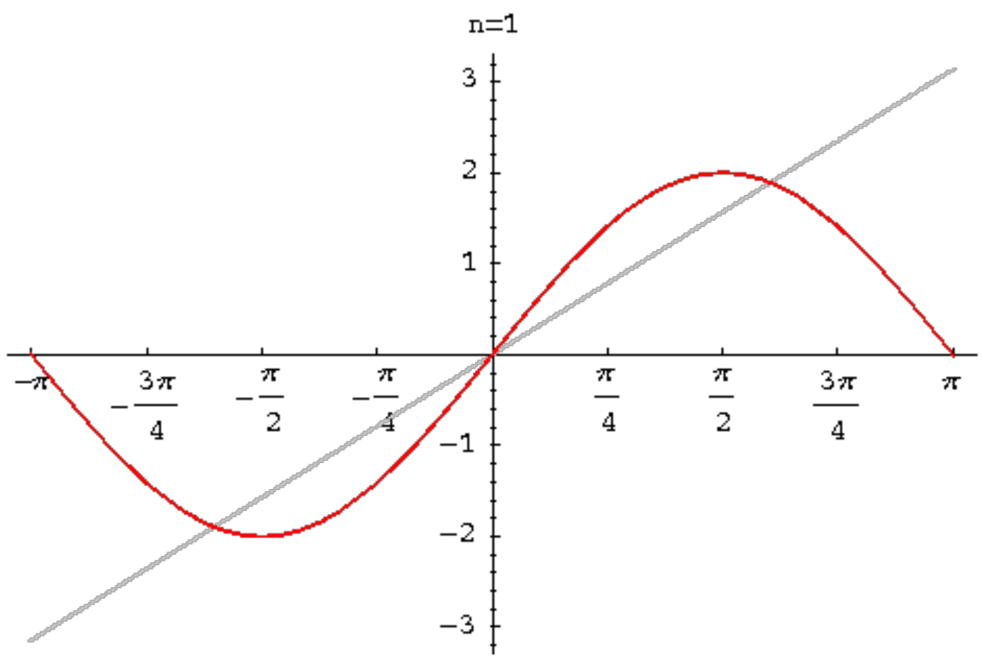
Earth is at an “eccentric” point, off the center of the deferent.

The center of the epicycle moves with constant speed around the Equant.

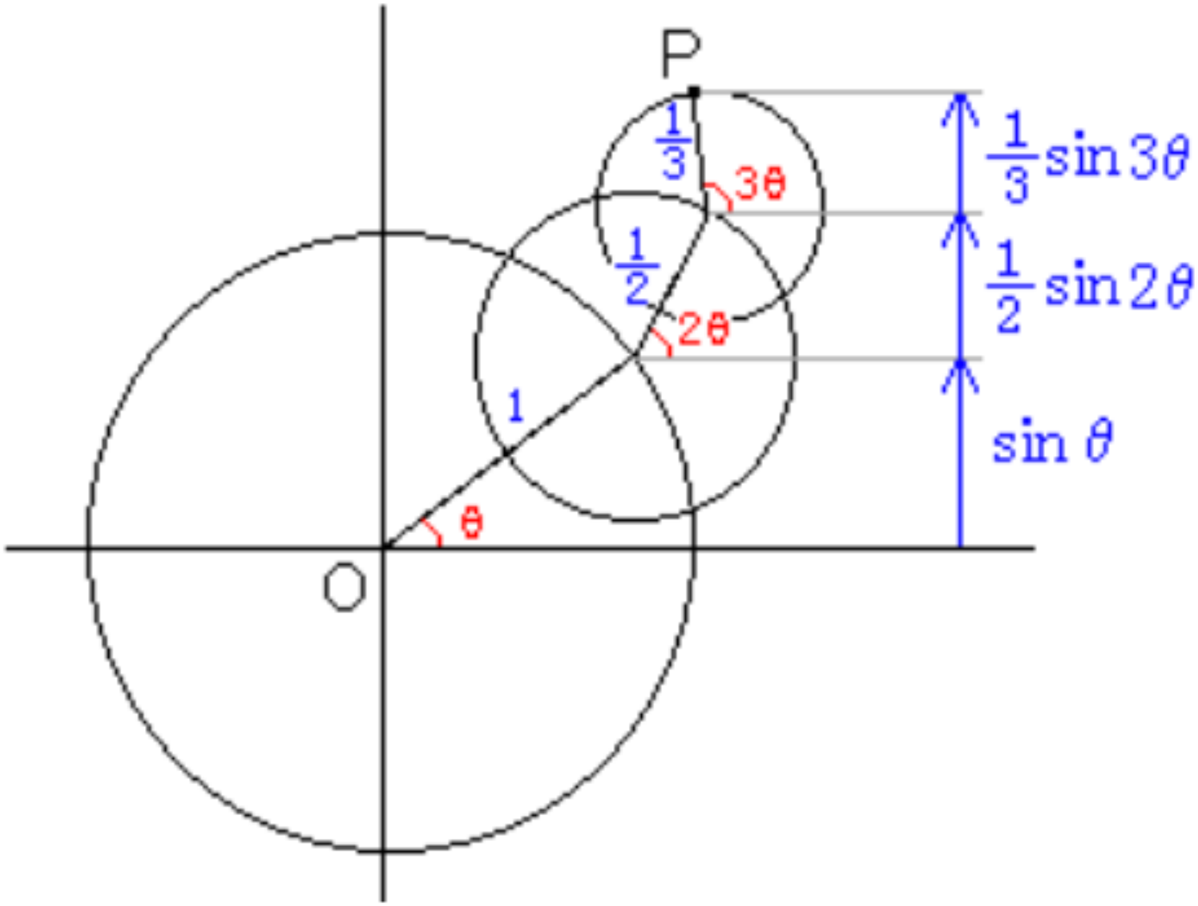


Why does the geocentric model work?

$$\boxed{f(x)=\frac{a_0}{2}+\sum_{1}^{\infty} a_n\cos(nx)+\sum_{1}^{\infty} b_n\sin(nx)}$$



Why does the geocentric model work?

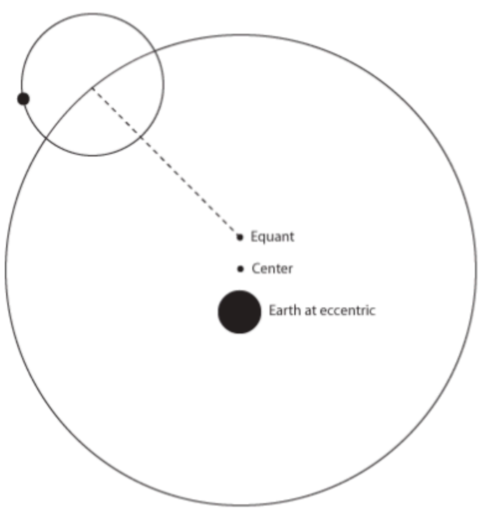


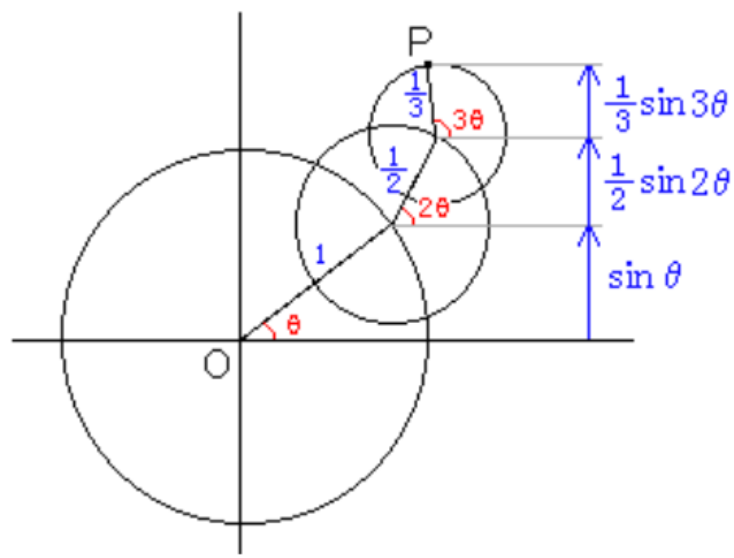
Epicycles!

Why does the geocentric model work?

$$f(x) = \frac{a_0}{2} + \sum_{1}^{\infty} a_n \cos(nx) + \sum_{1}^{\infty} b_n \sin(nx)$$

Equant **Epicycles**

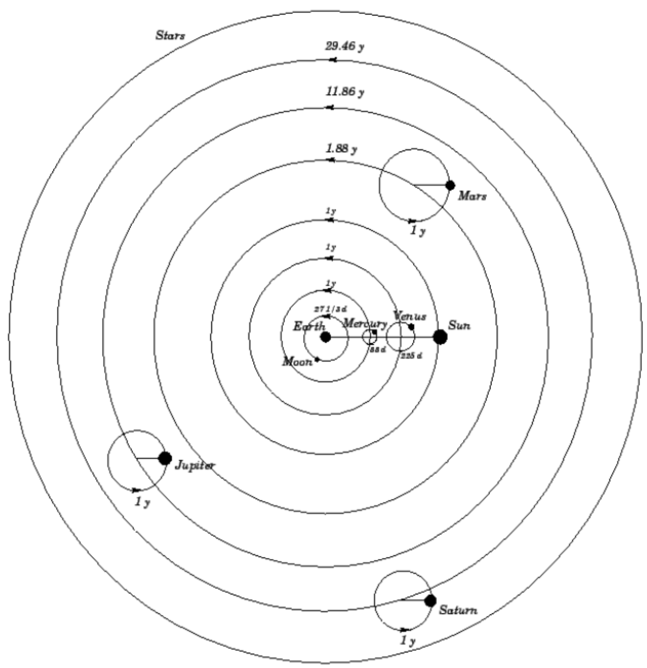


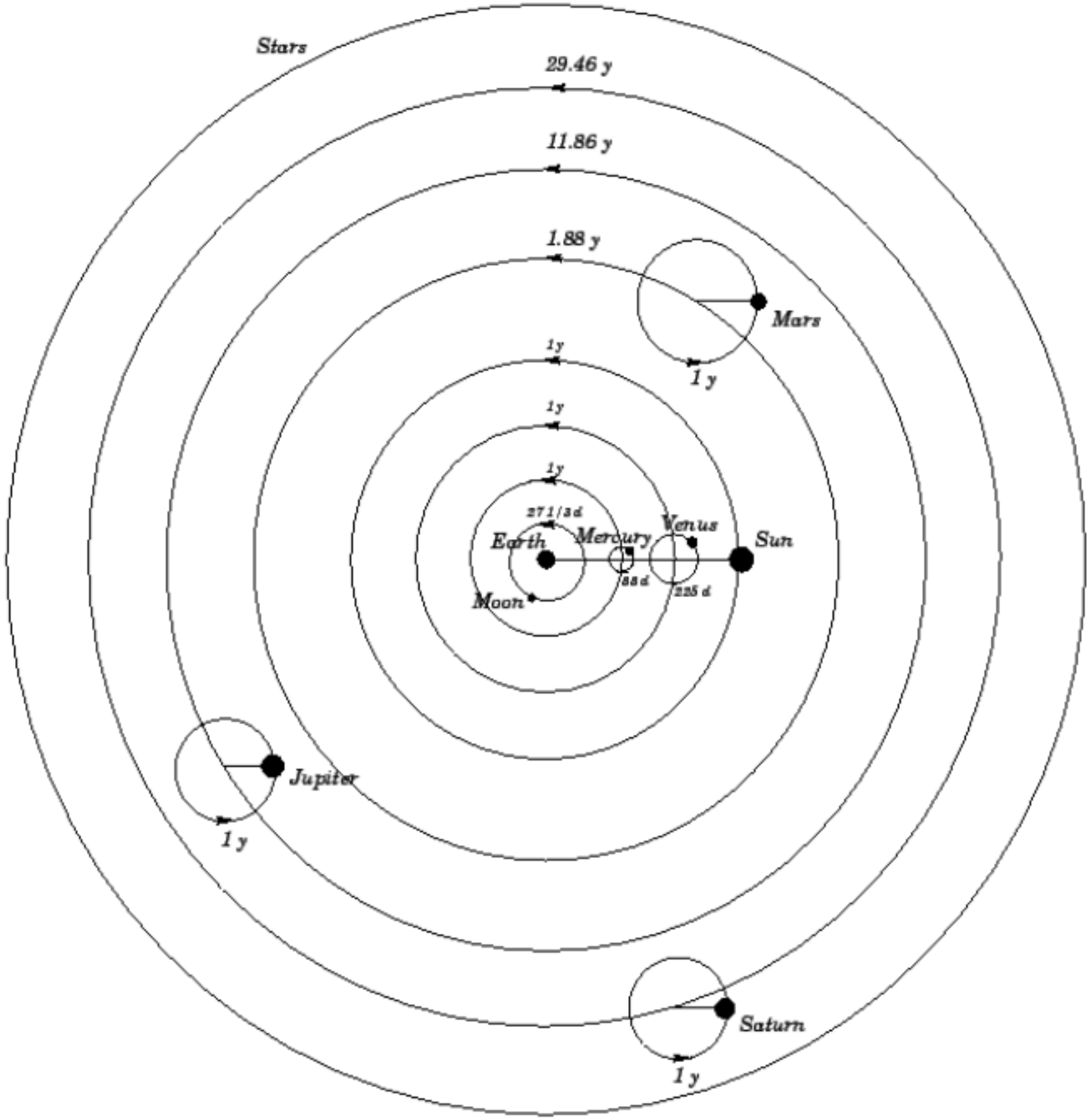


The geocentric model

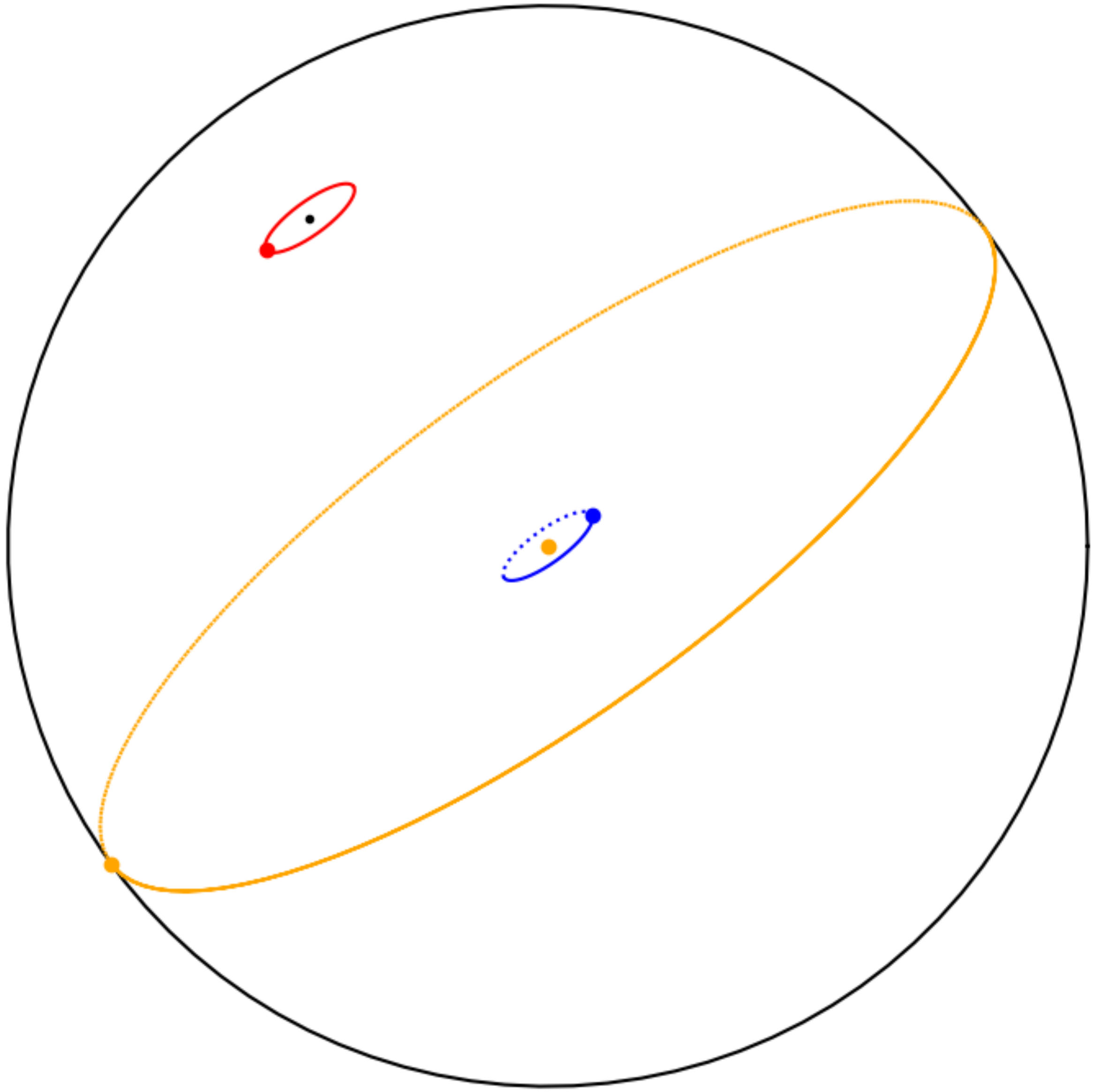
$$f(x)=\frac{a_0}{2}+\sum_{1}^{\infty} a_n\cos(nx)+\sum_{1}^{\infty} b_n\sin(nx)$$

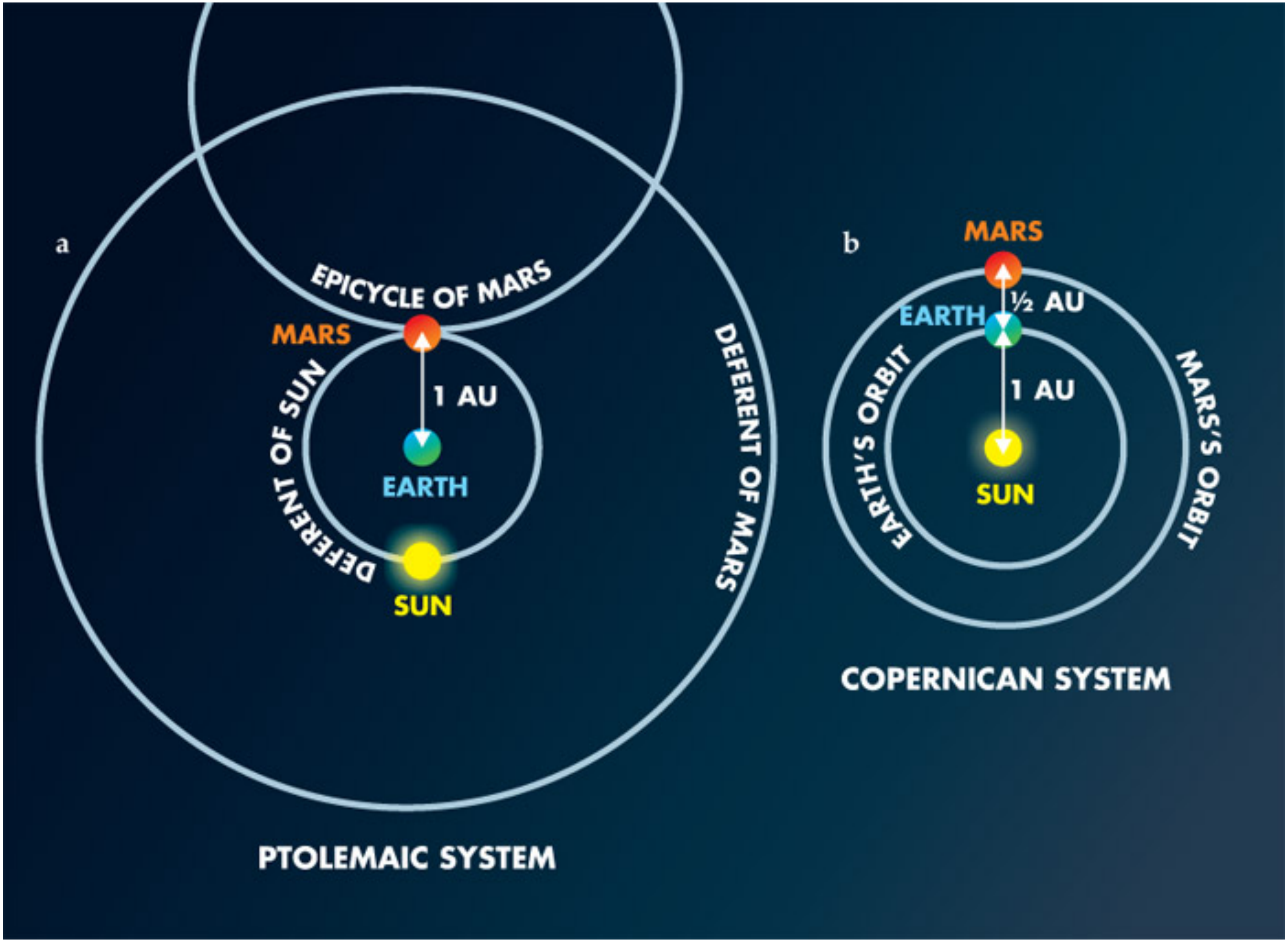
Equant **Epicycles**



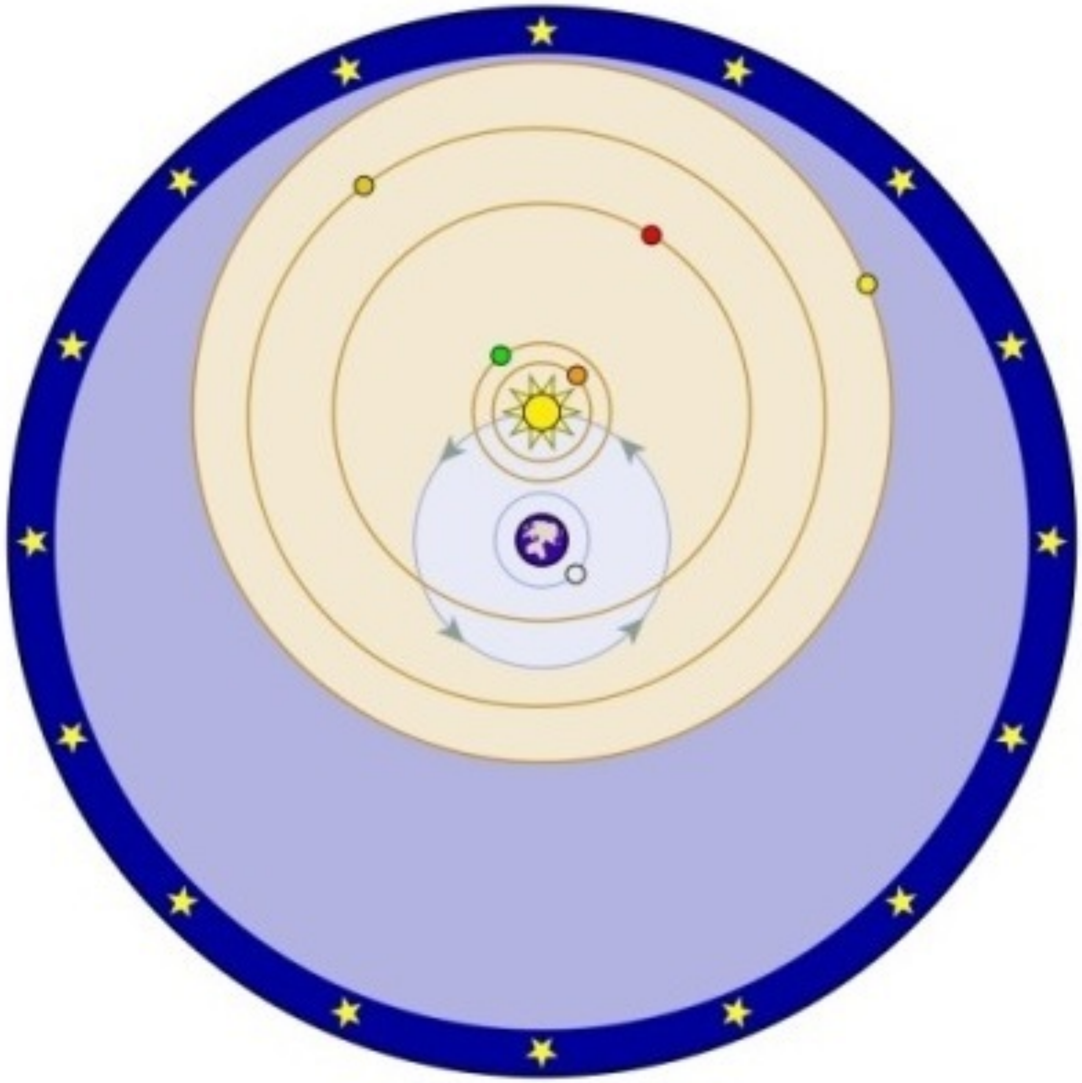


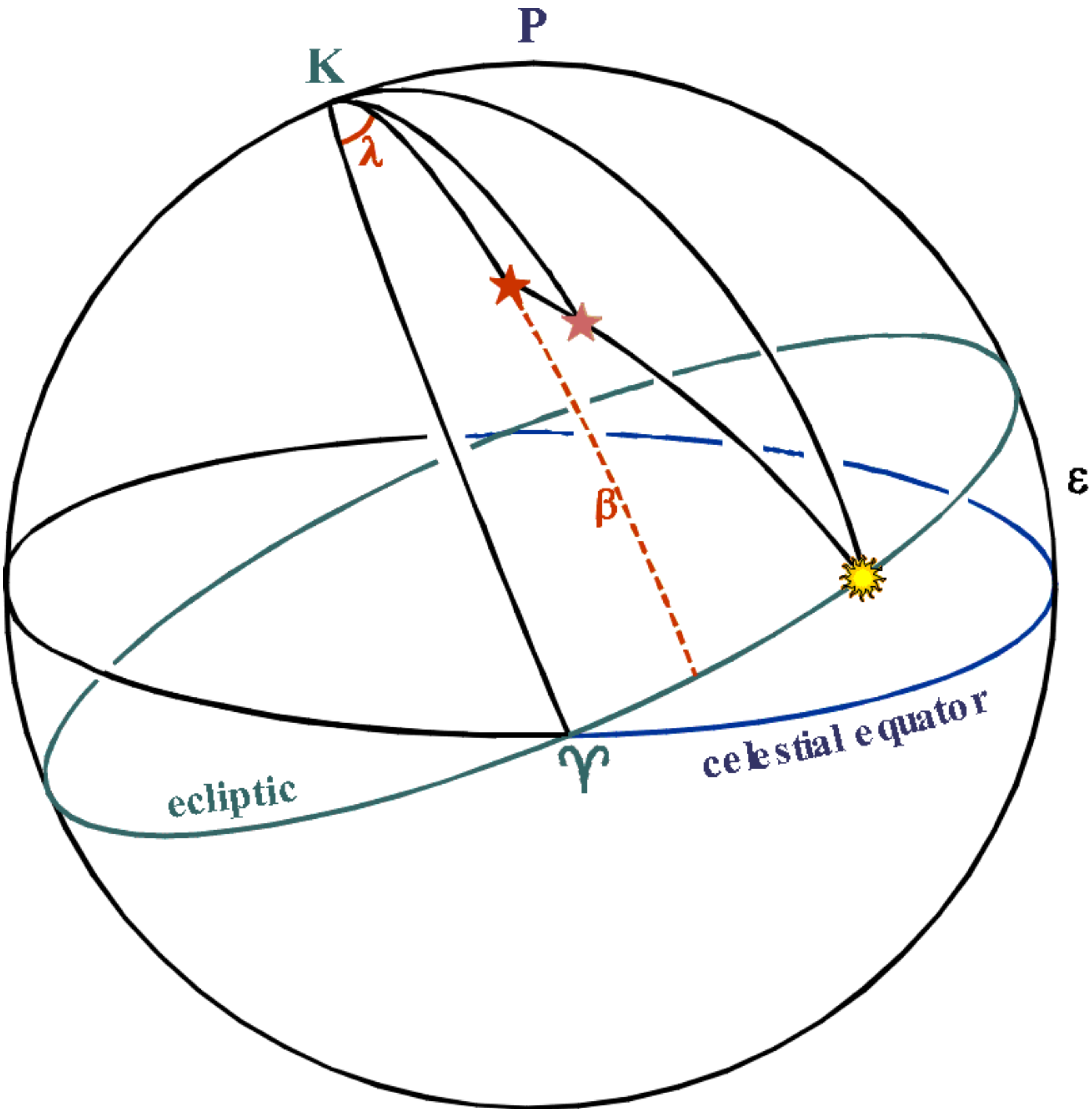
Stars
29.46 y
11.86 y
1.88 y
Mars
1 y
1y
1y
1y
271/3d
Earth
Mercury
Venus
Sun
88d
225 d
Moon
Jupiter
1 y
Saturn
1 y



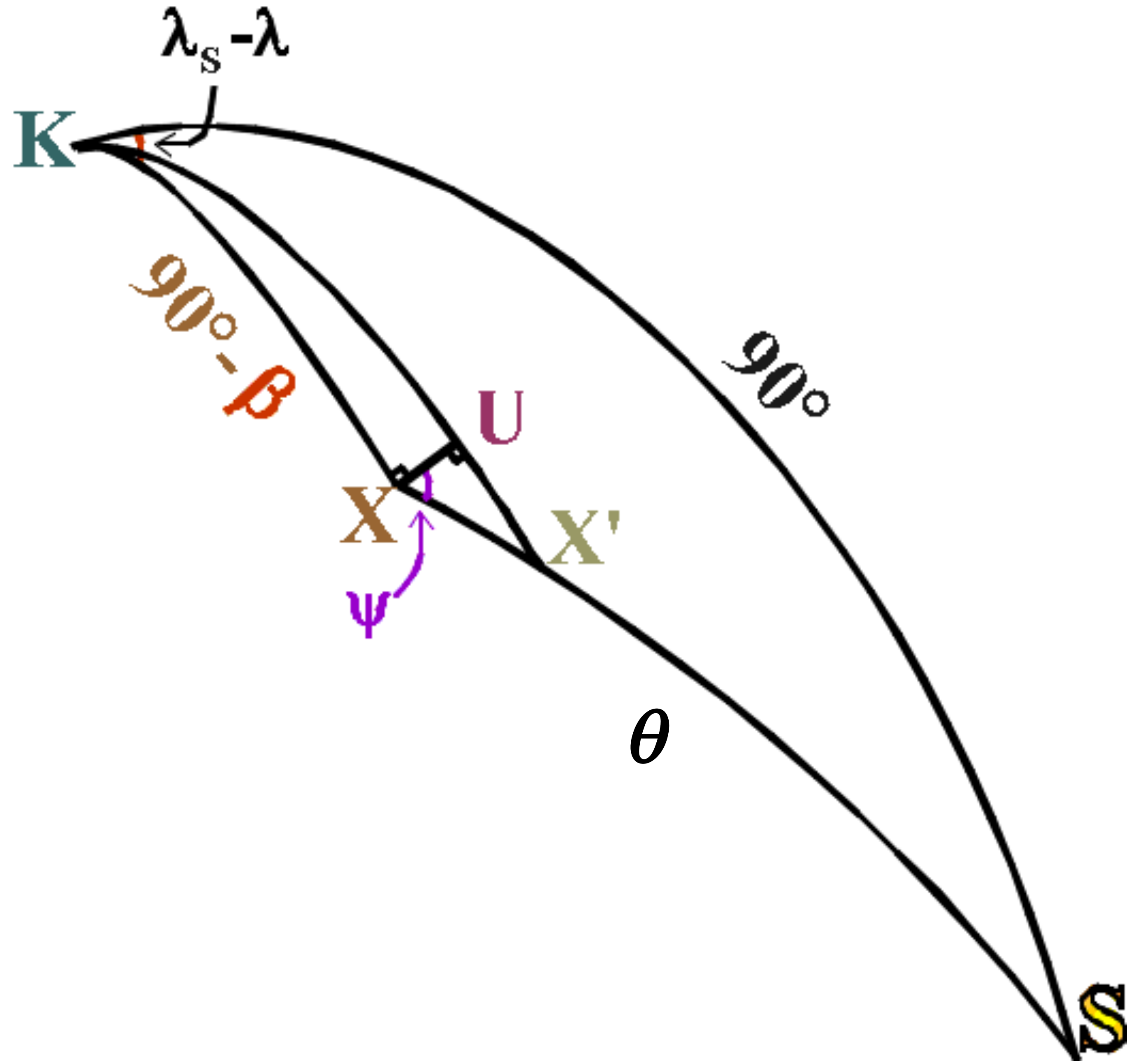

a
EPICYCLE OF MARS
MARS
DEFERENT OF SUN
1 AU
EARTH
SUN
DEFERENT OF MARS
PTOLEMAIC SYSTEM
b
MARS
½ AU
EARTH
EARTH'S ORBIT
1 AU
SUN
MARS'S ORBIT
COPERNICAN SYSTEM

Tycho’s model

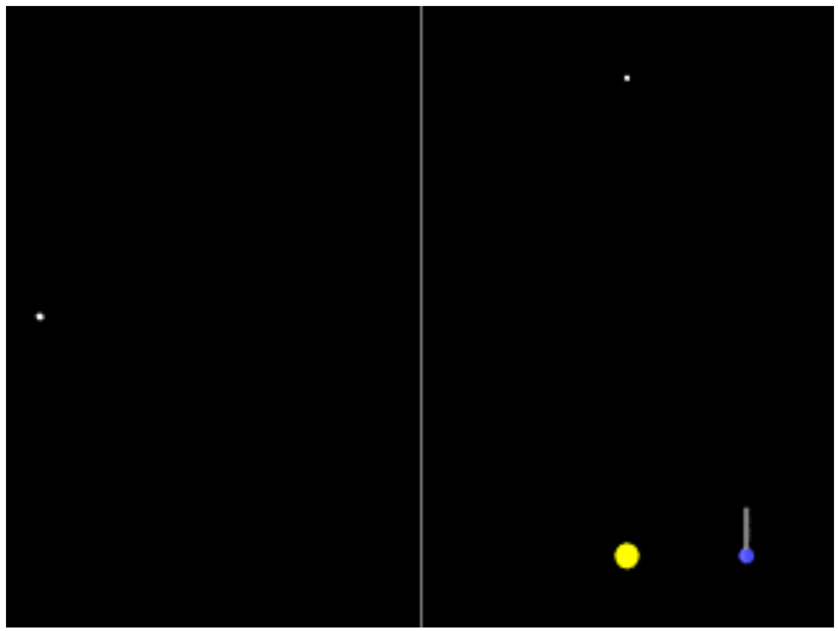


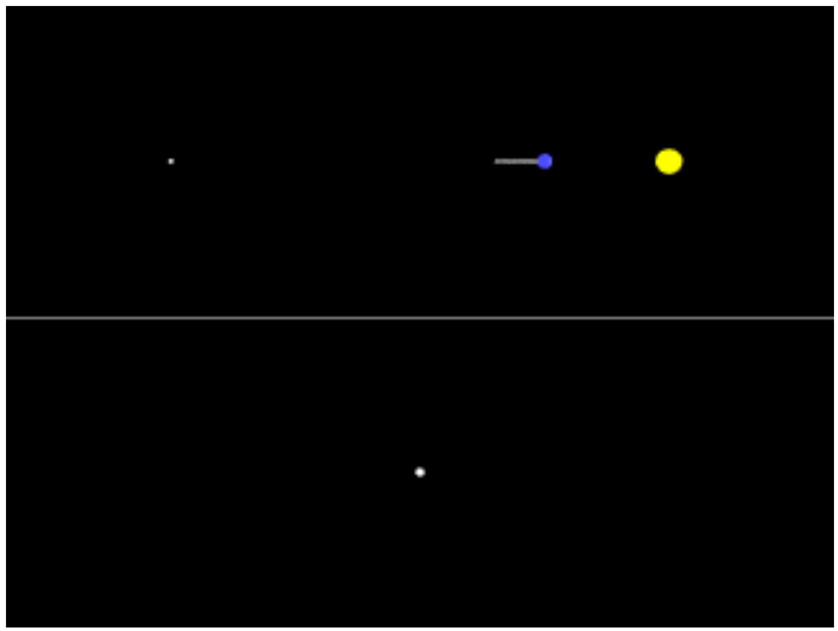


P
K
λ
β
ε
♈
ecliptic
celestial equator

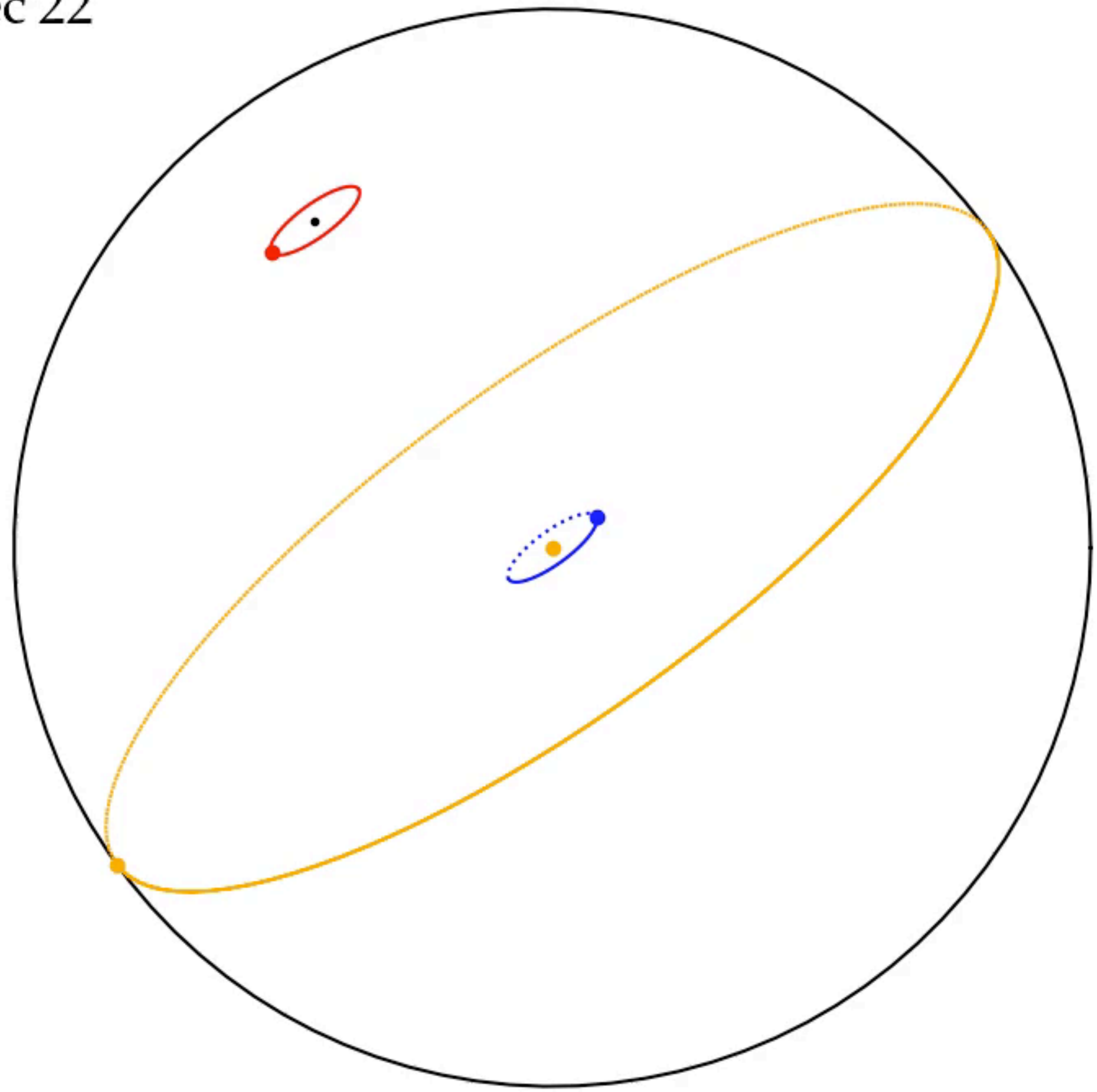


λs -λ
K
90°-β
90°
U
X
X'
ψ
θ
S

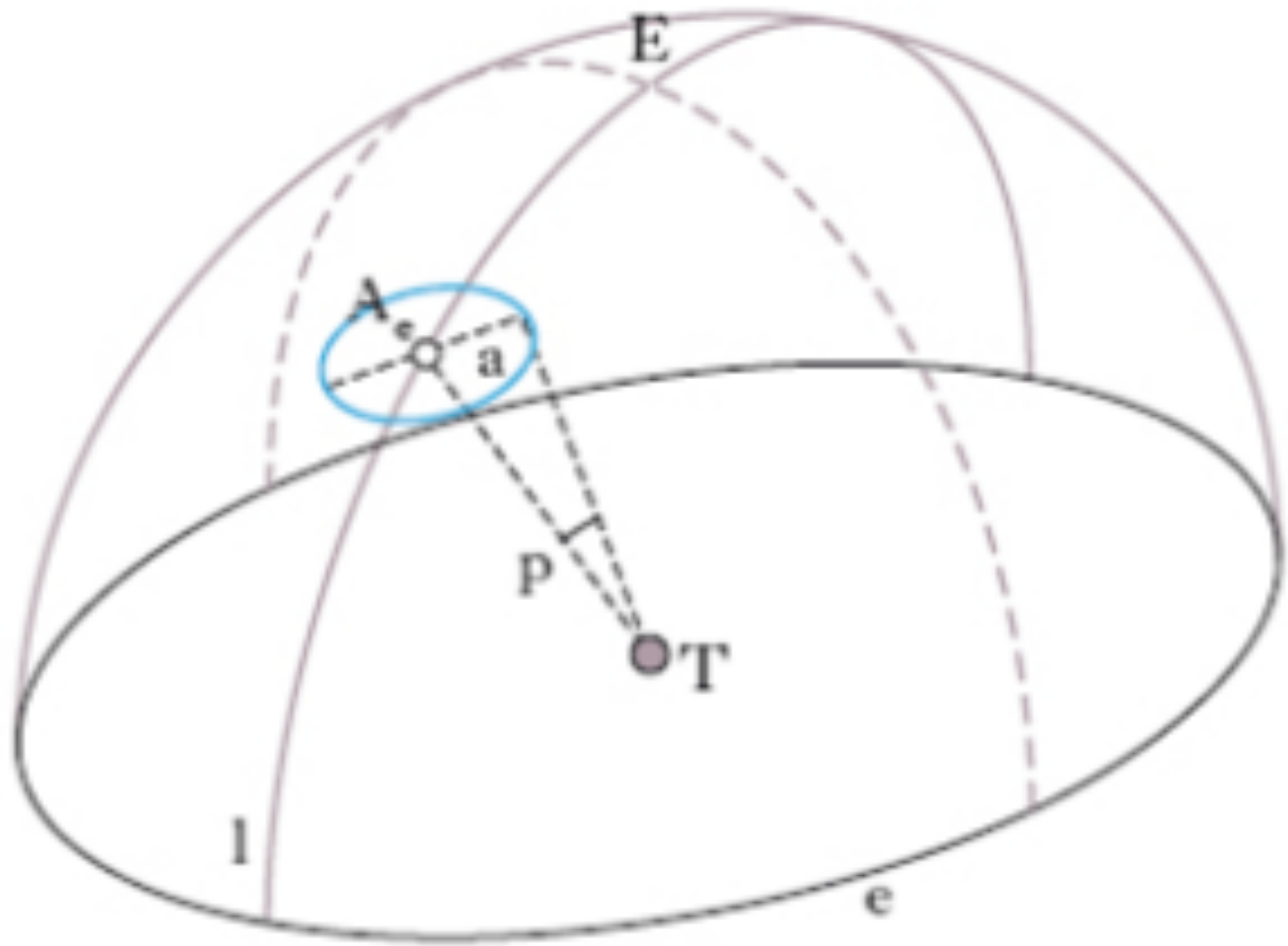




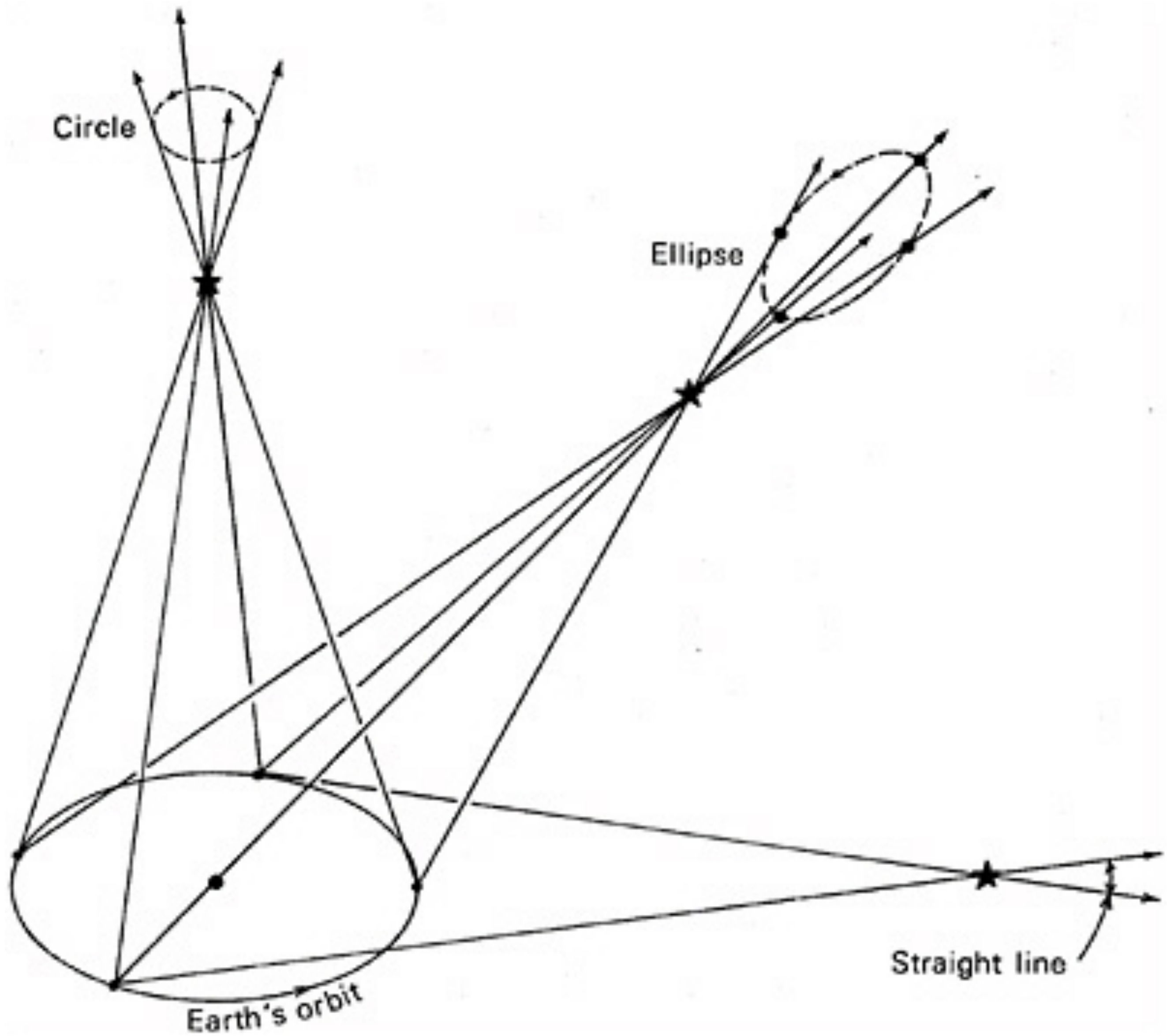
Dec 22



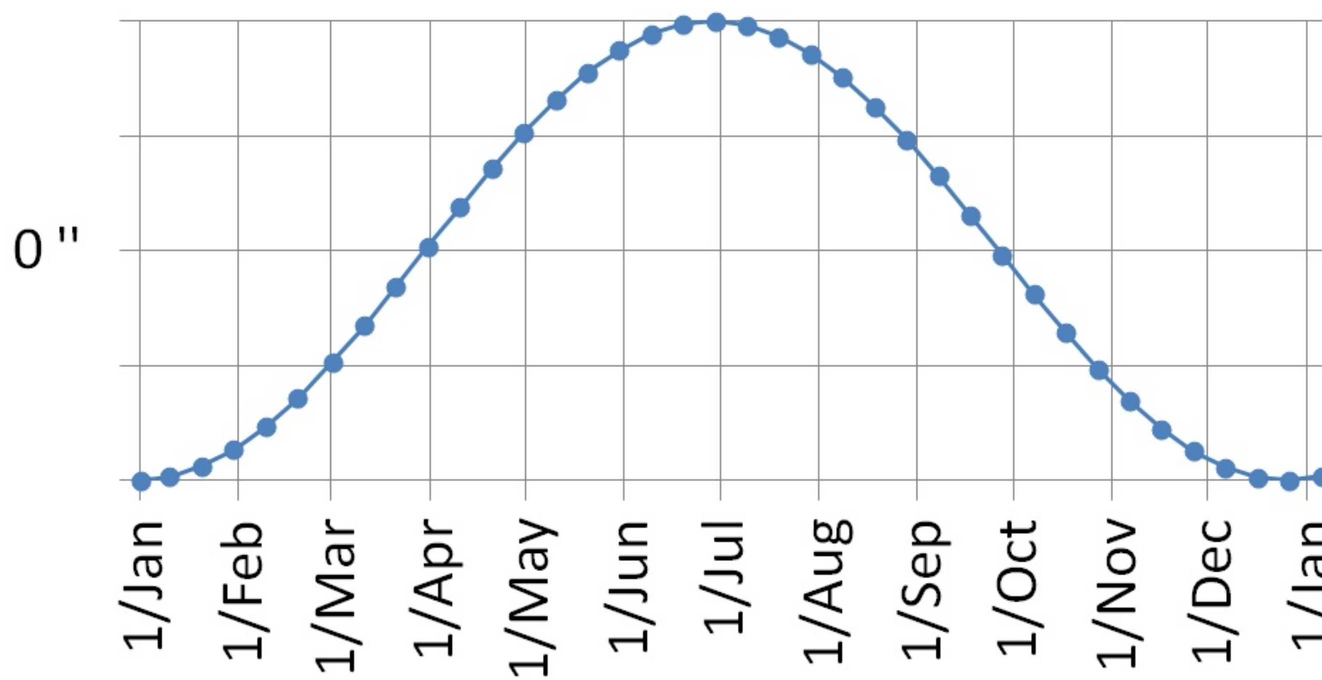
Parallax Ellipse

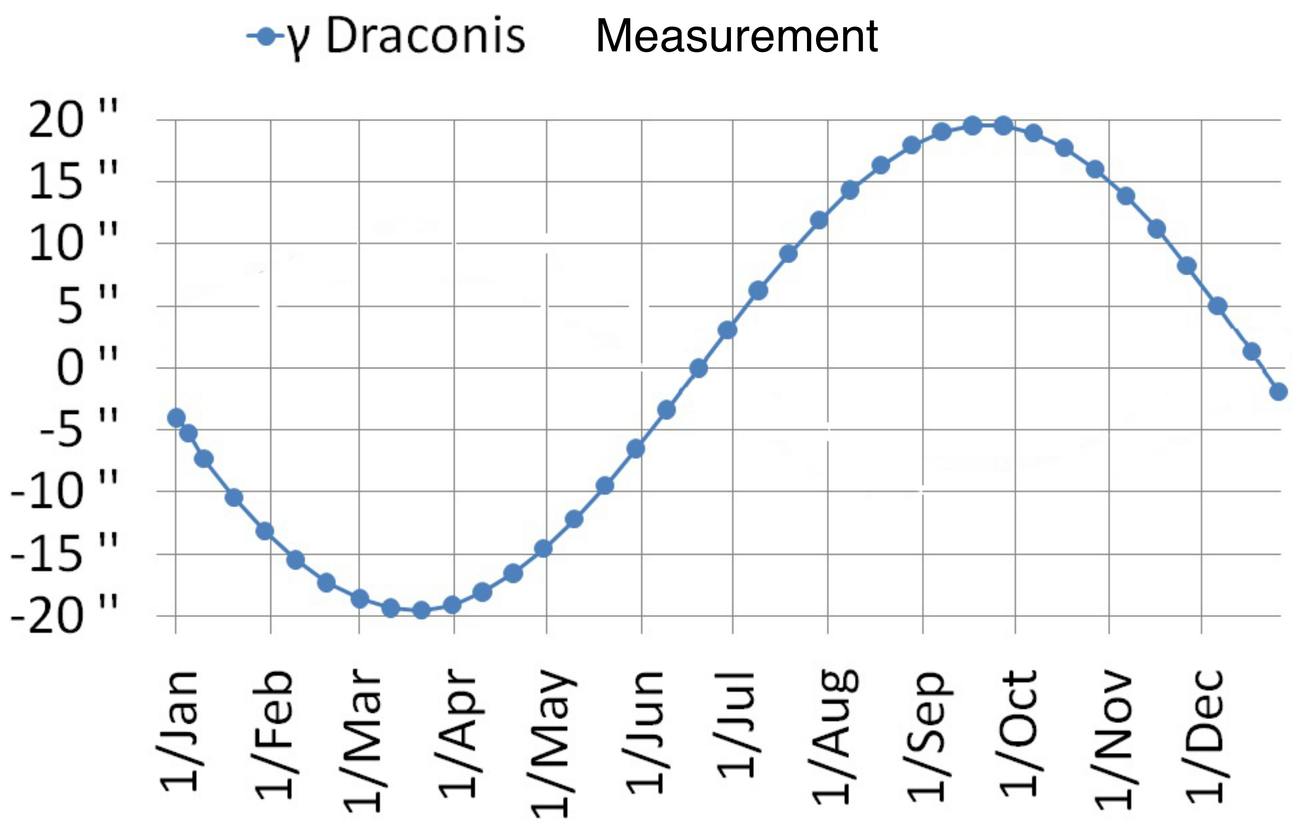


Parallax



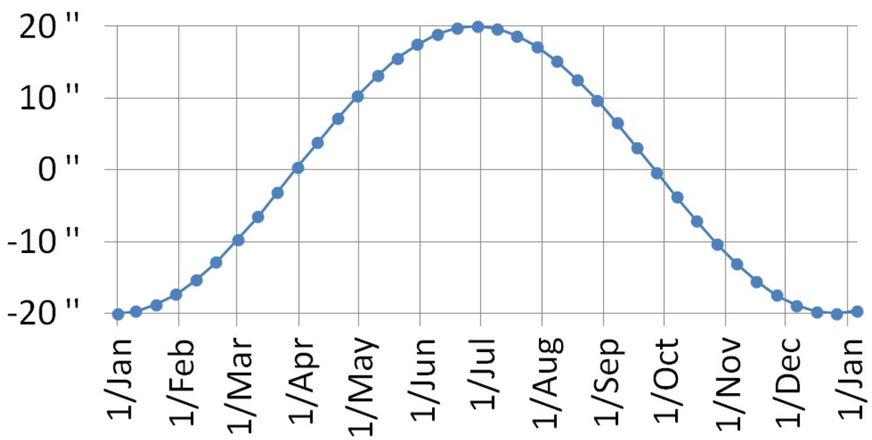
Parallax hypothesis



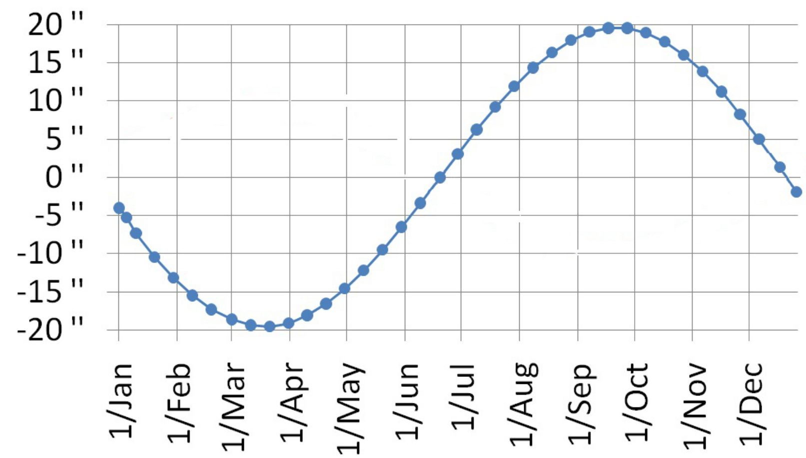


γ Draconis
Measurement
20 ''
15 ''
10 ''
5 ''
0 ''
-5 ''
-10 ''
-15 ''
-20 ''
1/Jan
1/Feb
1/Mar
1/Apr
1/May
1/Jun
1/Jul
1/Aug
1/Sep
1/Oct
1/Nov
1/Dec

Hypothesis

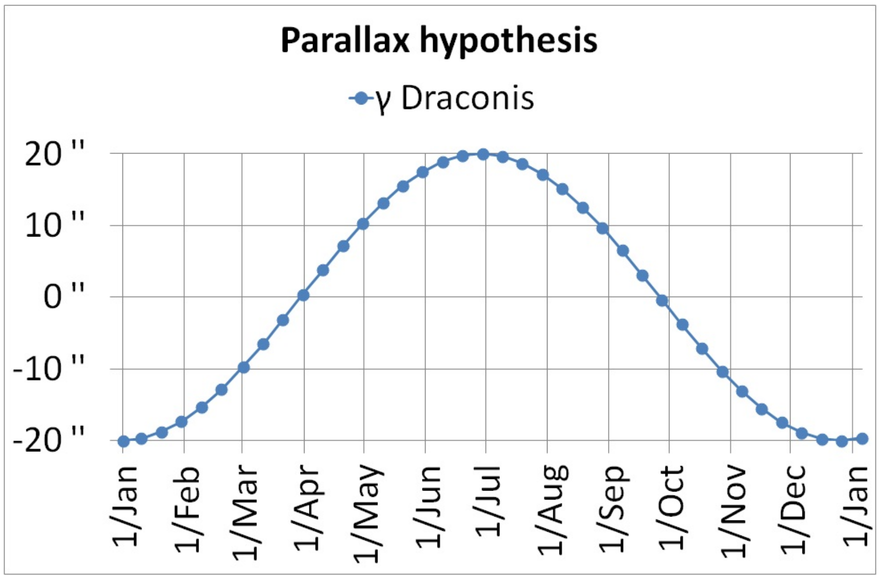


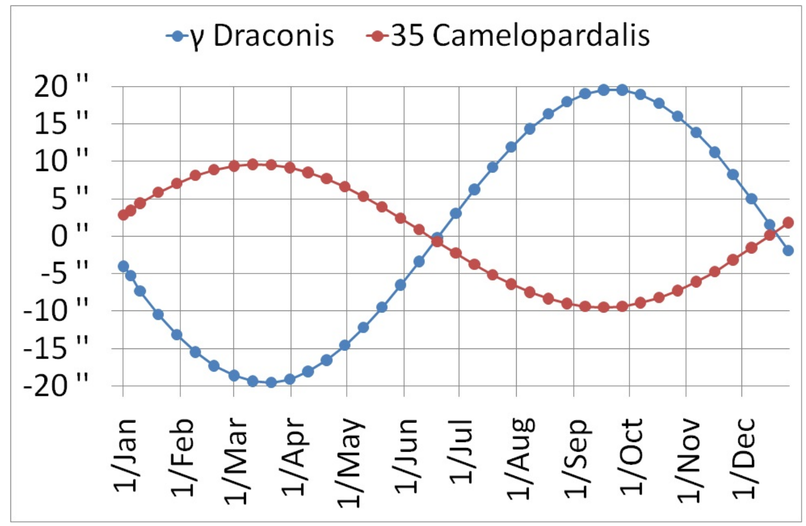
Measurement

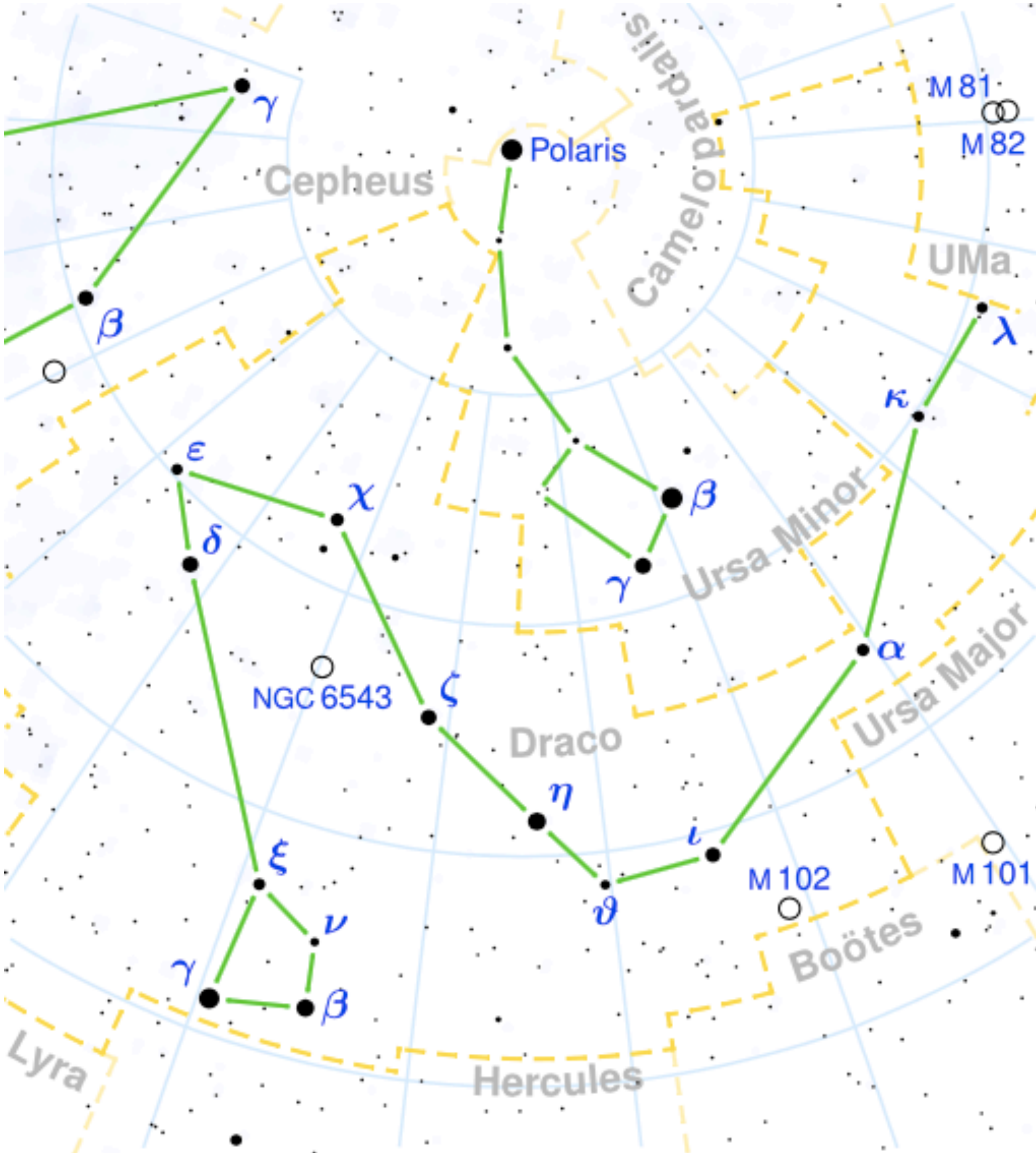


Hypothesis

Measurement

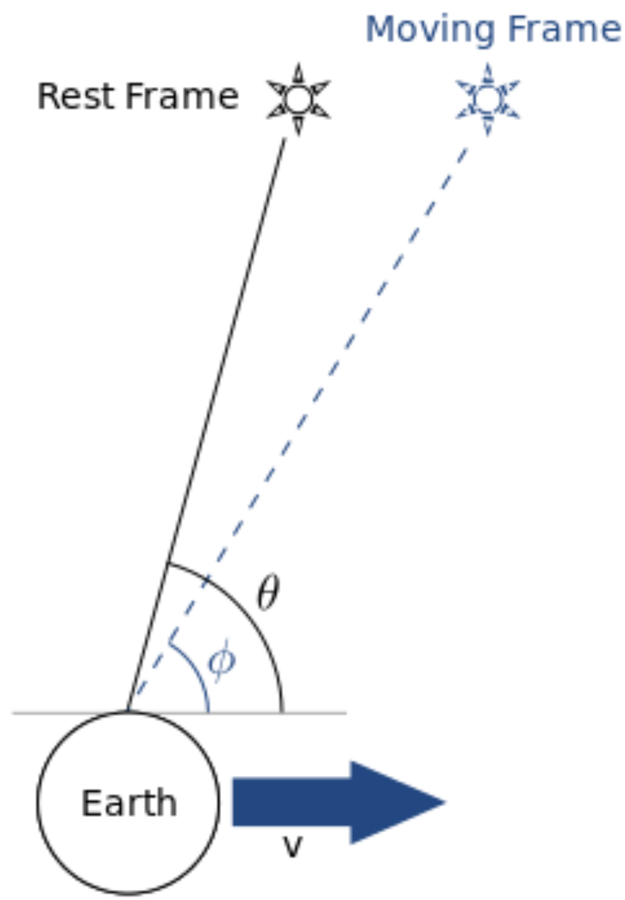


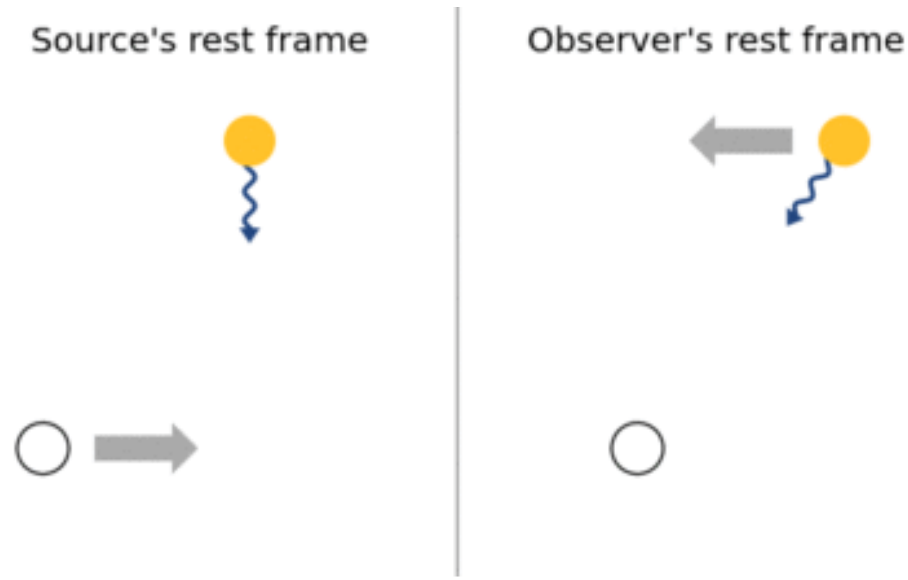


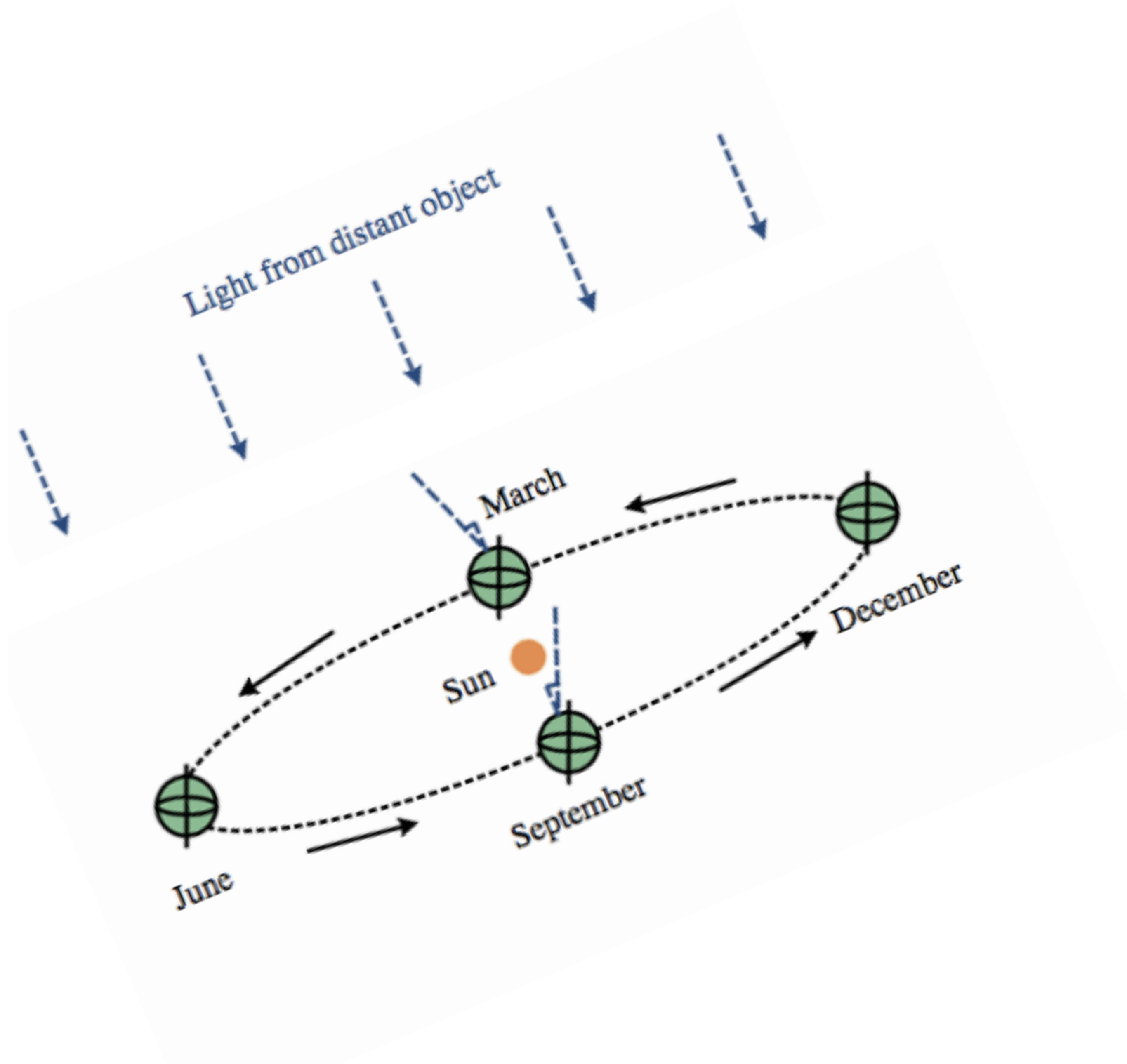


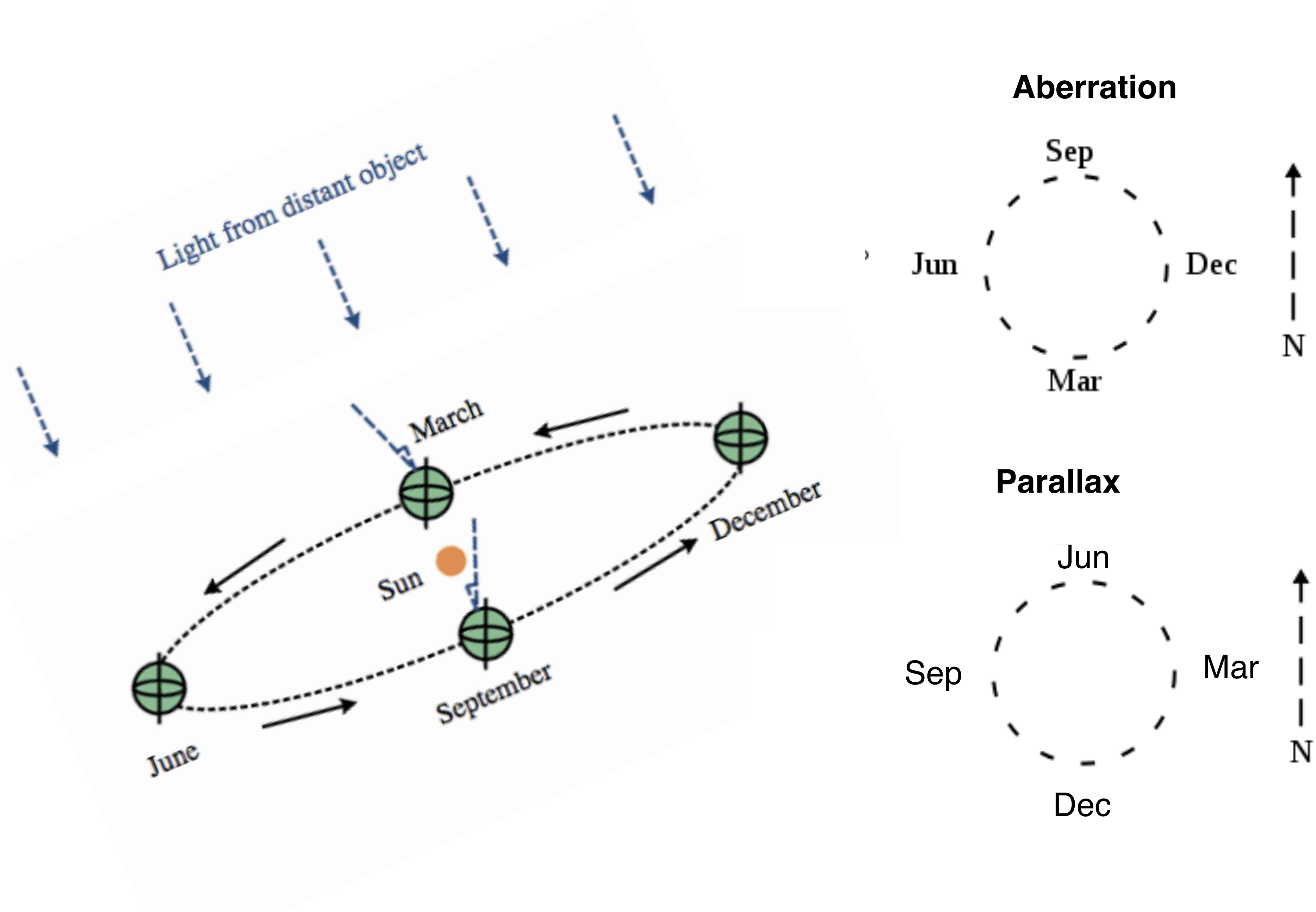
Polaris
Cepheus
Camelopardalis
UMa
M 81
M 82
Ursa Minor
Ursa Major
NGC 6543
Draco
M 102
M 101
Boötes
Hercules
Lyra

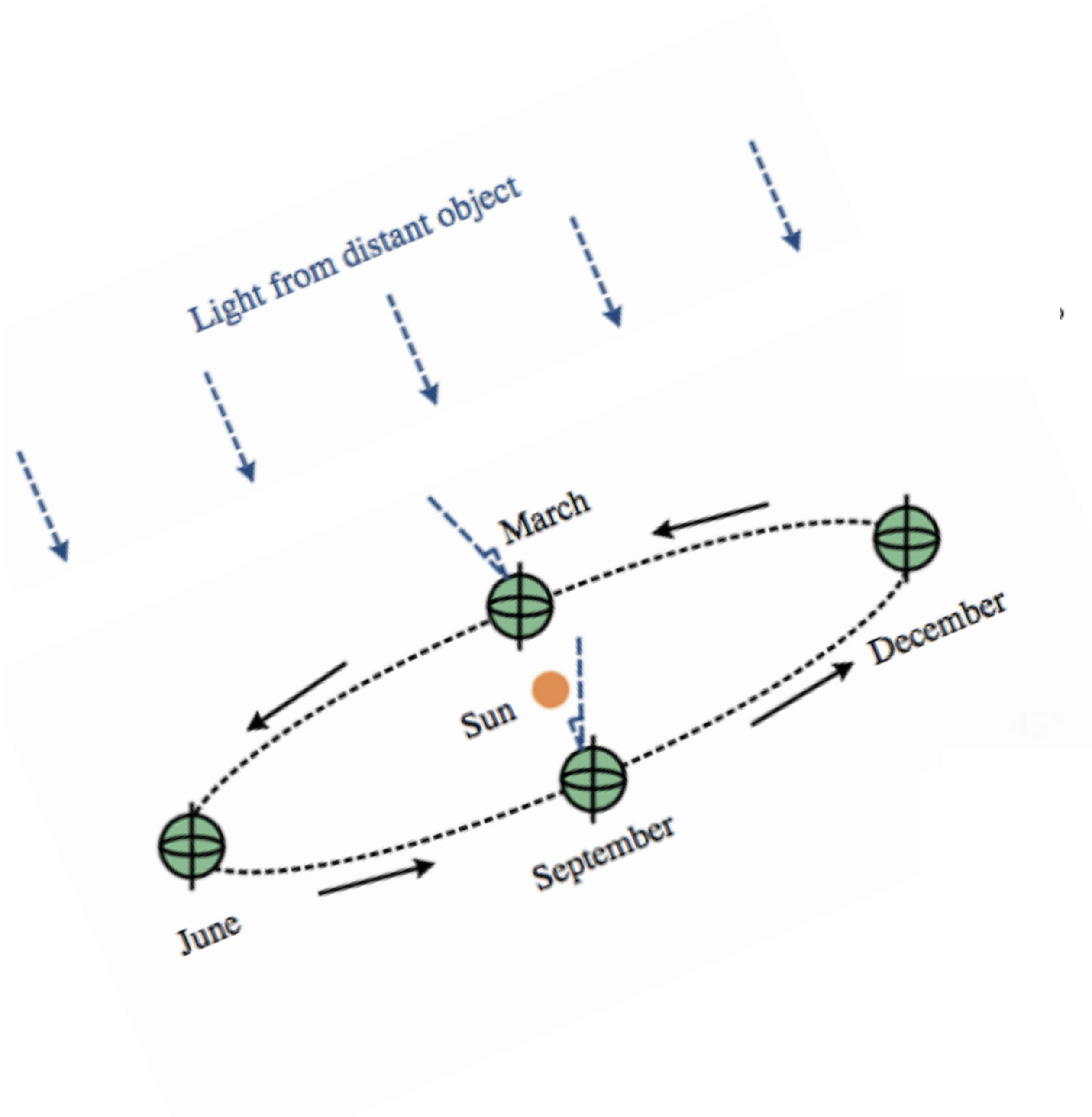
Aberration of Light



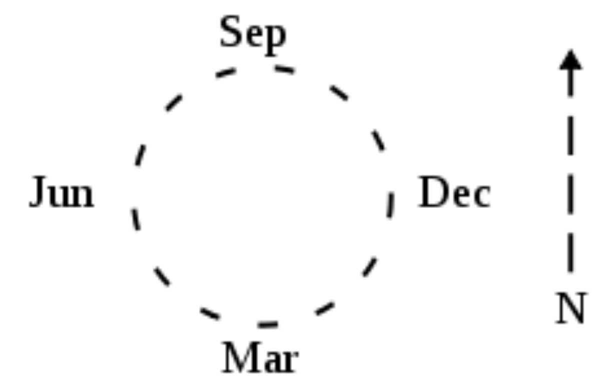

Source's rest frame
Observer's rest frame

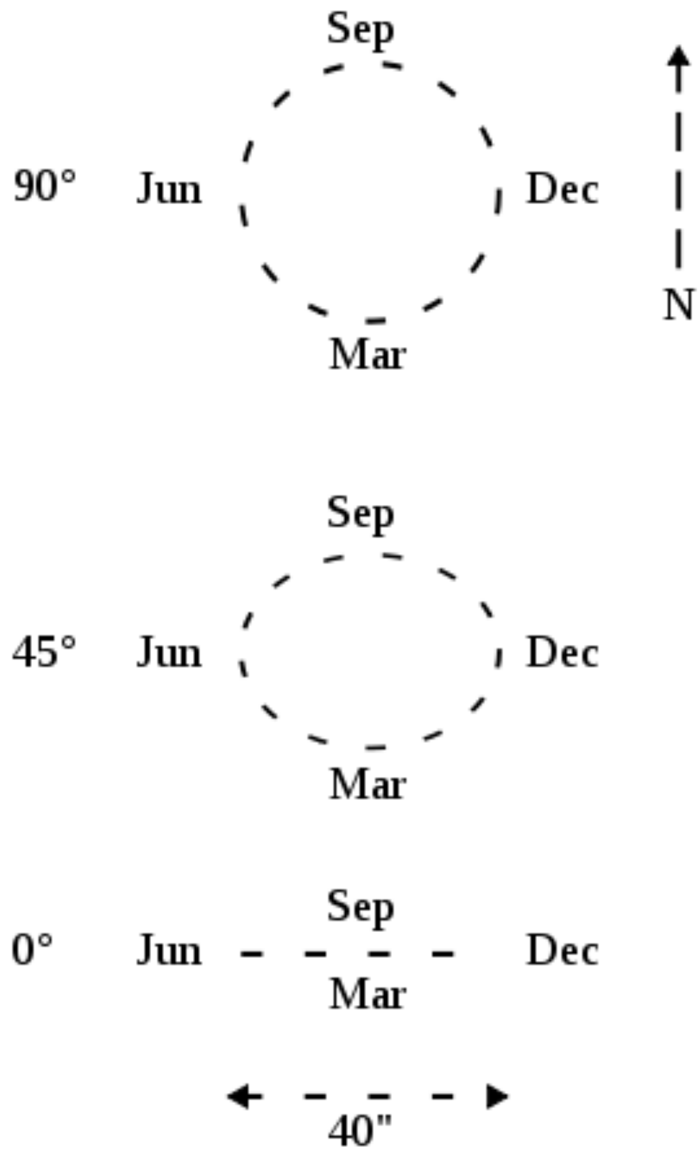

Light from distant object
March
Sun
December
September
June


Light from distant object
March
December
Sun
June
September
Aberration
Sep
Jun
Dec
Mar
N
Parallax
Jun
Sep
Mar
Dec
N

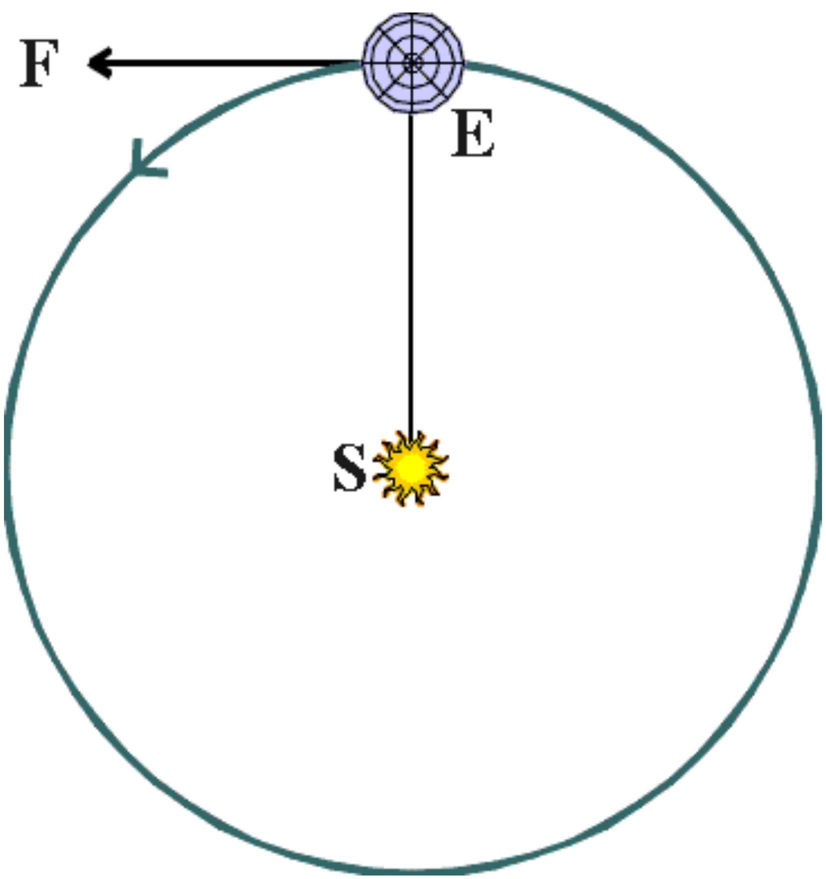

Light from distant object
March
Sun
December
September
June

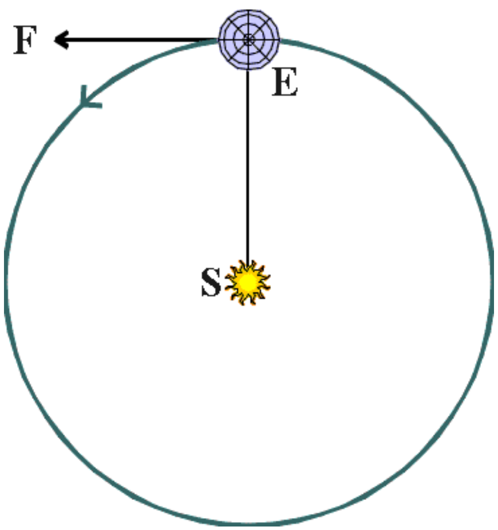
Aberration

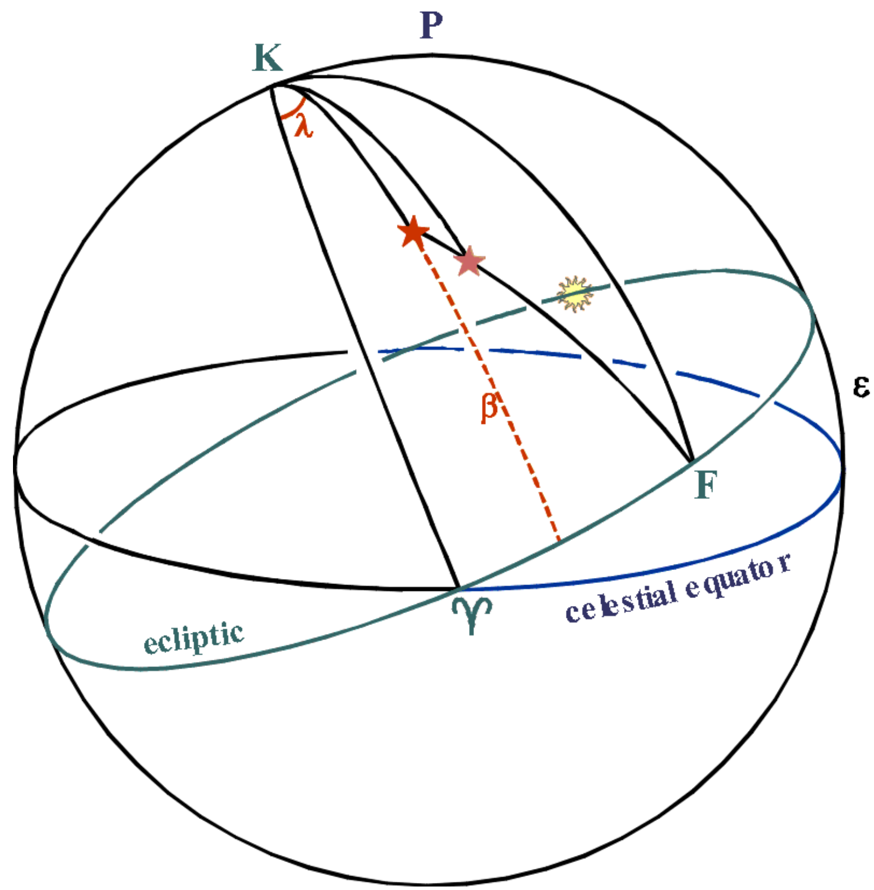

Sep
Jun
Dec
Mar
N

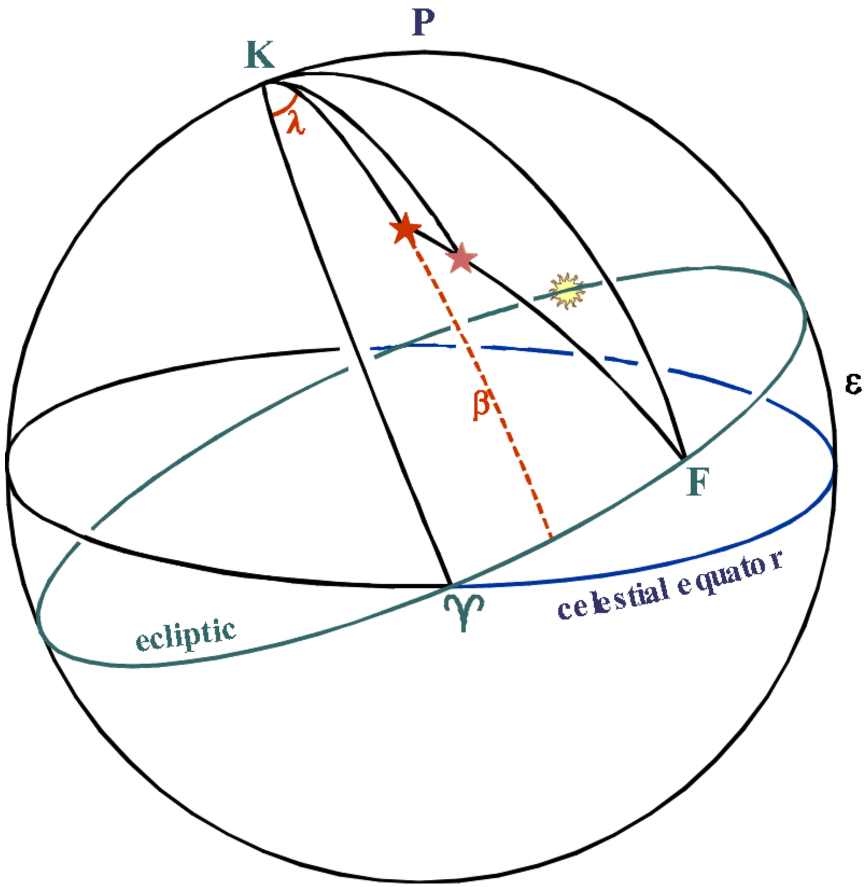

Sep
90°
Jun
Dec
N
Mar
Sep
45°
Jun
Dec
Mar
Sep
0°
Jun
Dec
Mar
40"

Earth's Apex

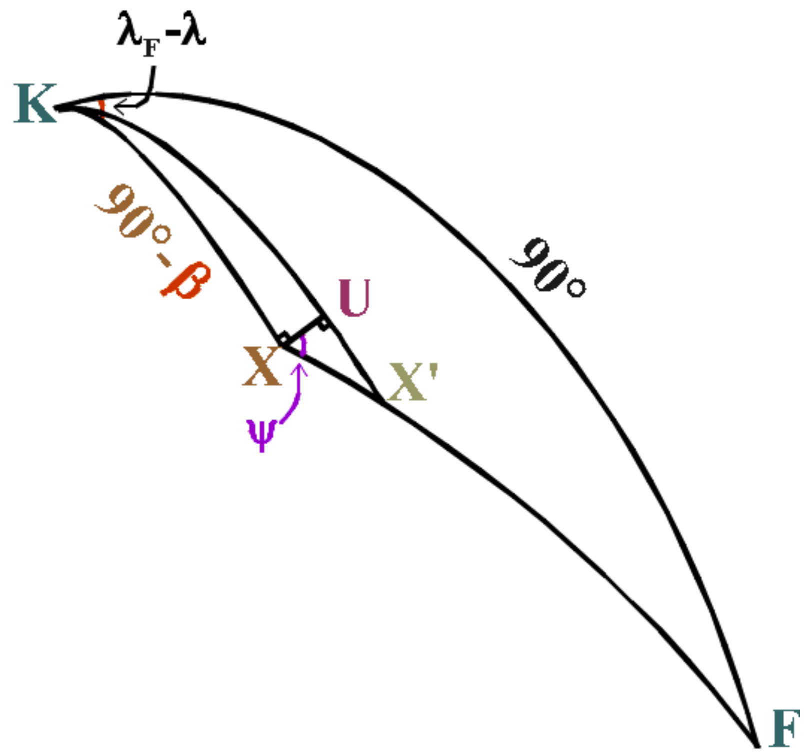



F
E
S


P
K
λ
ε
β
F
ecliptic
♈
celestial equator

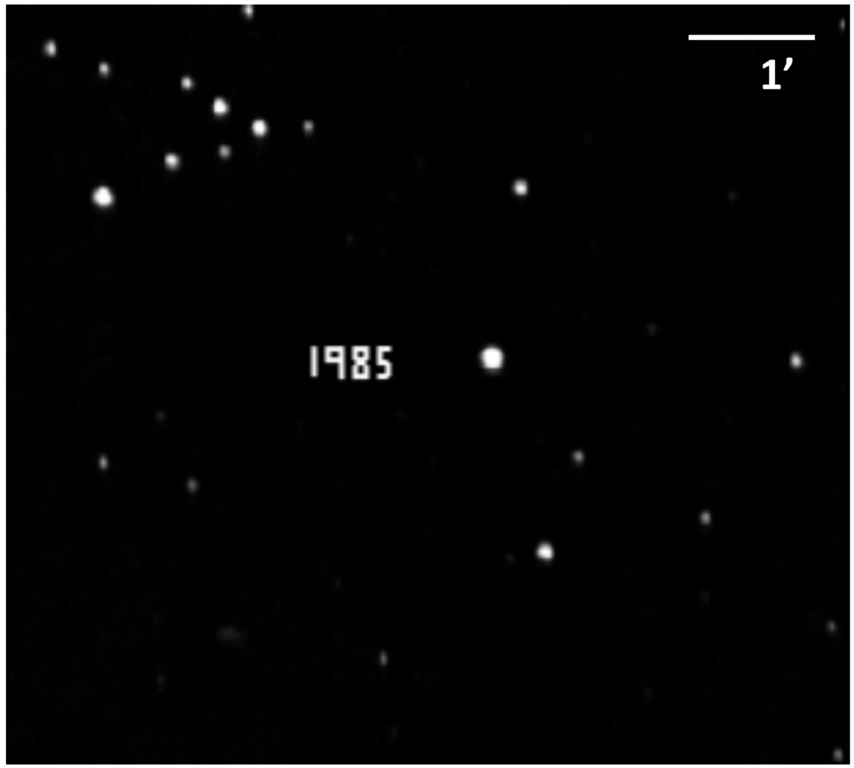


P
K
λ
β
ε
F
ecliptic
♈
celestial equator



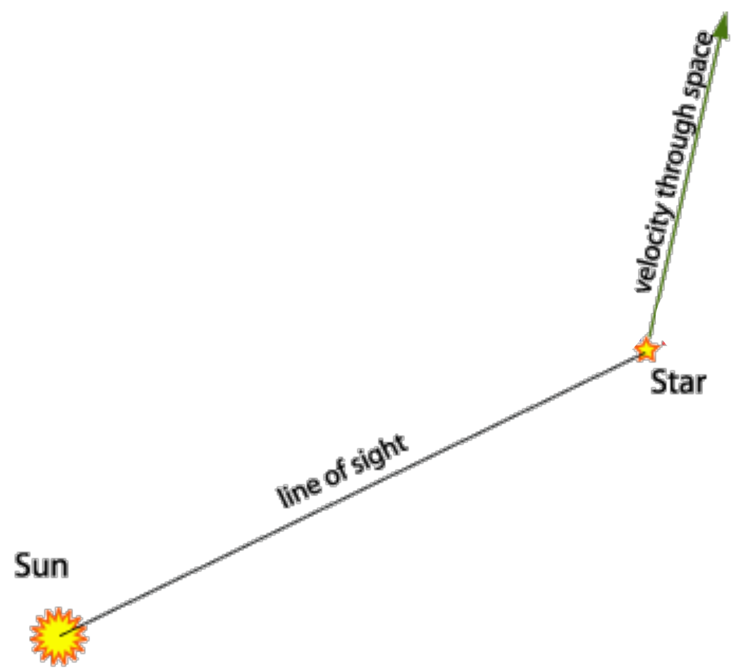
$\lambda_F - \lambda$
K
90° - β
90°
U
X
X'
ψ
F

Proper Motion

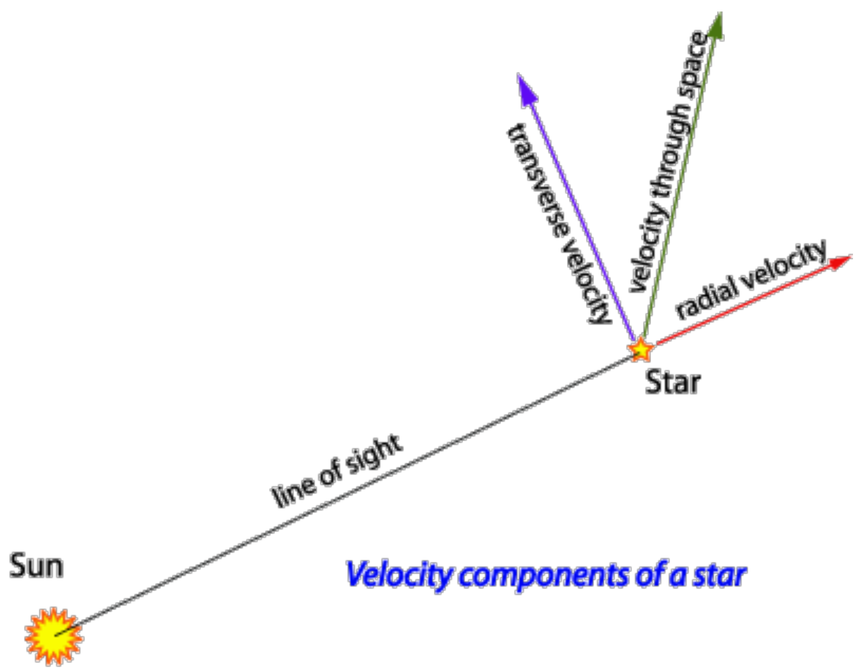


Barnard's Star

How do we measure proper motion?

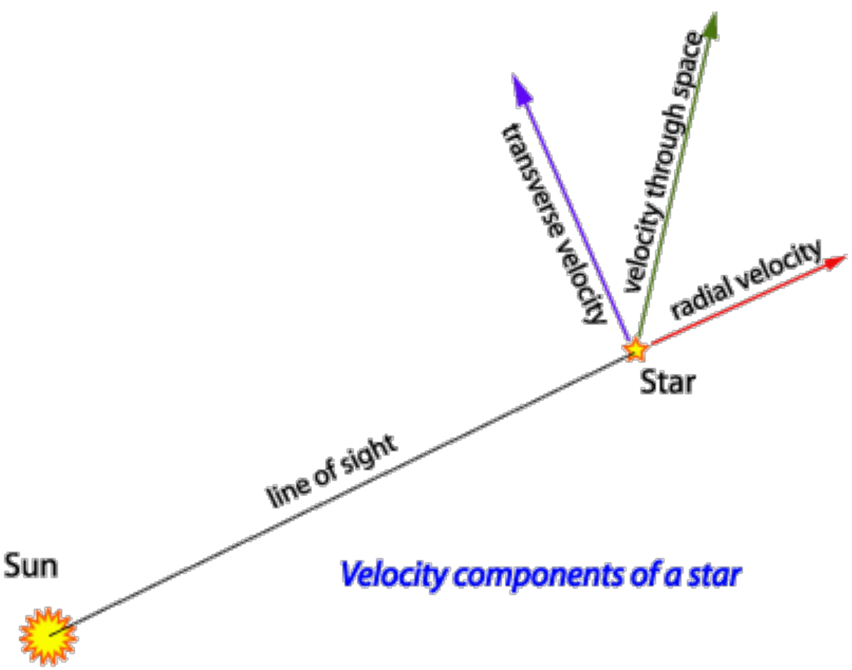


Stellar velocity components



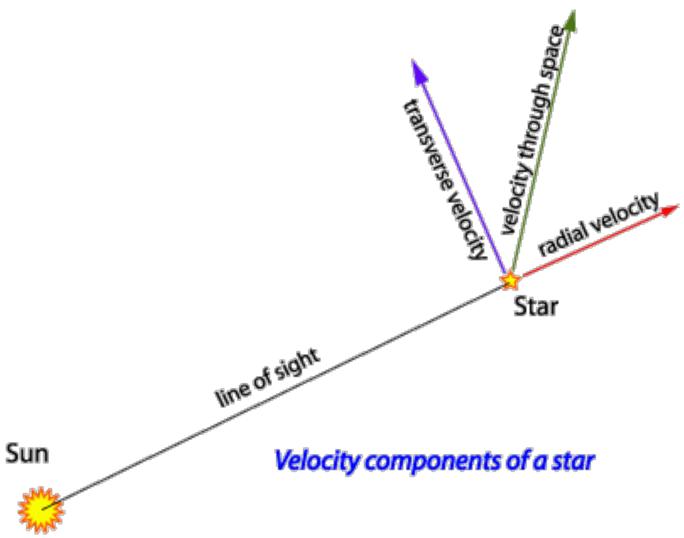
Velocity components of a star

Stellar velocity components



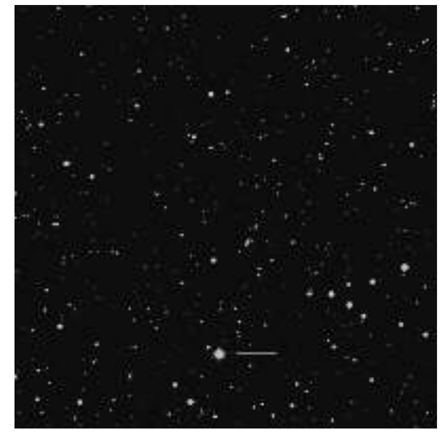
We see the *transverse velocity* as a star's "*proper motion*", which changes its position in the sky.

Stellar Motions



Barnard's star

1950



2000

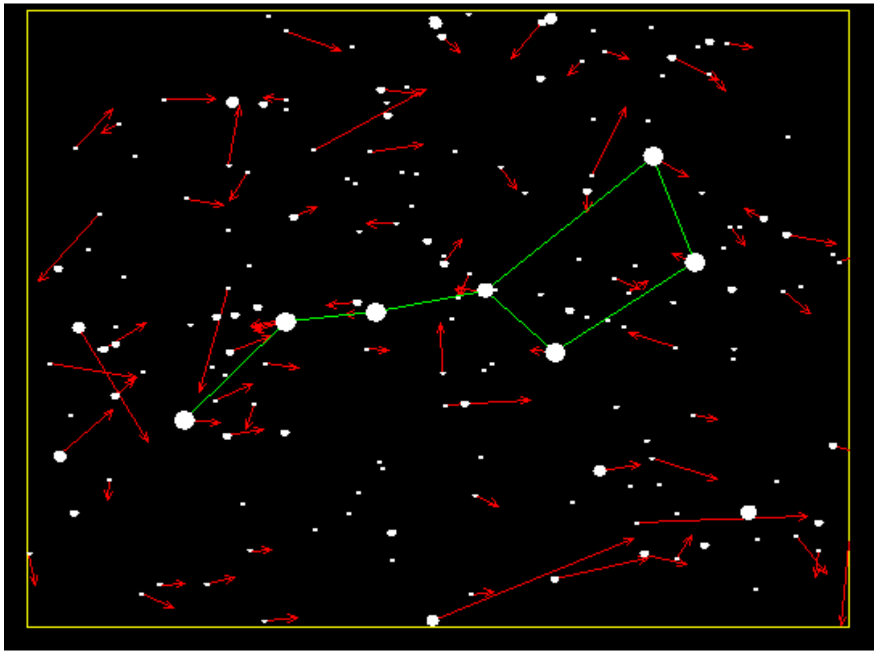
Largest proper motion - **10.3 ”/yr**
(crosses half the moon in a human lifetime)

***Proper motion** is measured in* ***arcsec per year**.*

Typical proper motion: 0.1 ”/yr

Stellar Motions

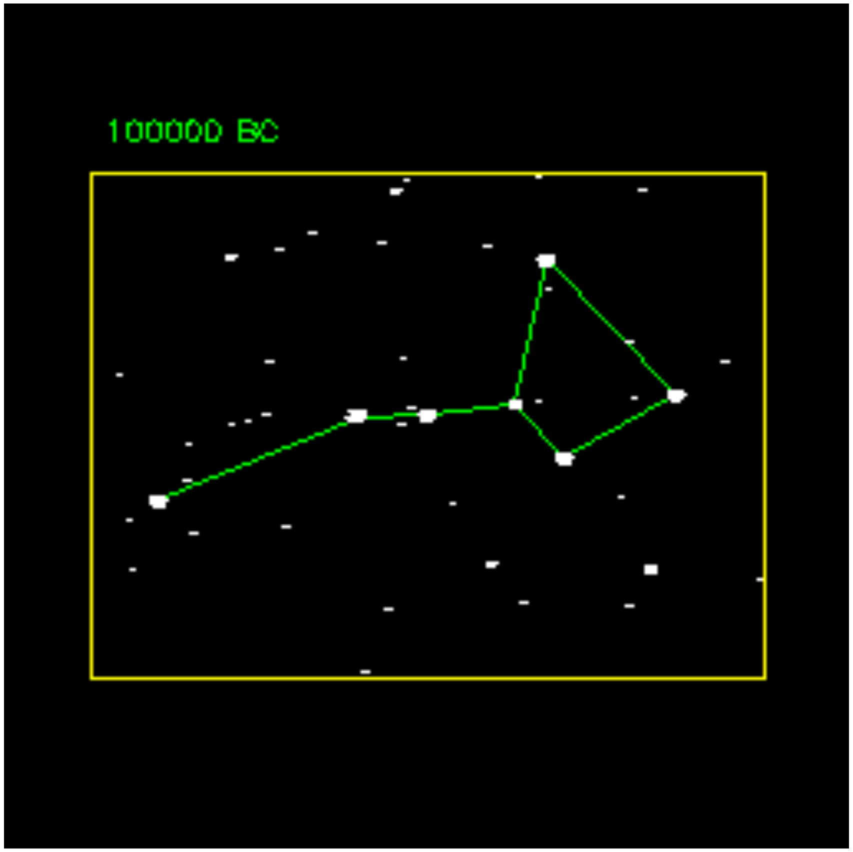
Proper motions of stars at the vicinity of the Big Dipper



Constellations change over time

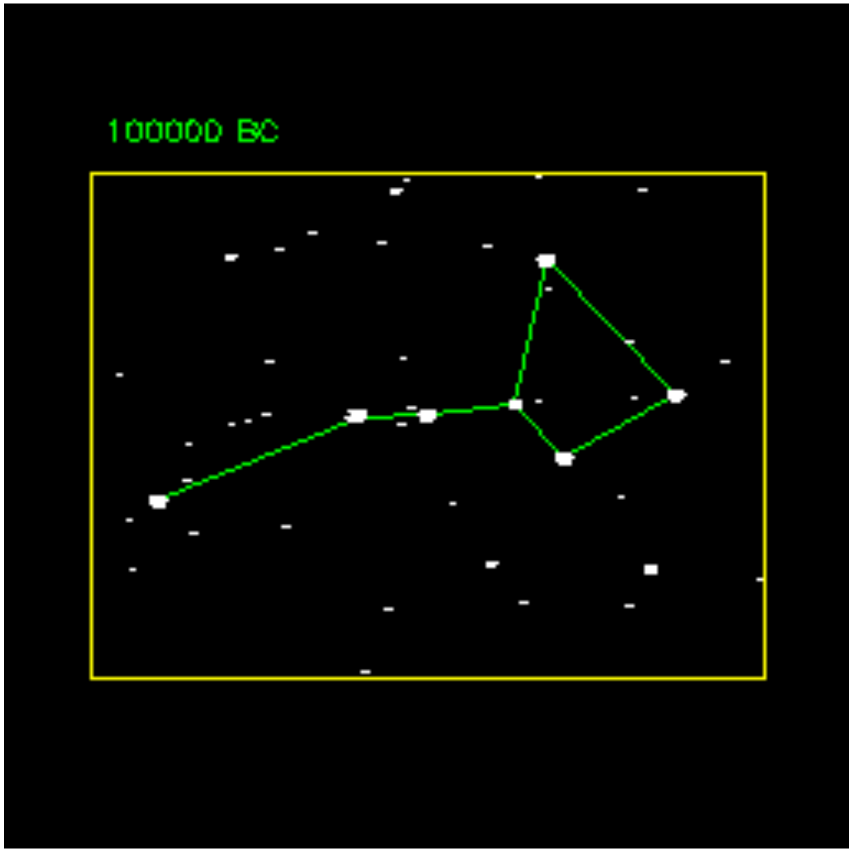
Stellar Motions

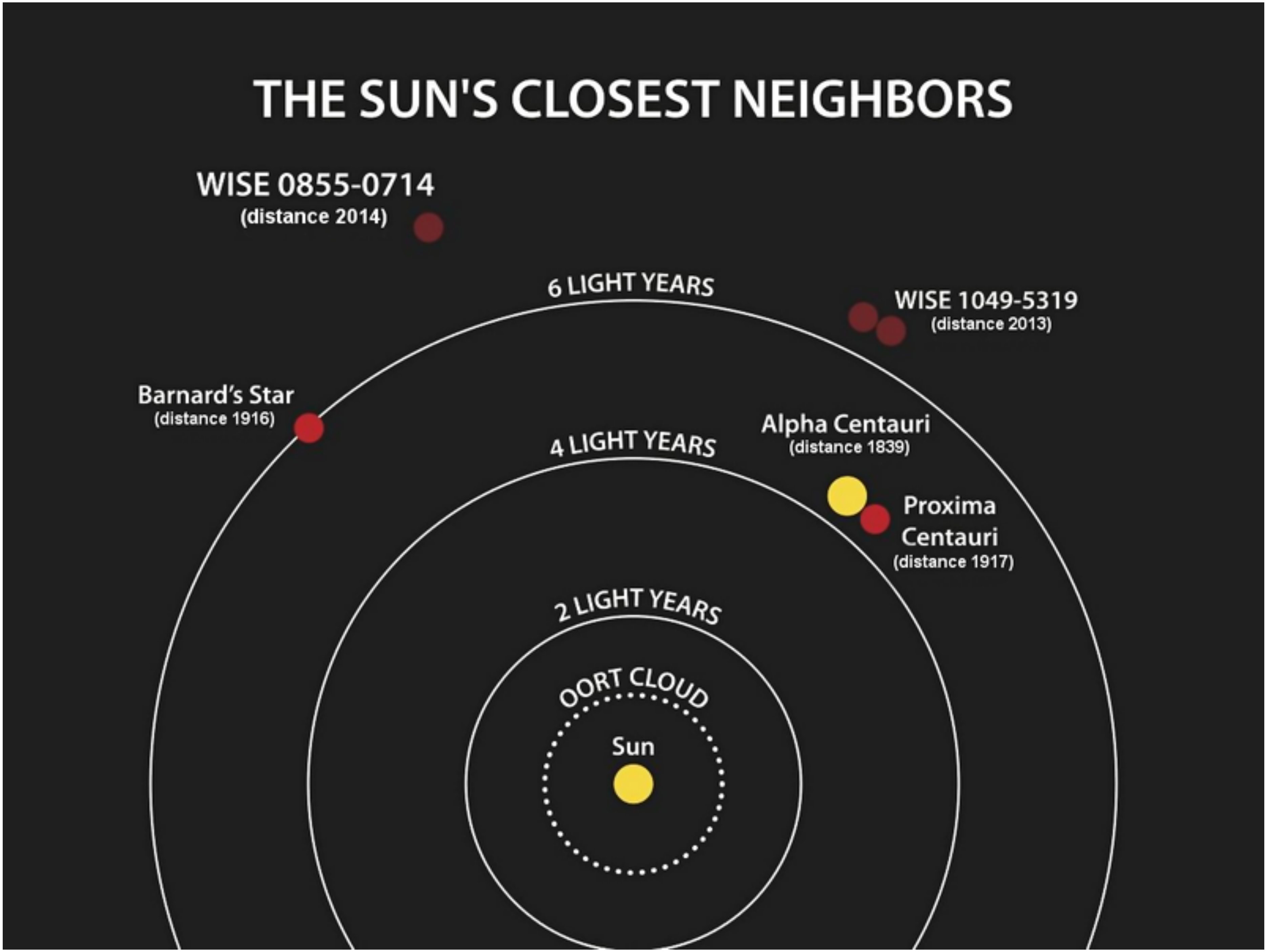
Constellations change over time

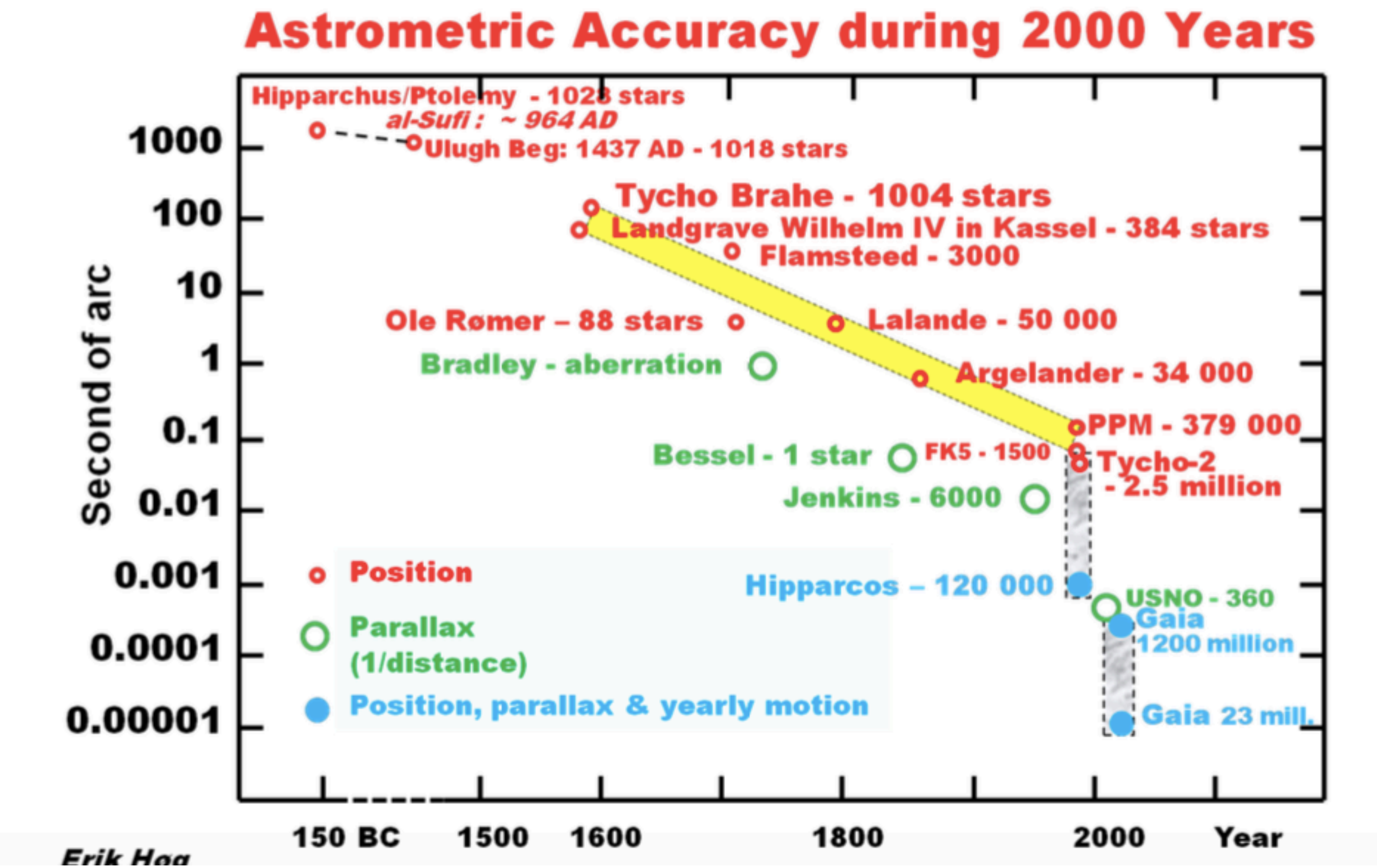


Stellar Motions

Constellations change over time

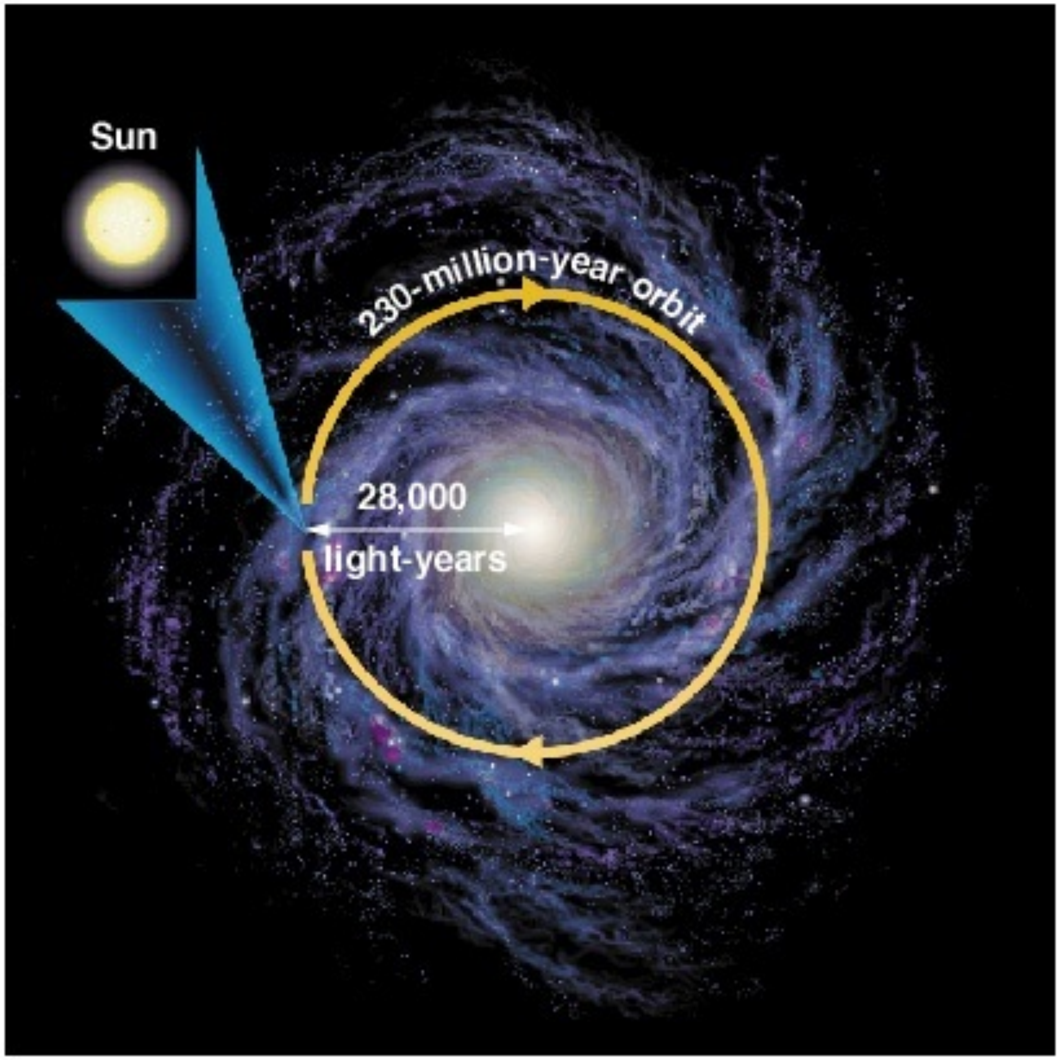



THE SUN'S CLOSEST NEIGHBORS
WISE 0855-0714
(distance 2014)
6 LIGHT YEARS
WISE 1049-5319
(distance 2013)
Barnard's Star
(distance 1916)
Alpha Centauri
(distance 1839)
4 LIGHT YEARS
Proxima
Centauri
(distance 1917)
2 LIGHT YEARS
OORT CLOUD
Sun

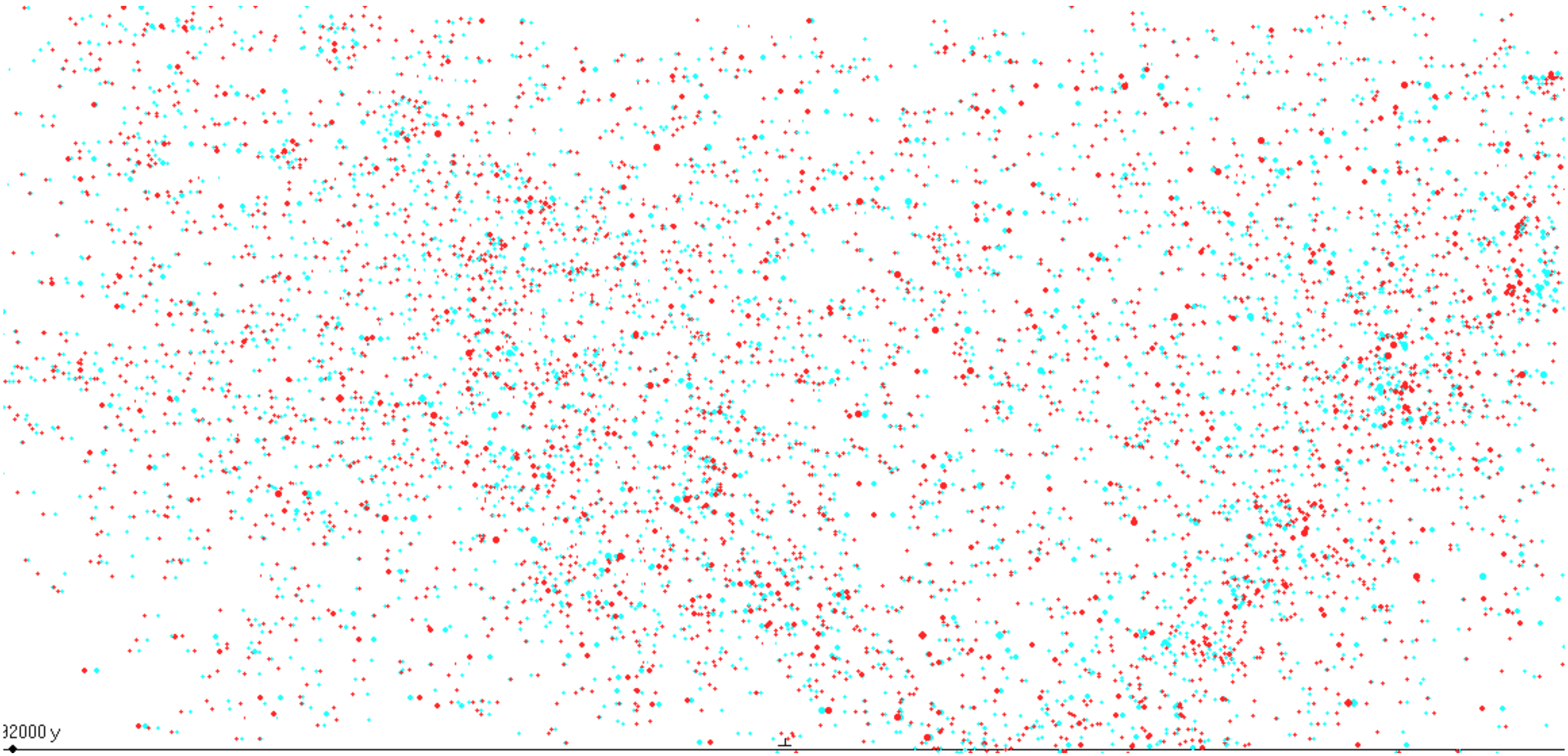


Astrometric Accuracy during 2000 Years
Hipparchus/Ptolemy - 1028 stars
al-Sufi : ~ 964 AD
Ulugh Beg: 1437 AD - 1018 stars
Tycho Brahe - 1004 stars
Landgrave Wilhelm IV in Kassel - 384 stars
Flamsteed - 3000
Ole Rømer – 88 stars
Lalande - 50 000
Bradley - aberration
Argelander - 34 000
PPM - 379 000
Bessel - 1 star
FK5 - 1500
Tycho-2
- 2.5 million
Jenkins - 6000
Hipparcos – 120 000
USNO - 360
Gaia
1200 million
Gaia 23 mill.
Position
Parallax
(1/distance)
Position, parallax & yearly motion
Second of arc
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
150 BC
1500
1600
1800
2000
Year
Erik Høg

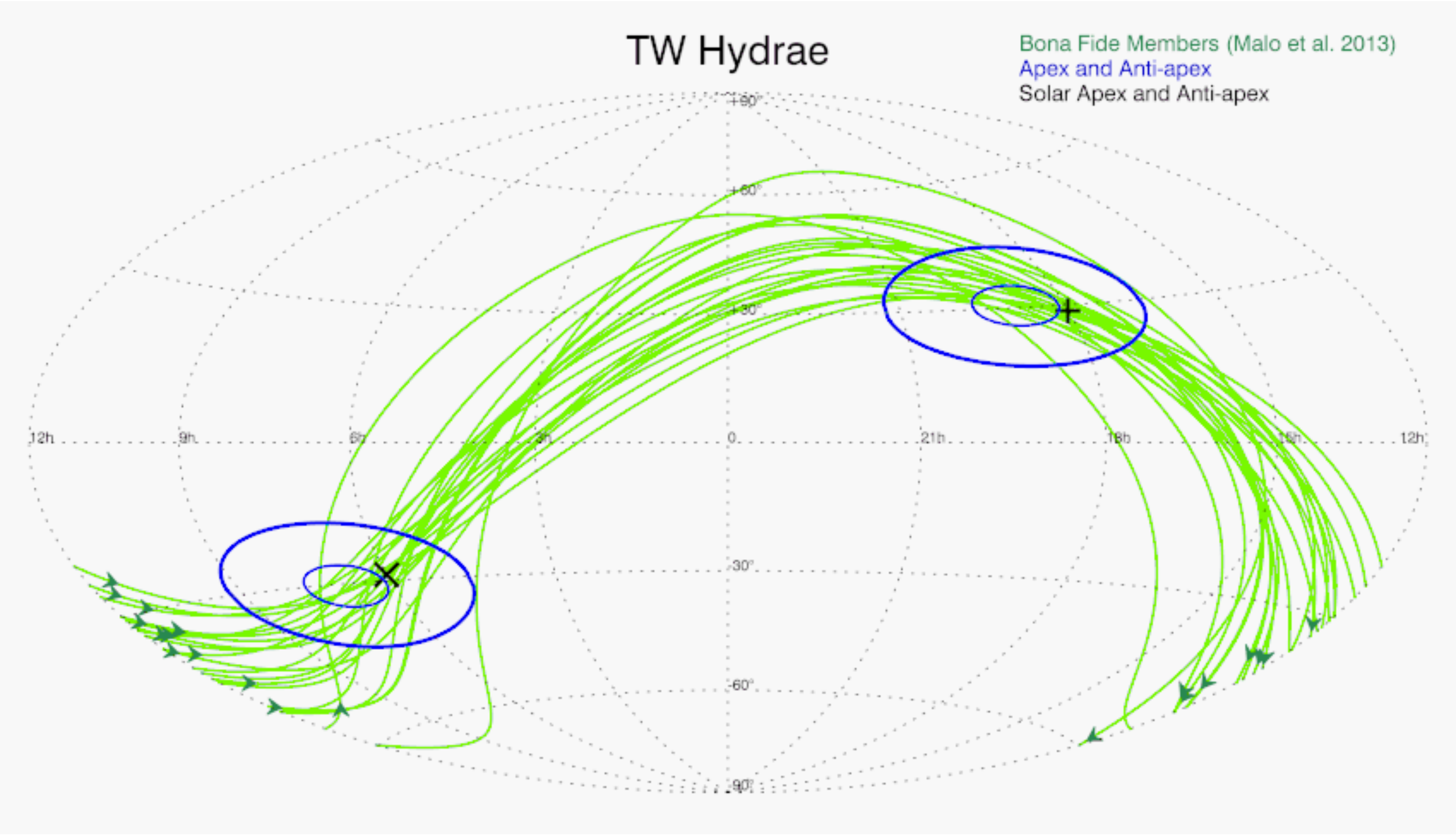
Solar Orbit



Solar Apex and Anti-Apex



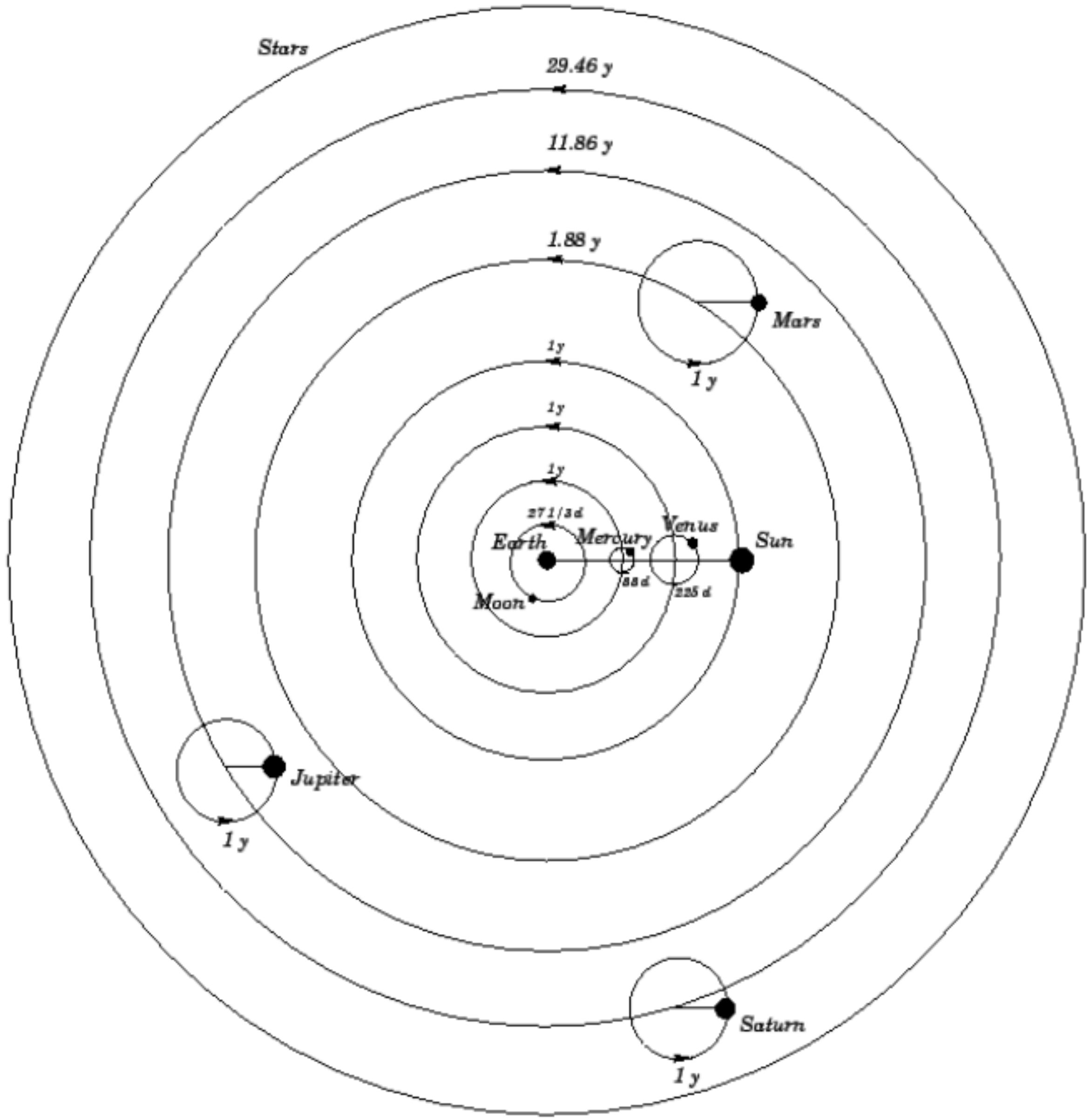
Solar Apex and Anti-Apex



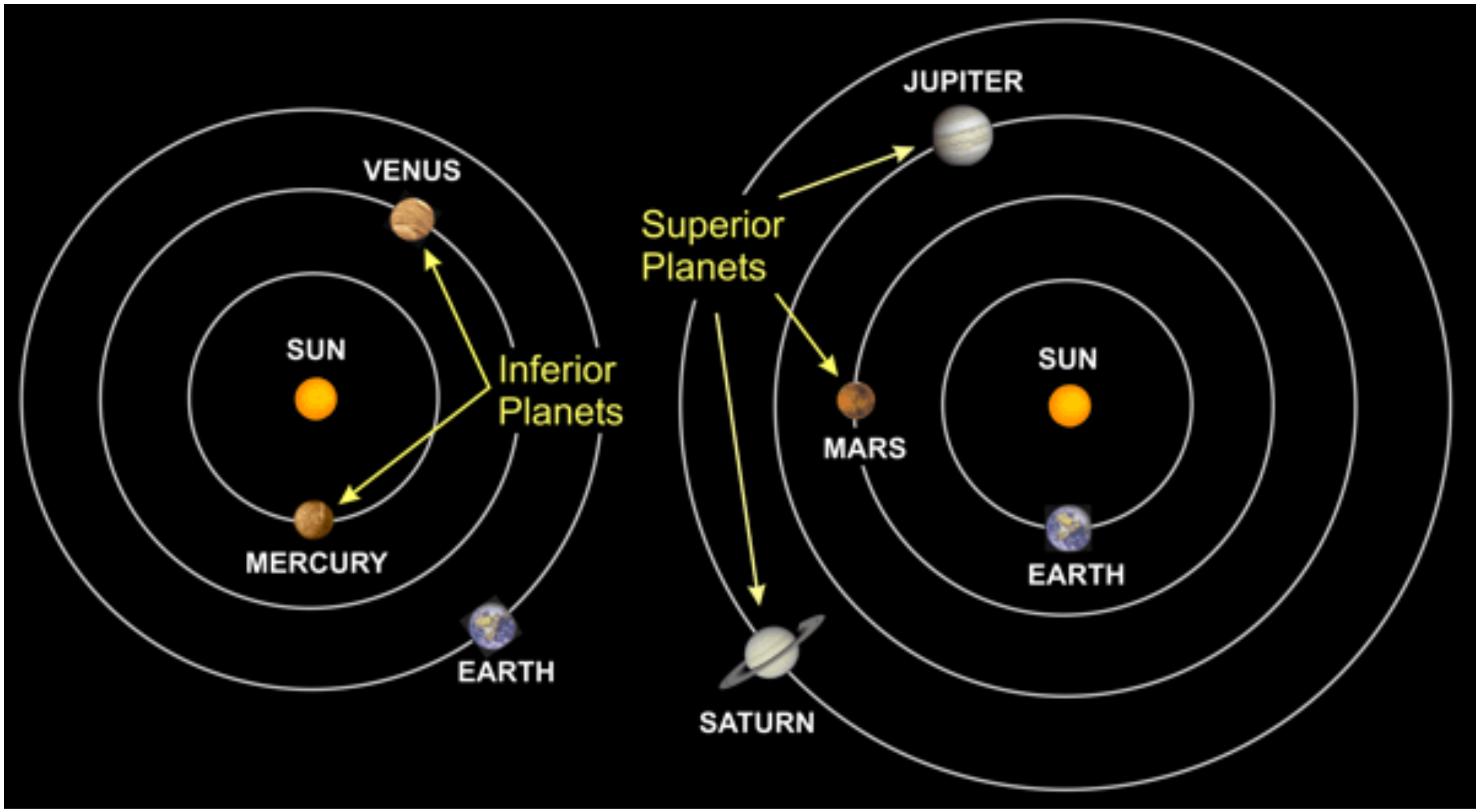
Elongation

angle between a Planet and the Sun

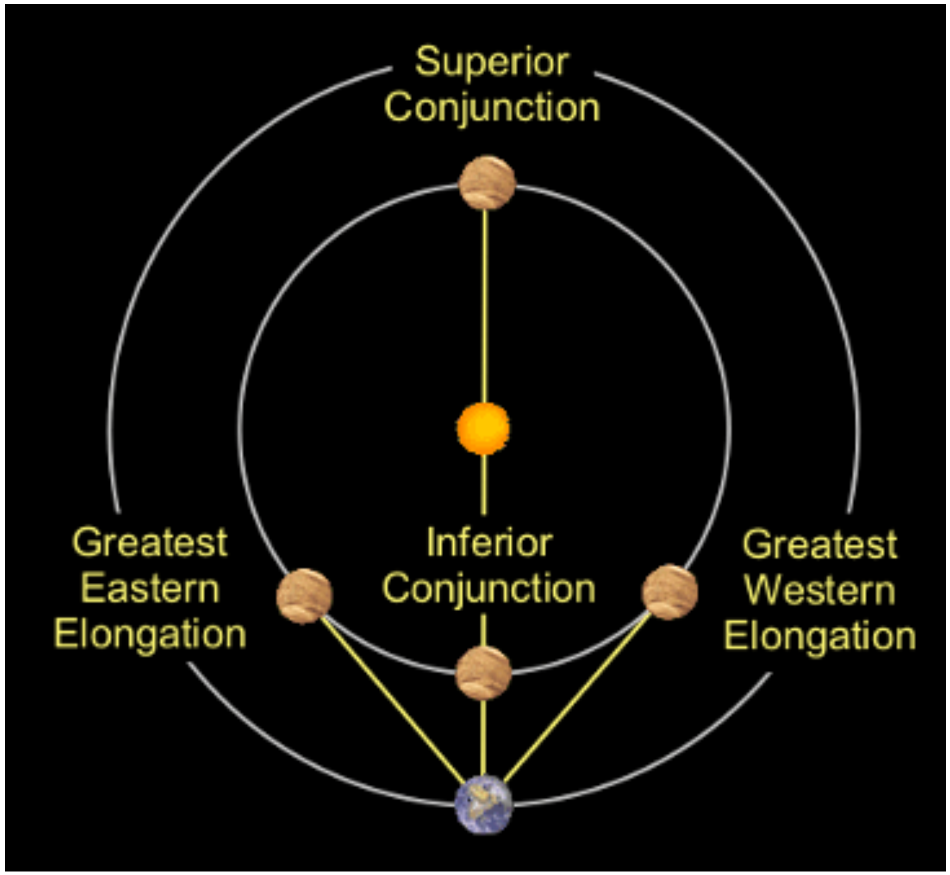
The Ptolemaic Model



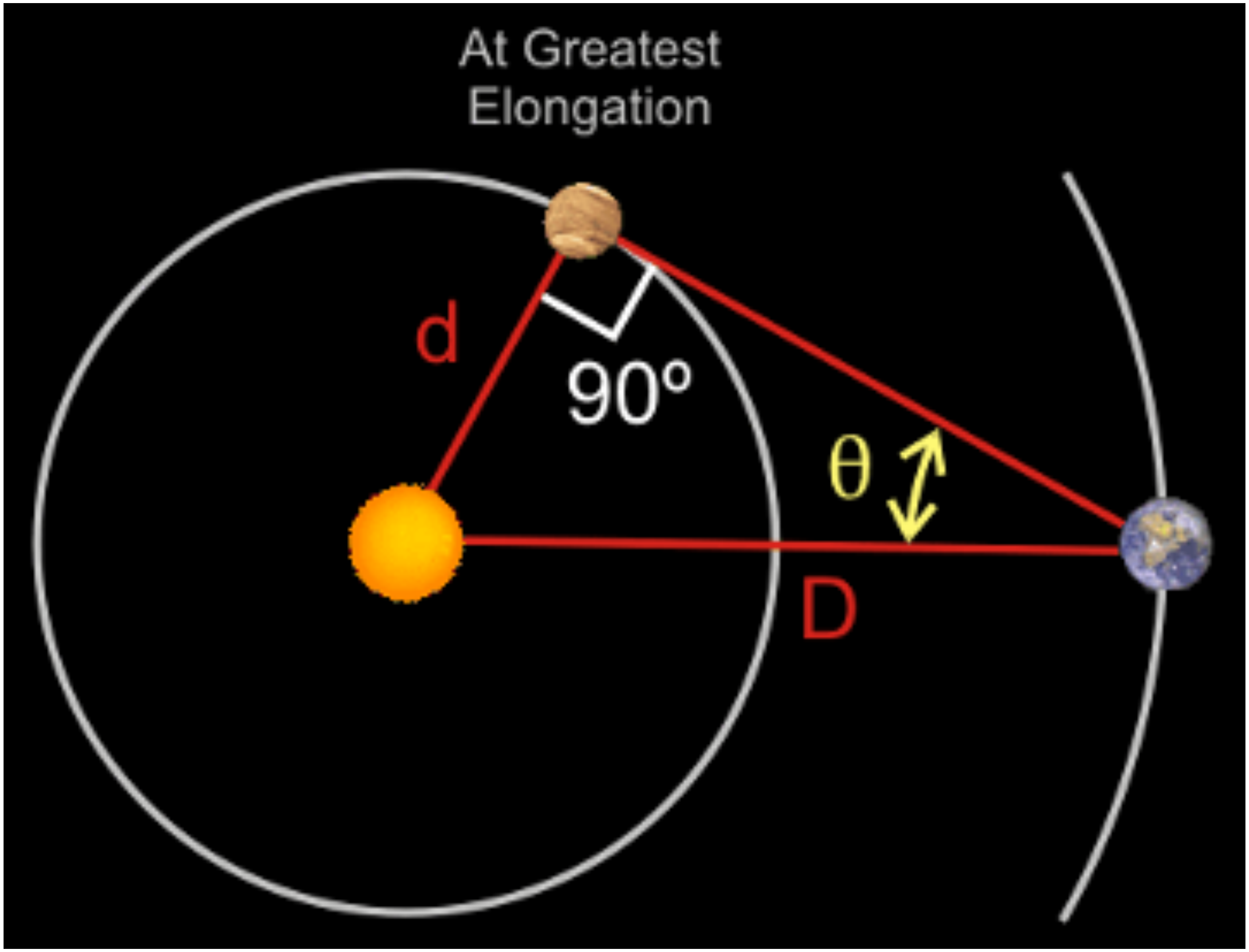
Inferior and Superior planets in the Copernican Model



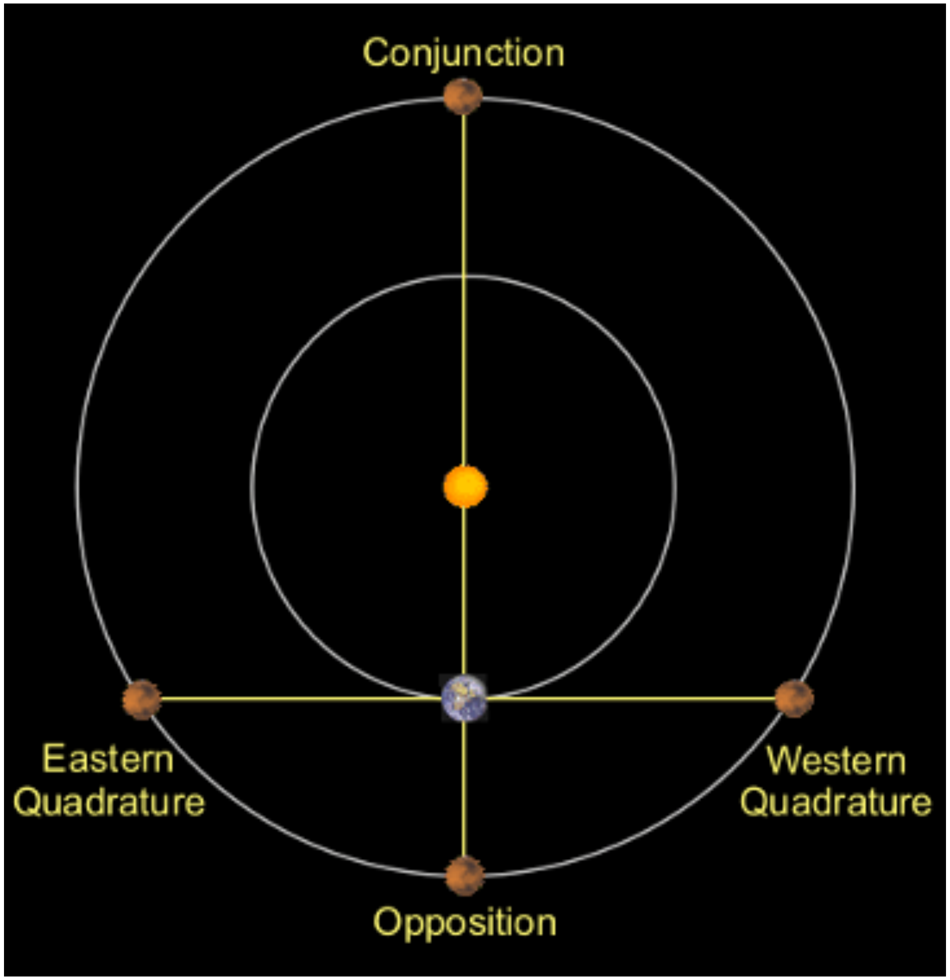
Inferior planets : special points

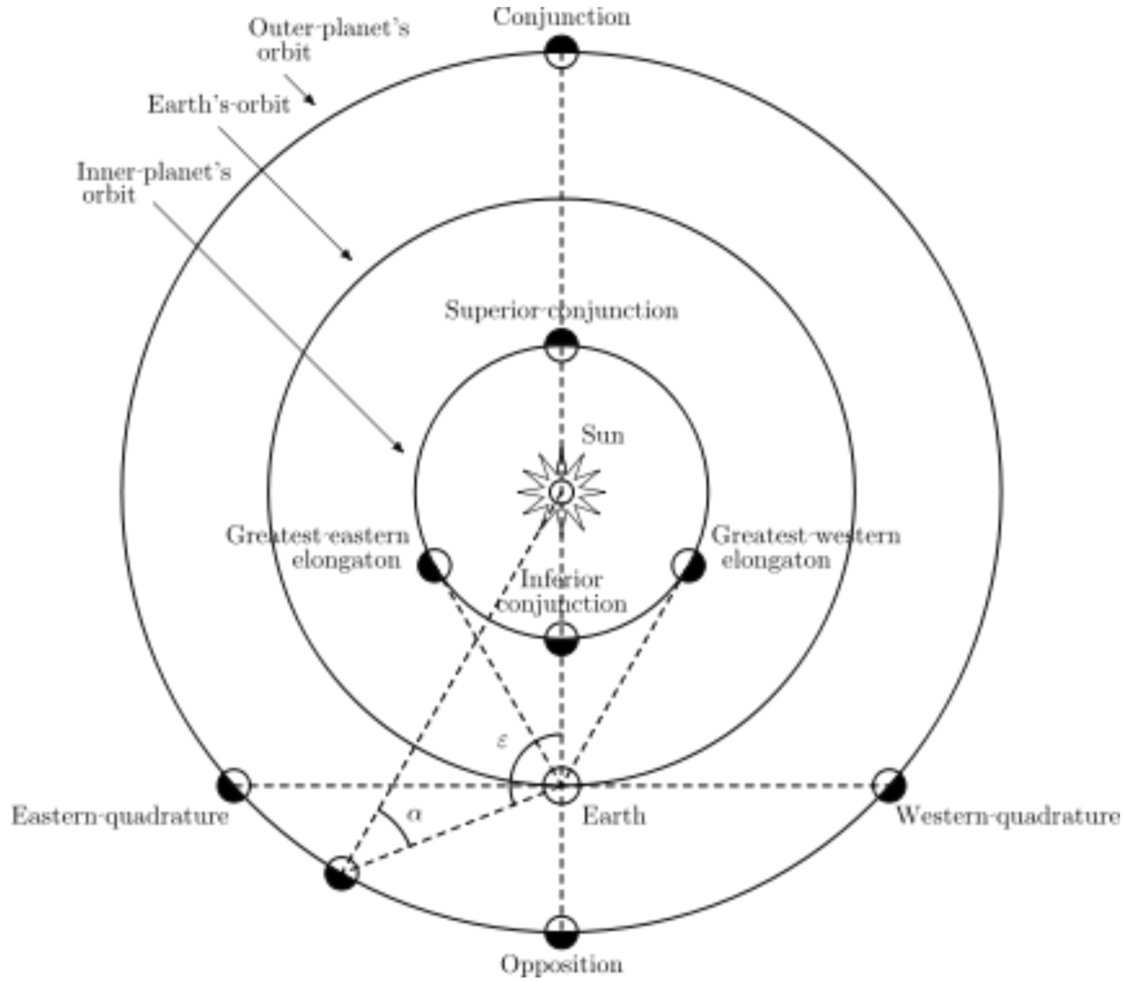


Distance to the inferior planets

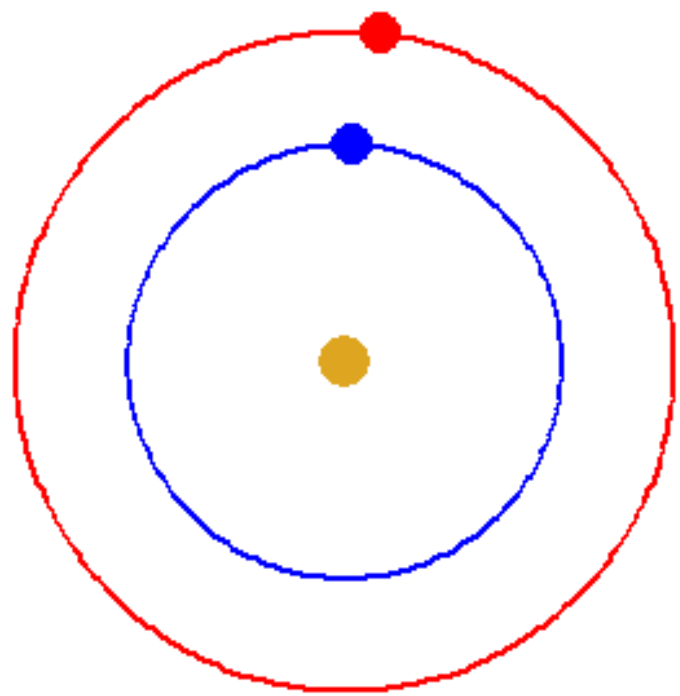


Superior planets : special points

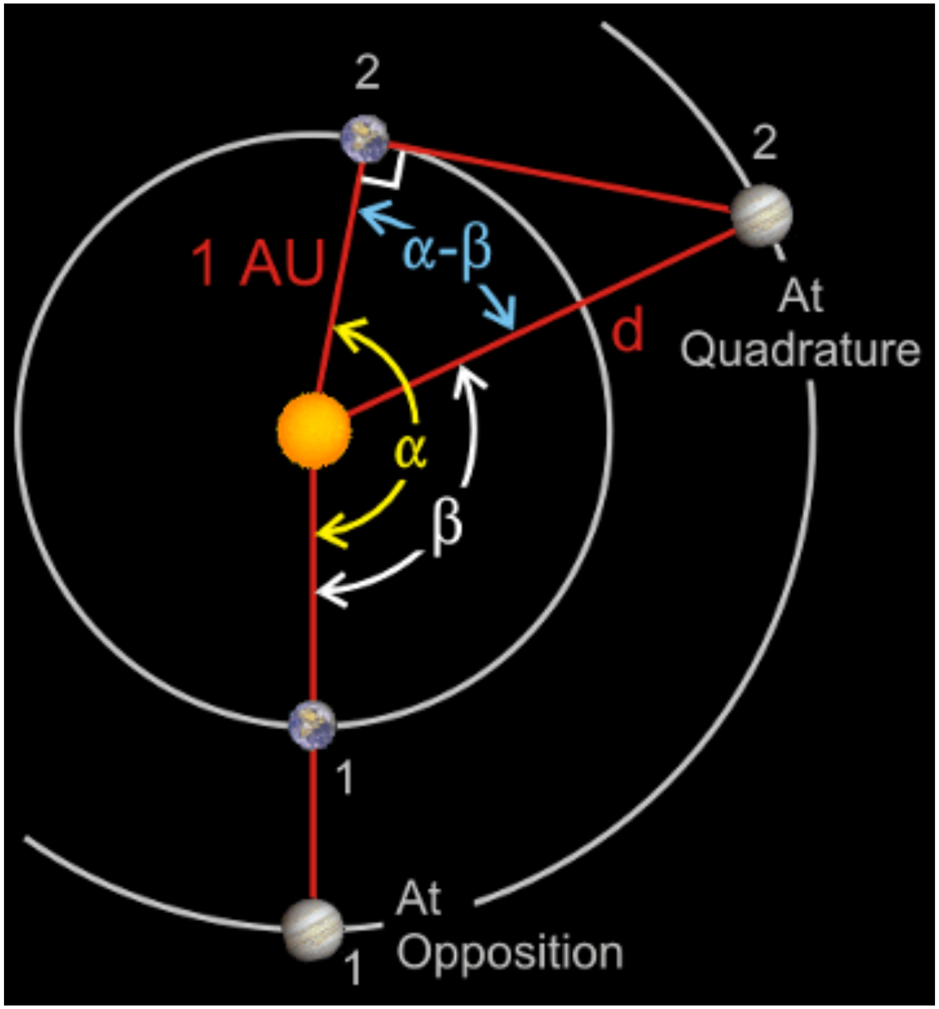




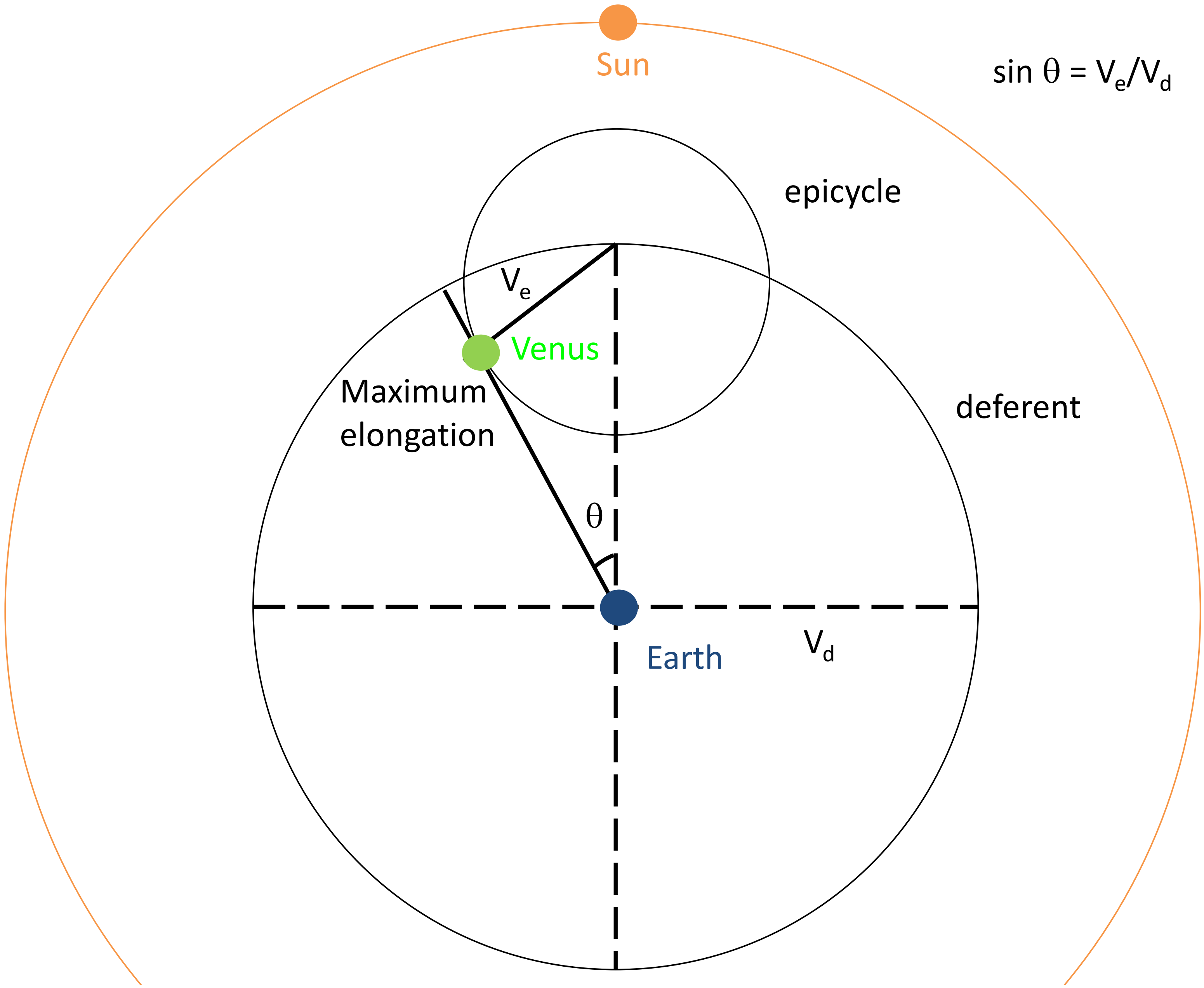
Conjunction
Outer-planet's orbit
Earth's-orbit
Inner-planet's orbit
Superior-conjunction
Sun
Greatest-eastern elongaton
Greatest-western elongaton
Inferior conjunction
ε
Eastern-quadrature
α
Earth
Western-quadrature
Opposition

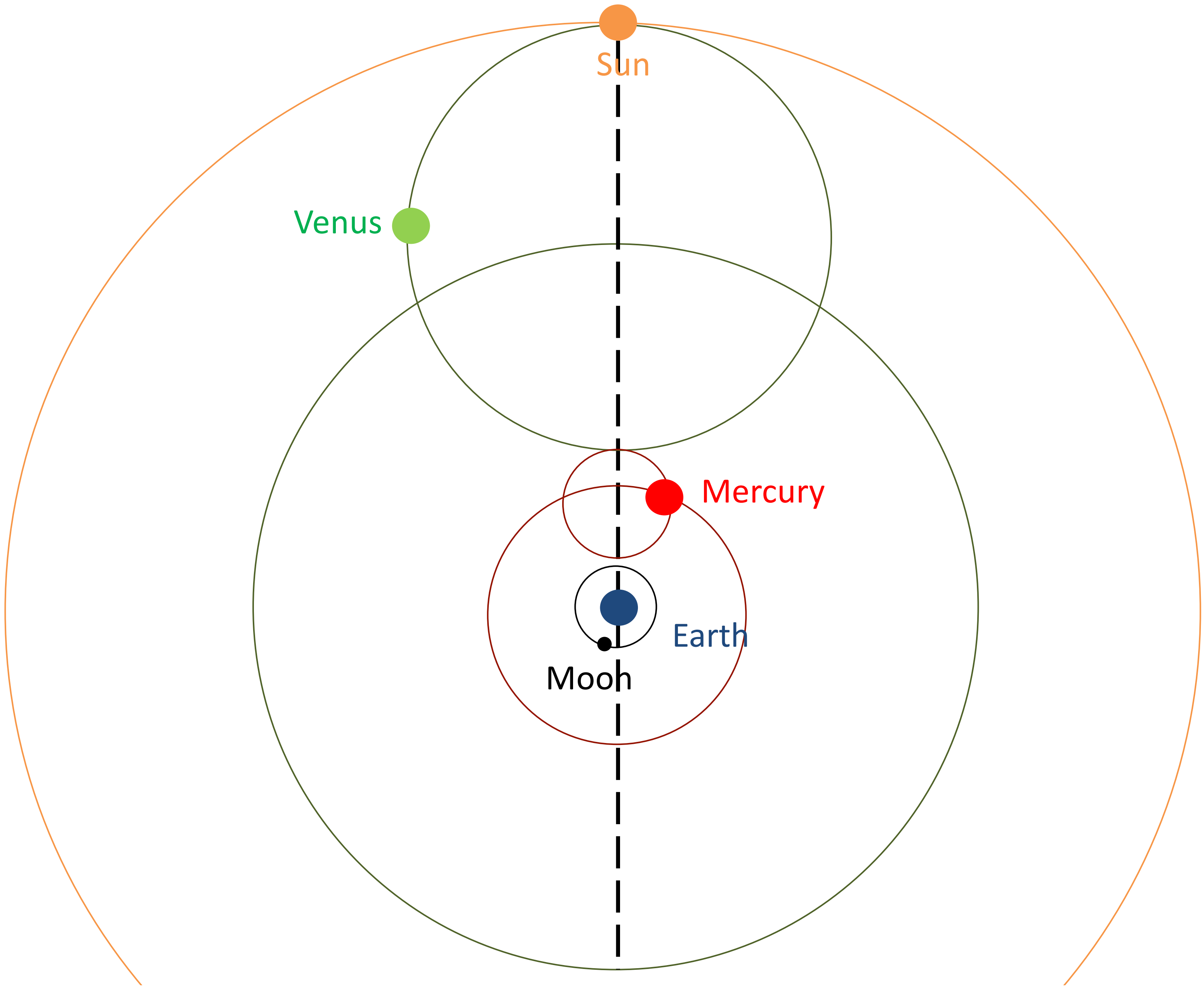


Distances to the superior planets



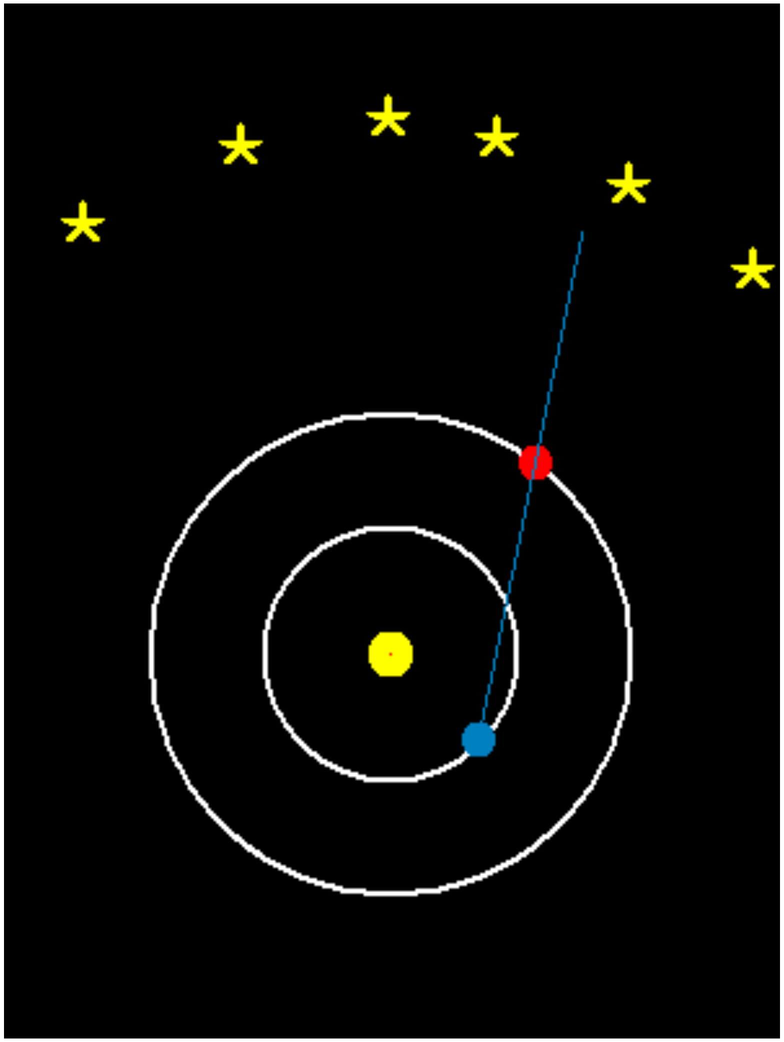
Distance to the inferior planets: Ptolemaic System



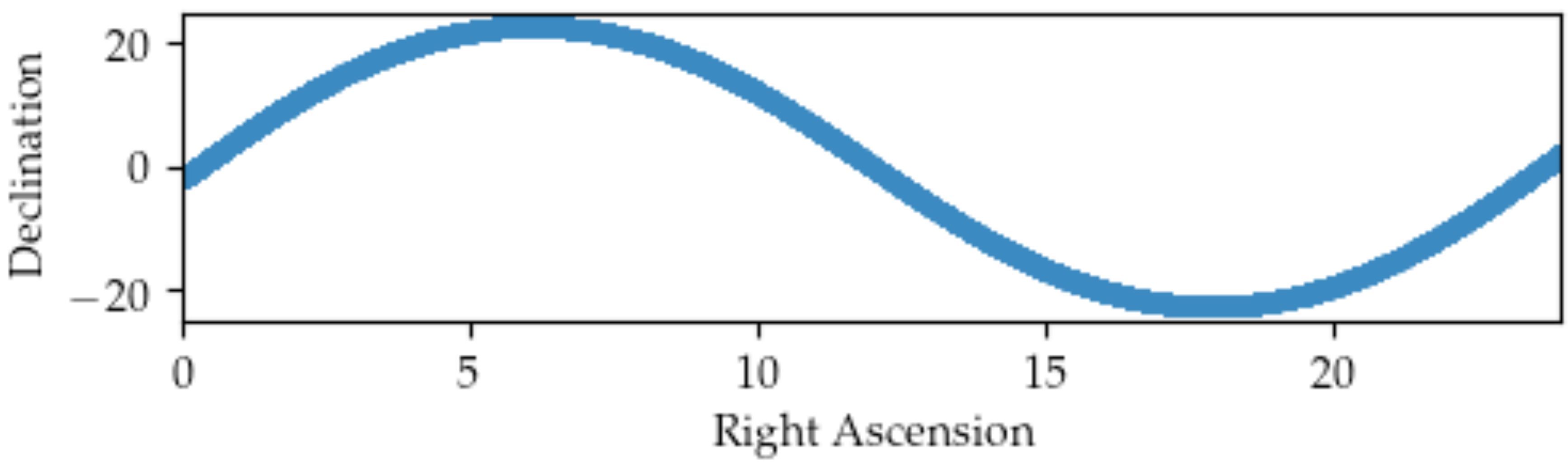

Sun
Venus
Mercury
Earth
Moon

Retrograde Motion

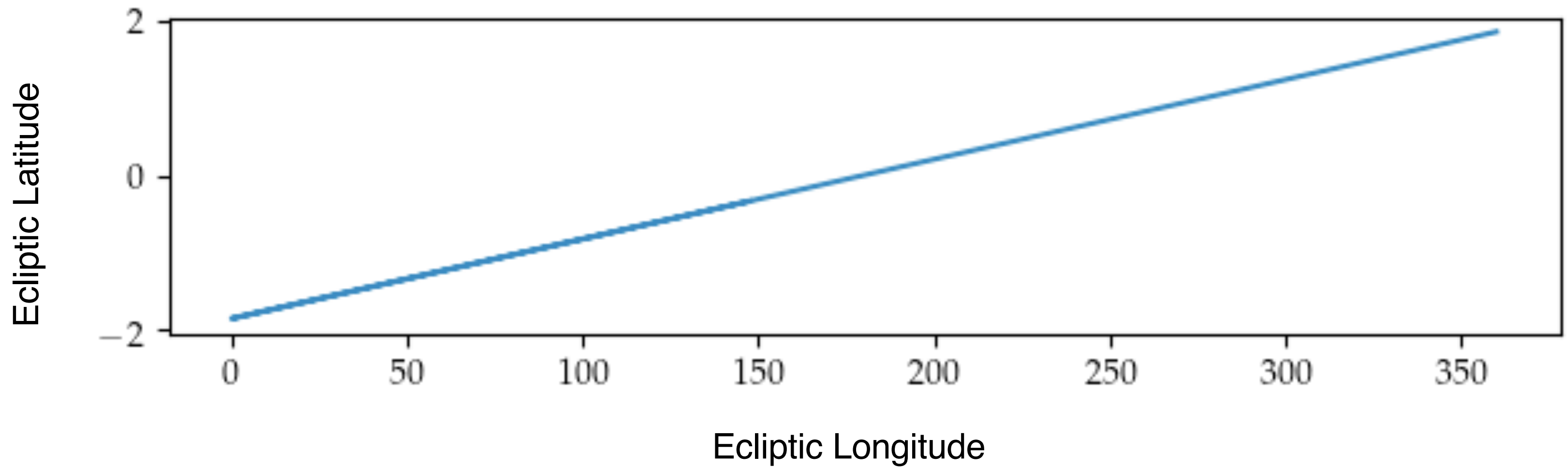
Retrograde Motion

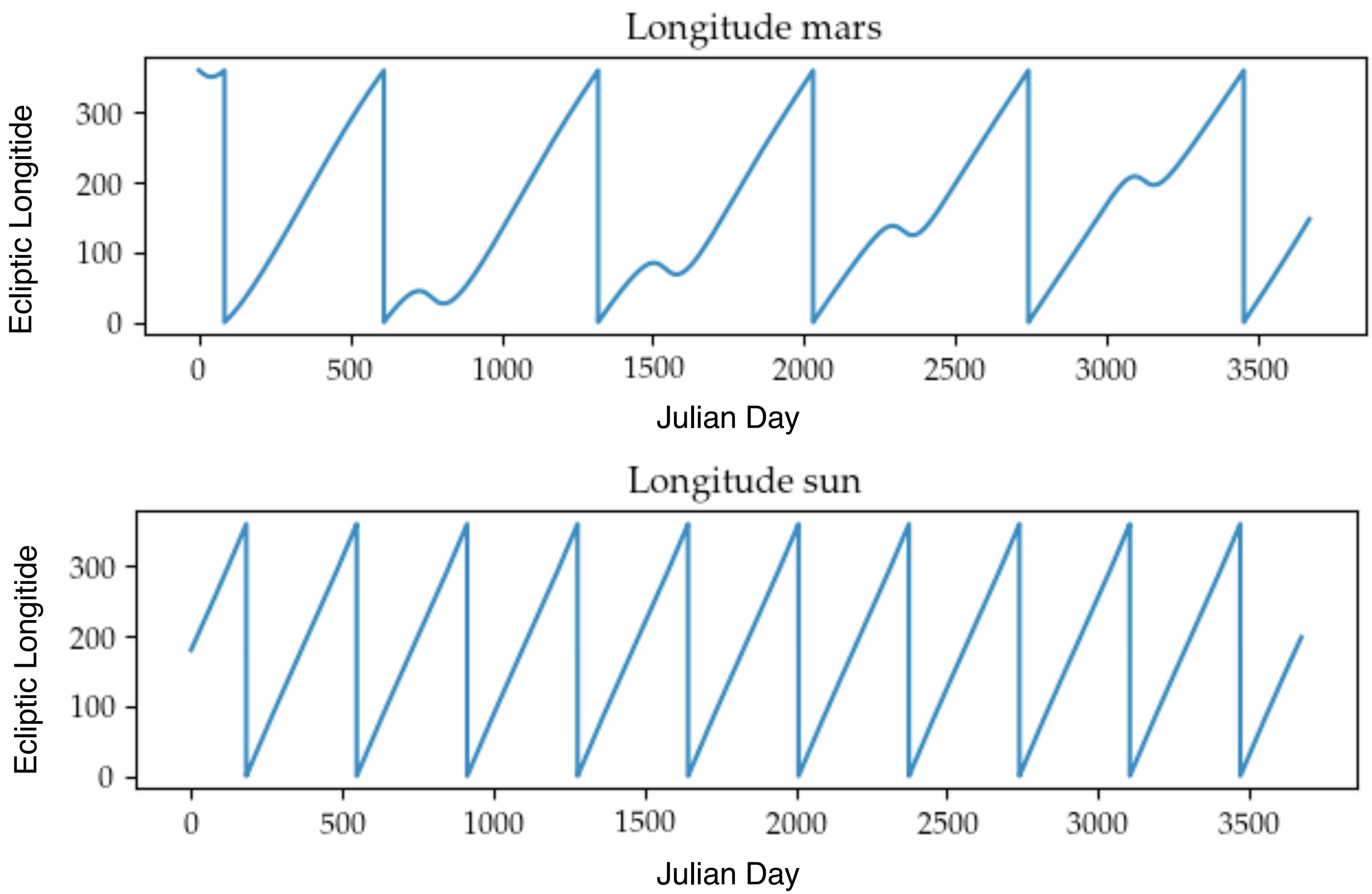


Mars Path in the Sky – Equatorial Coordinates

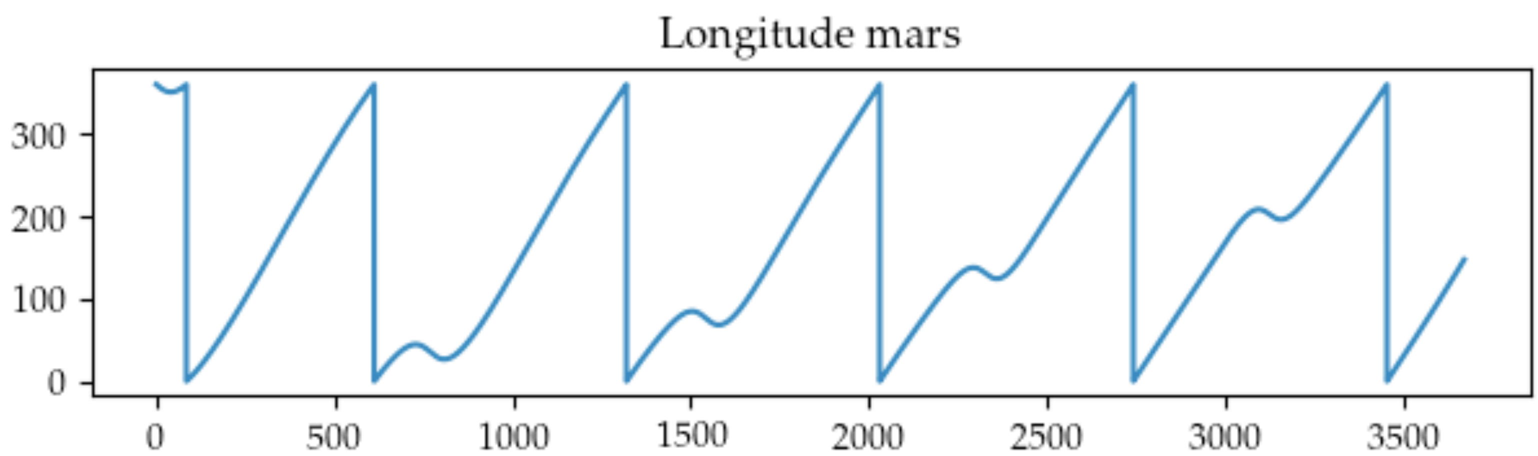


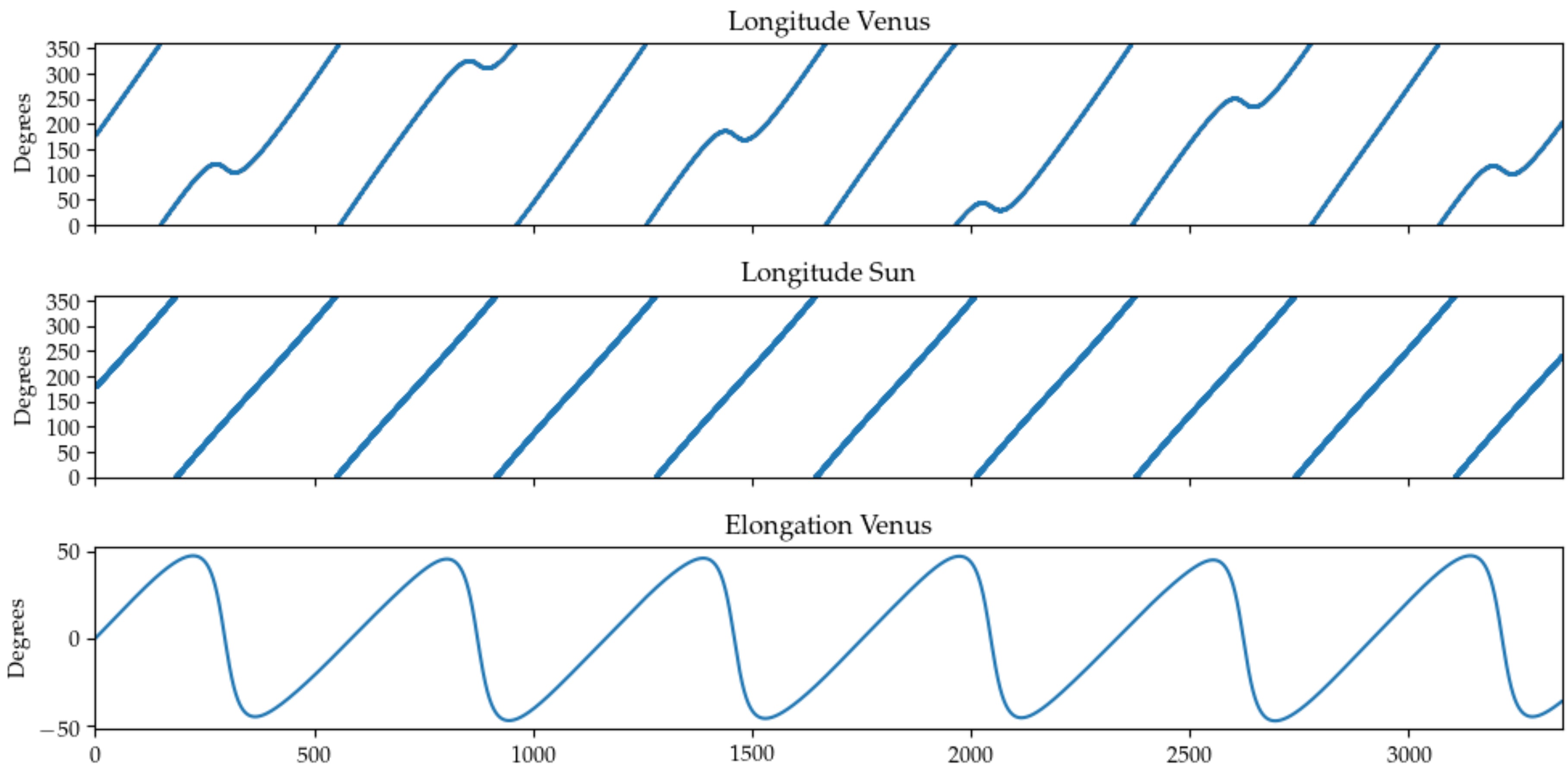
Mars Path in the Sky – Ecliptic Coordinates



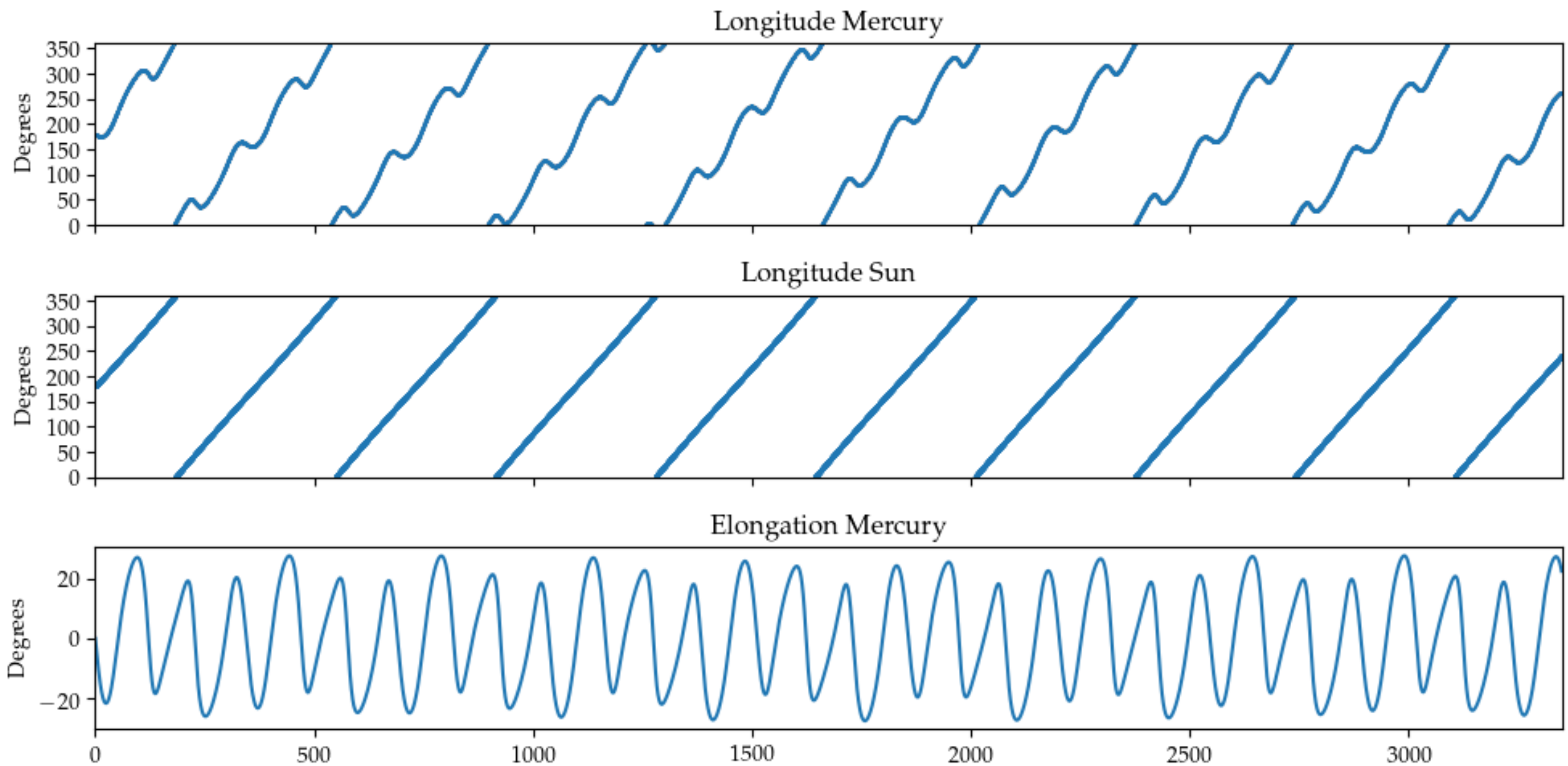


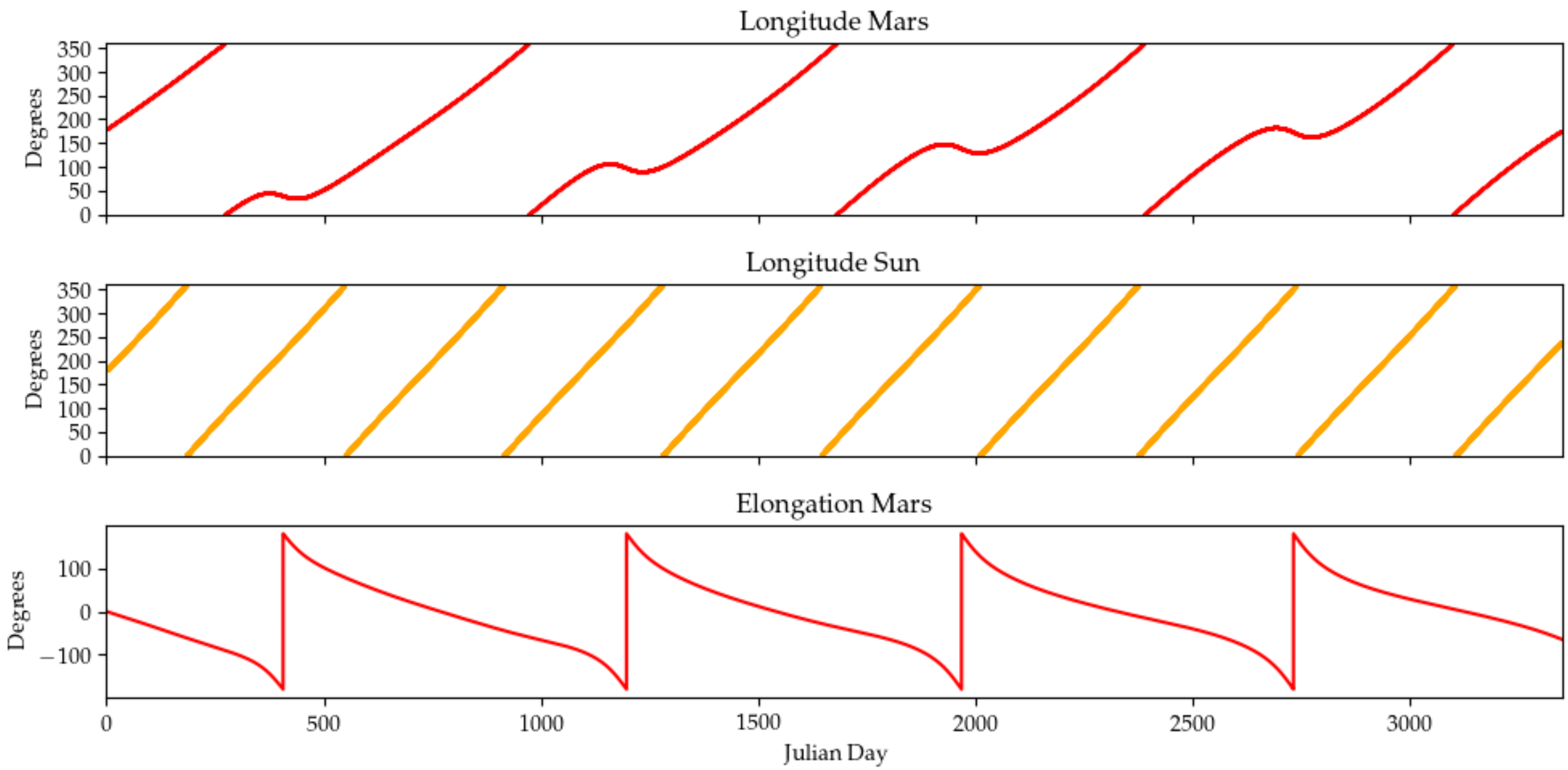
Longitude mars
Ecliptic Longitide
0
100
200
300
0
500
1000
1500
2000
2500
3000
3500
Julian Day
Longitude sun
Ecliptic Longitide
0
100
200
300
0
500
1000
1500
2000
2500
3000
3500
Julian Day


Longitude mars
0
100
200
300
0
500
1000
1500
2000
2500
3000
3500

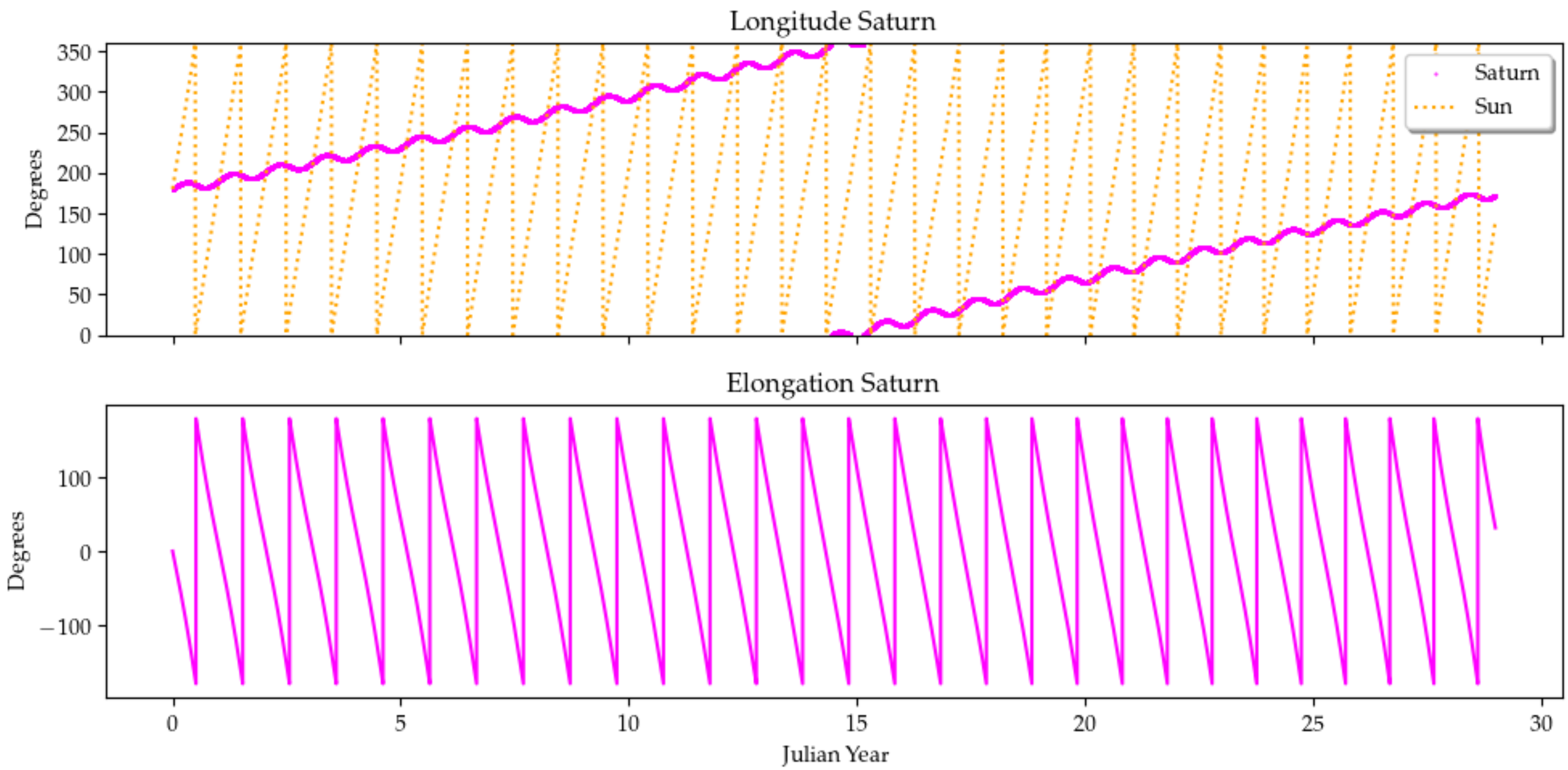


Longitude Venus
Degrees
350
300
250
200
150
100
50
0
Longitude Sun
Degrees
350
300
250
200
150
100
50
0
Elongation Venus
Degrees
50
0
−50
0
500
1000
1500
2000
2500
3000

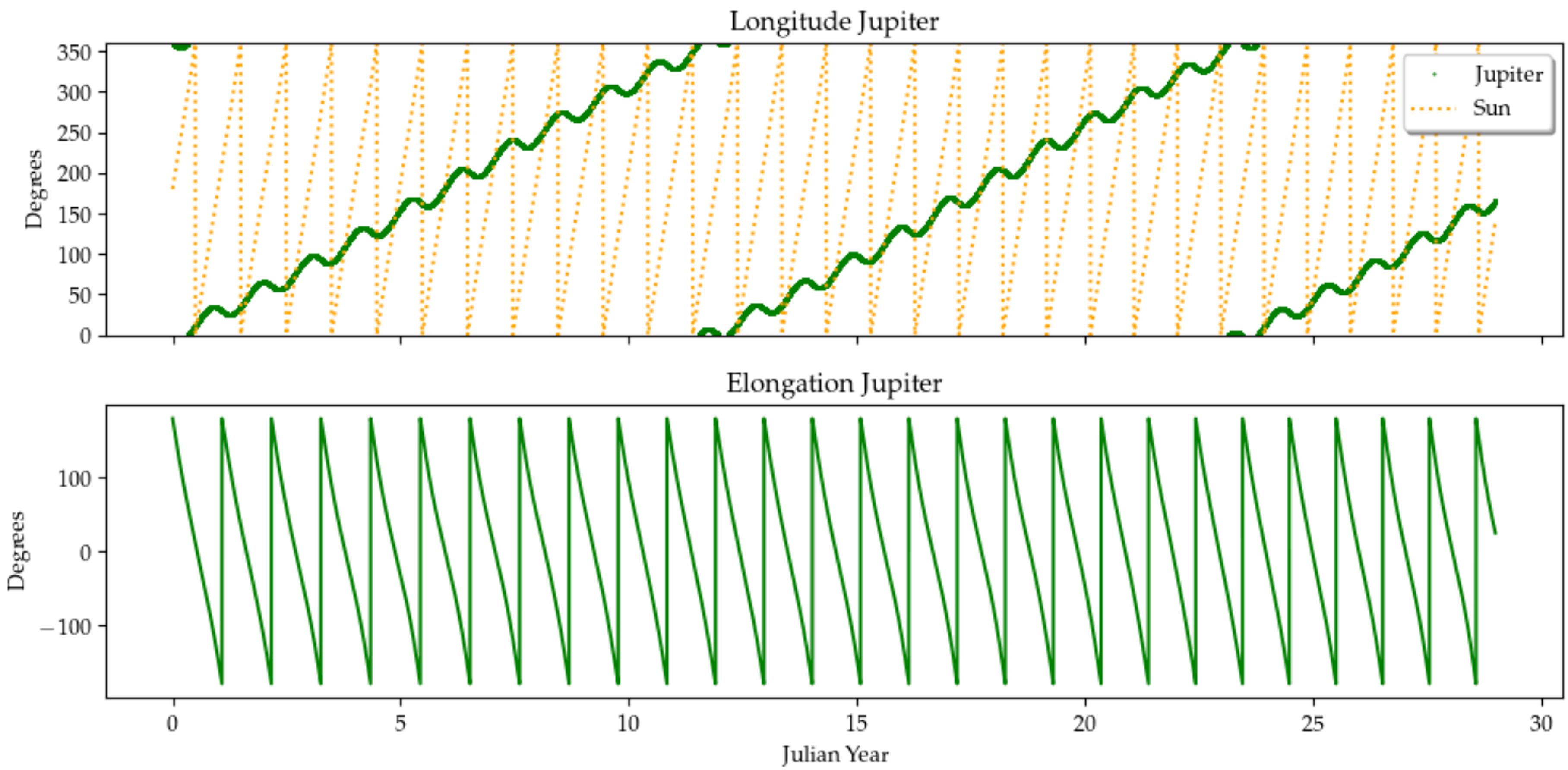

Longitude Mercury
Degrees
350
300
250
200
150
100
50
0
Longitude Sun
Degrees
350
300
250
200
150
100
50
0
Elongation Mercury
Degrees
20
0
−20
0
500
1000
1500
2000
2500
3000

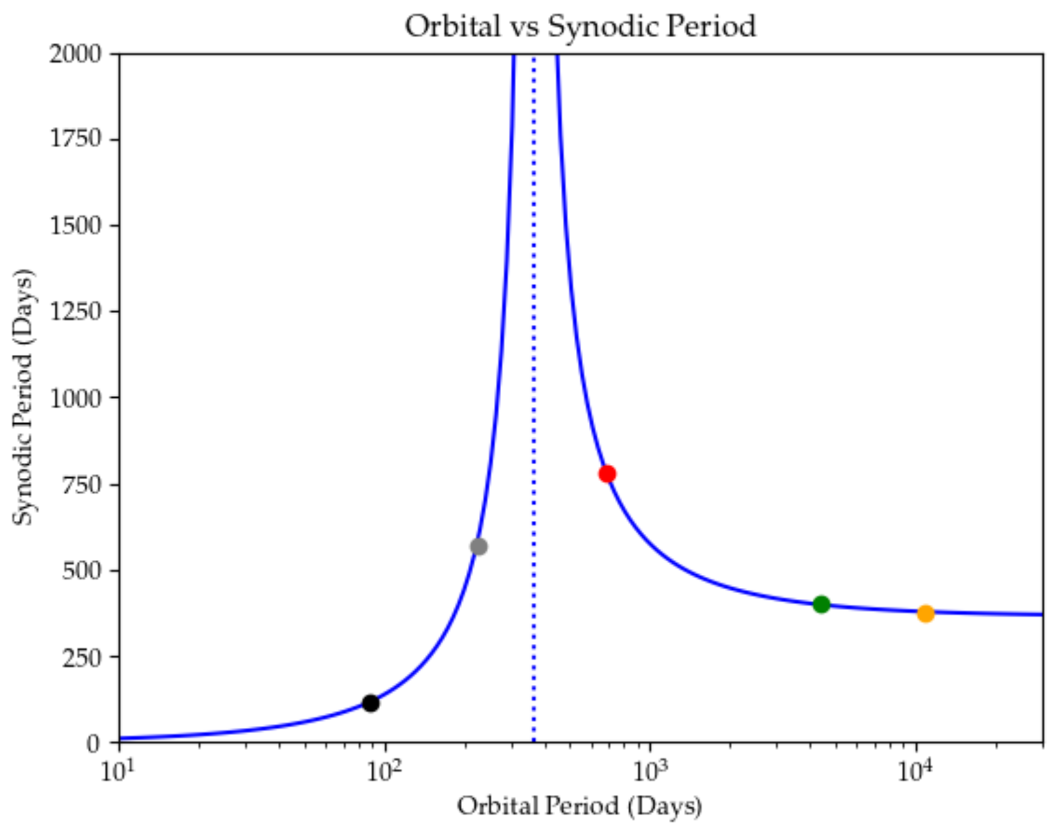


Longitude Mars
Degrees
350
300
250
200
150
100
50
0
Longitude Sun
Degrees
350
300
250
200
150
100
50
0
Elongation Mars
Degrees
100
0
−100
0
500
1000
1500
2000
2500
3000
Julian Day



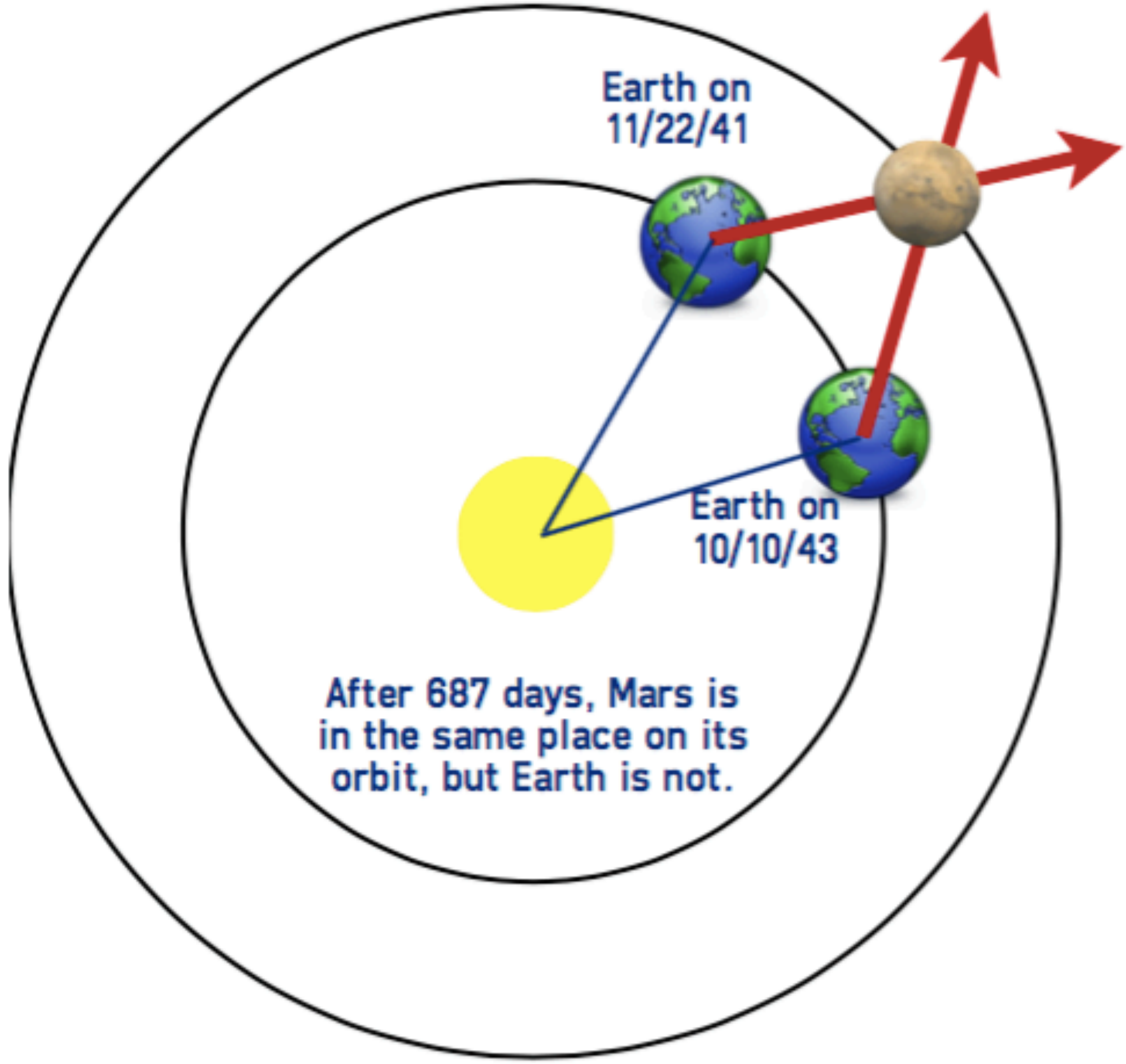
Longitude Saturn
Saturn
Sun
Degrees
350
300
250
200
150
100
50
0
Elongation Saturn
Degrees
100
0
−100
0
5
10
15
20
25
30
Julian Year

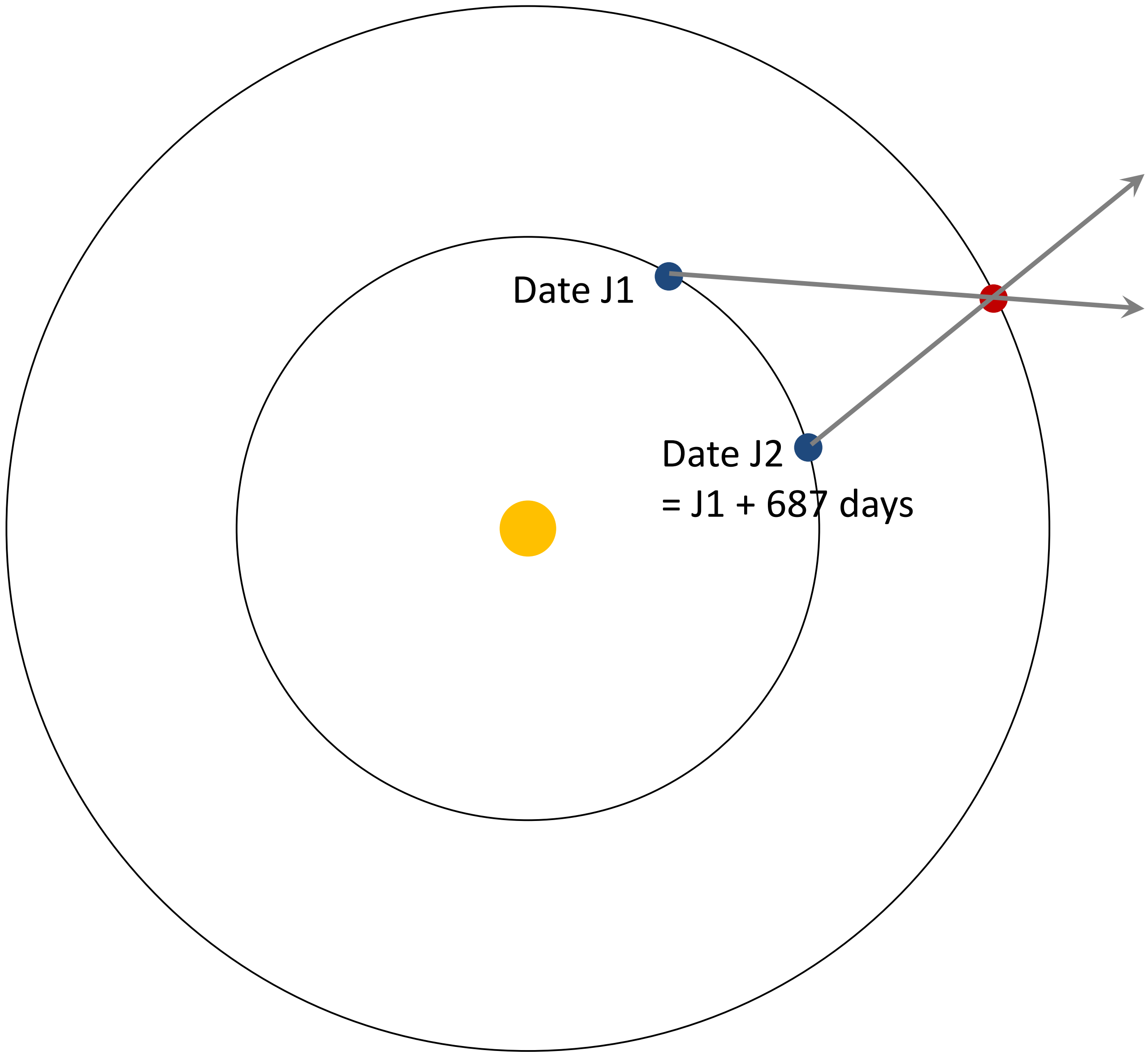

Longitude Jupiter
Degrees
350
300
250
200
150
100
50
0
Jupiter
Sun
Elongation Jupiter
Degrees
100
0
−100
0
5
10
15
20
25
30
Julian Year



Orbital vs Synodic Period
2000
1750
1500
1250
1000
750
500
250
0
Synodic Period (Days)
10^1
10^2
10^3
10^4
Orbital Period (Days)

Constructing an Orbit




Date J1
Date J2
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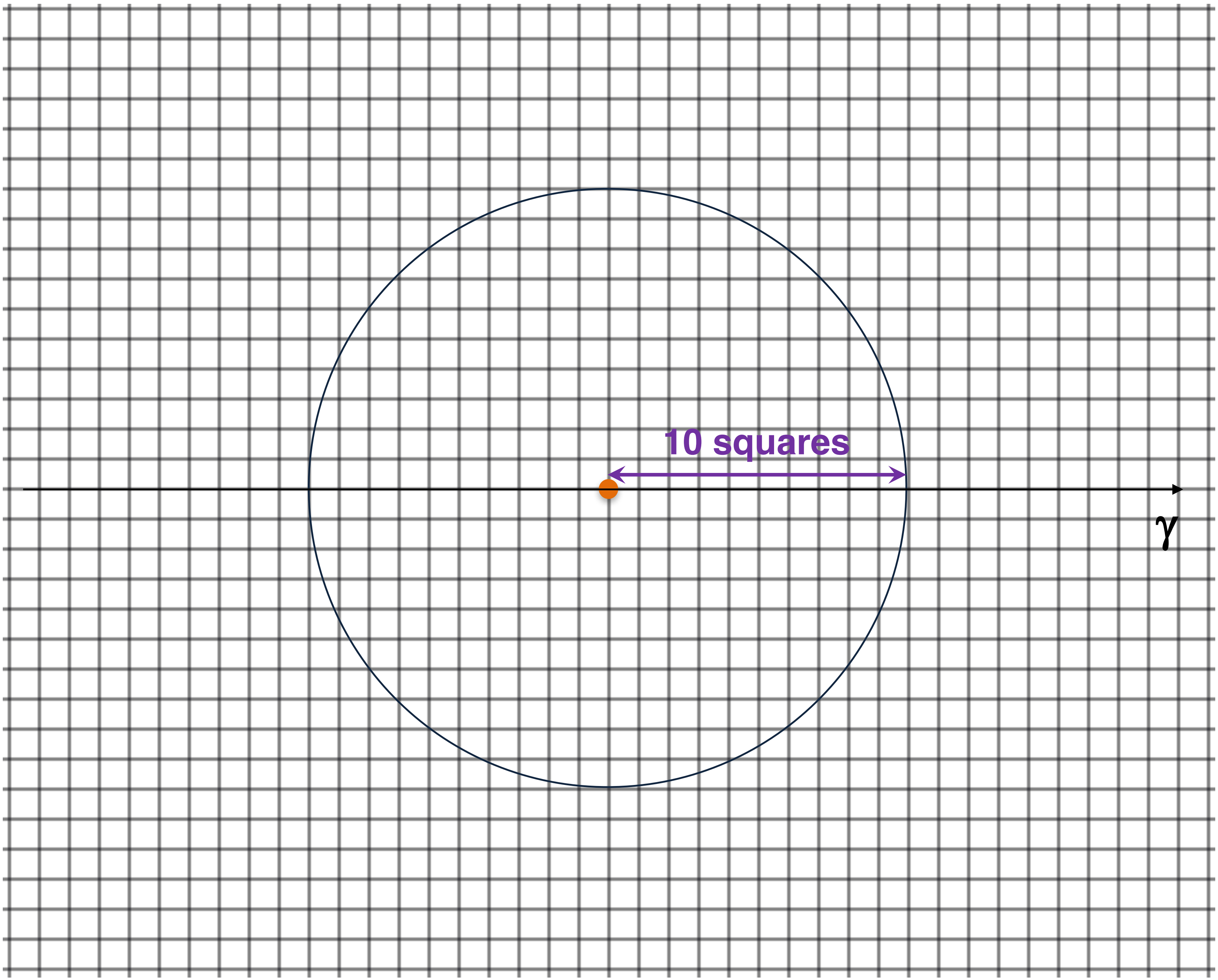
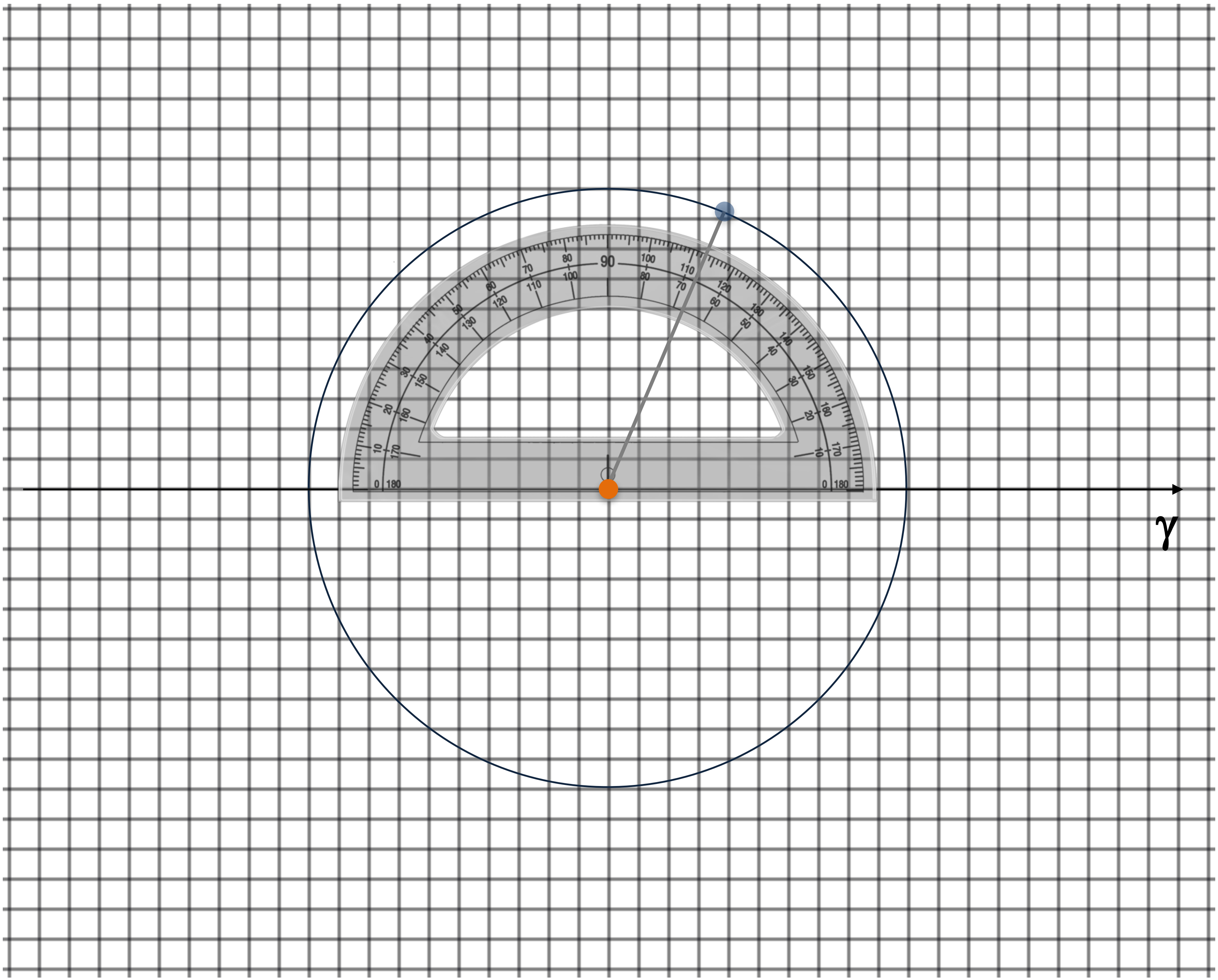

10 squares
γ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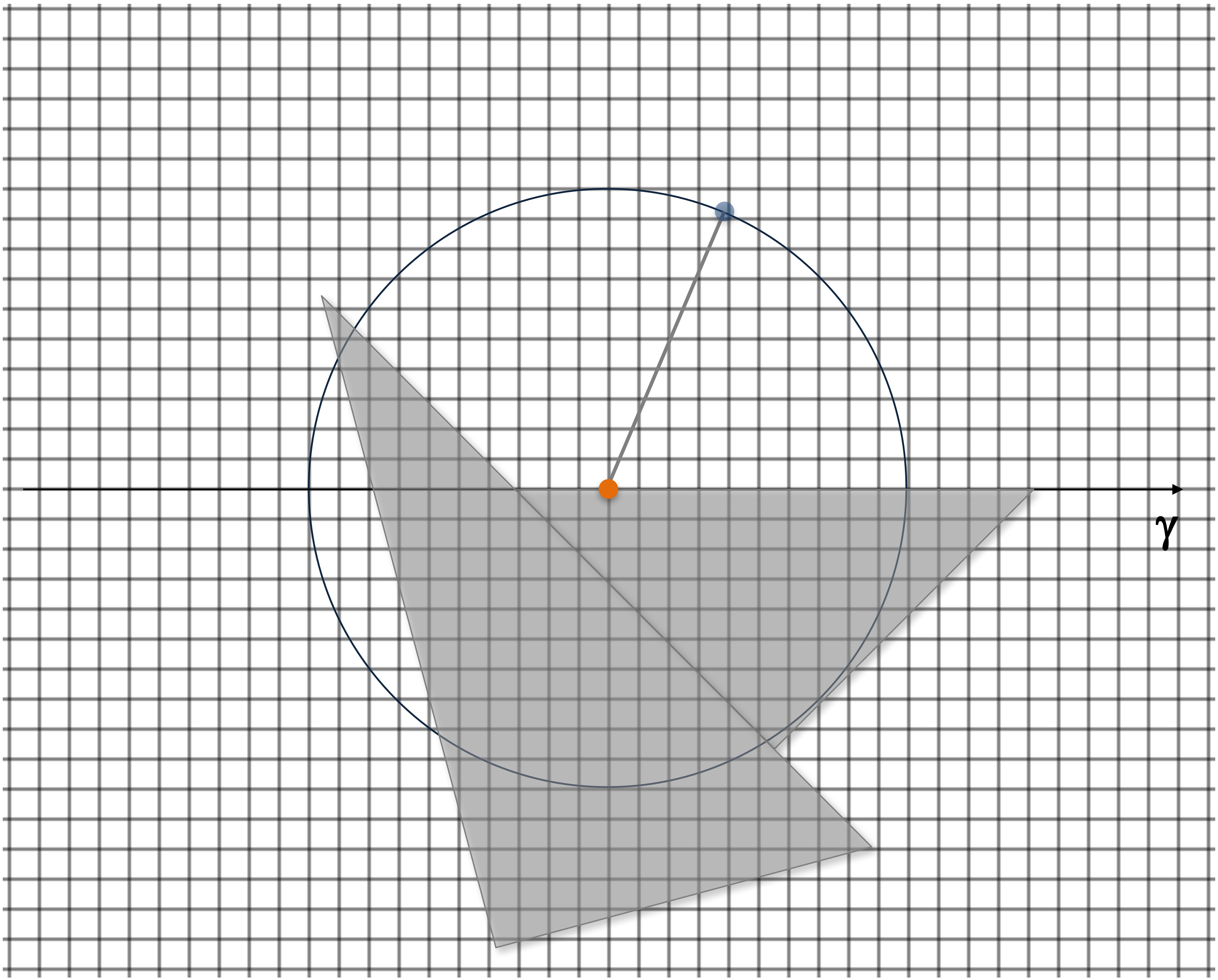
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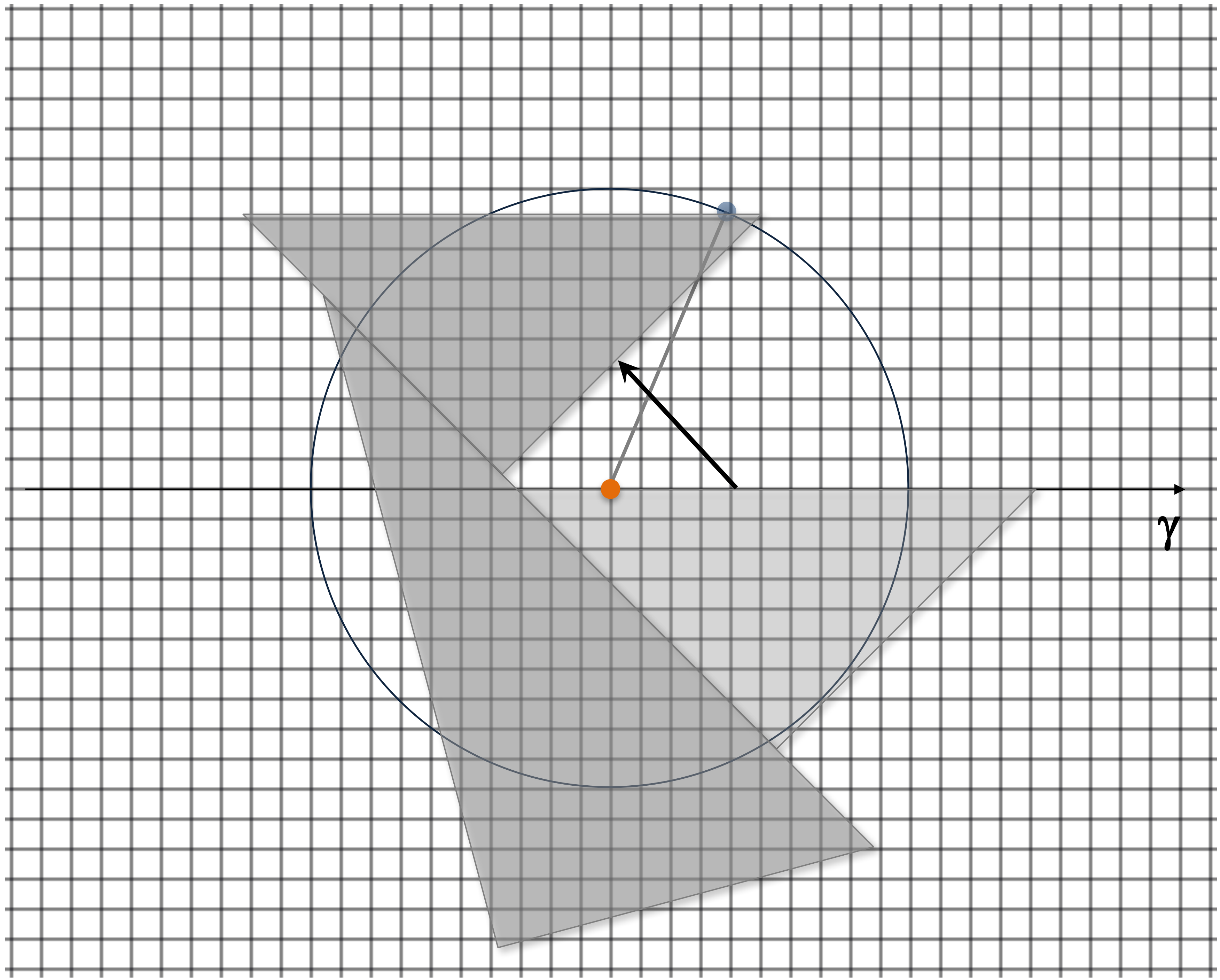

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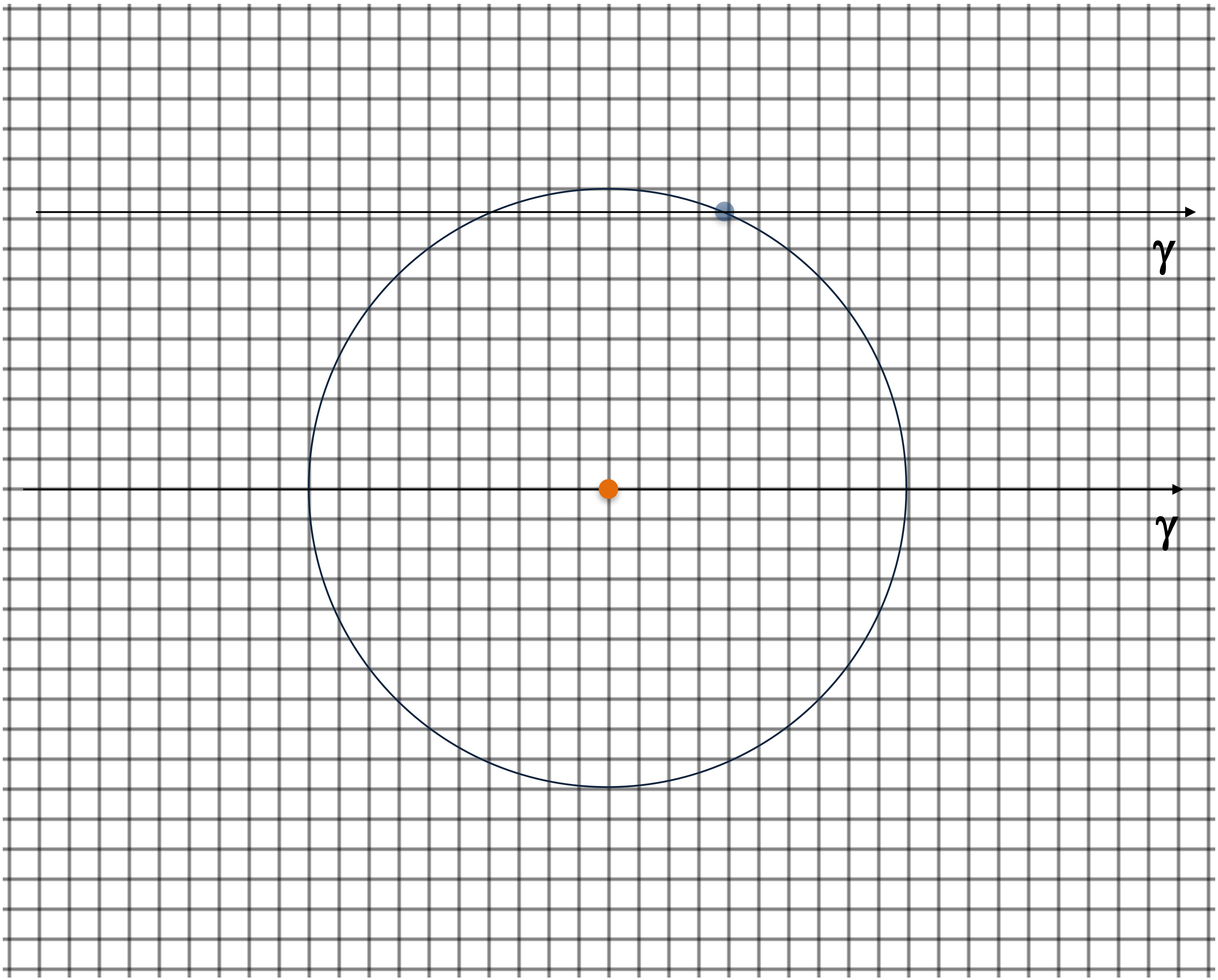

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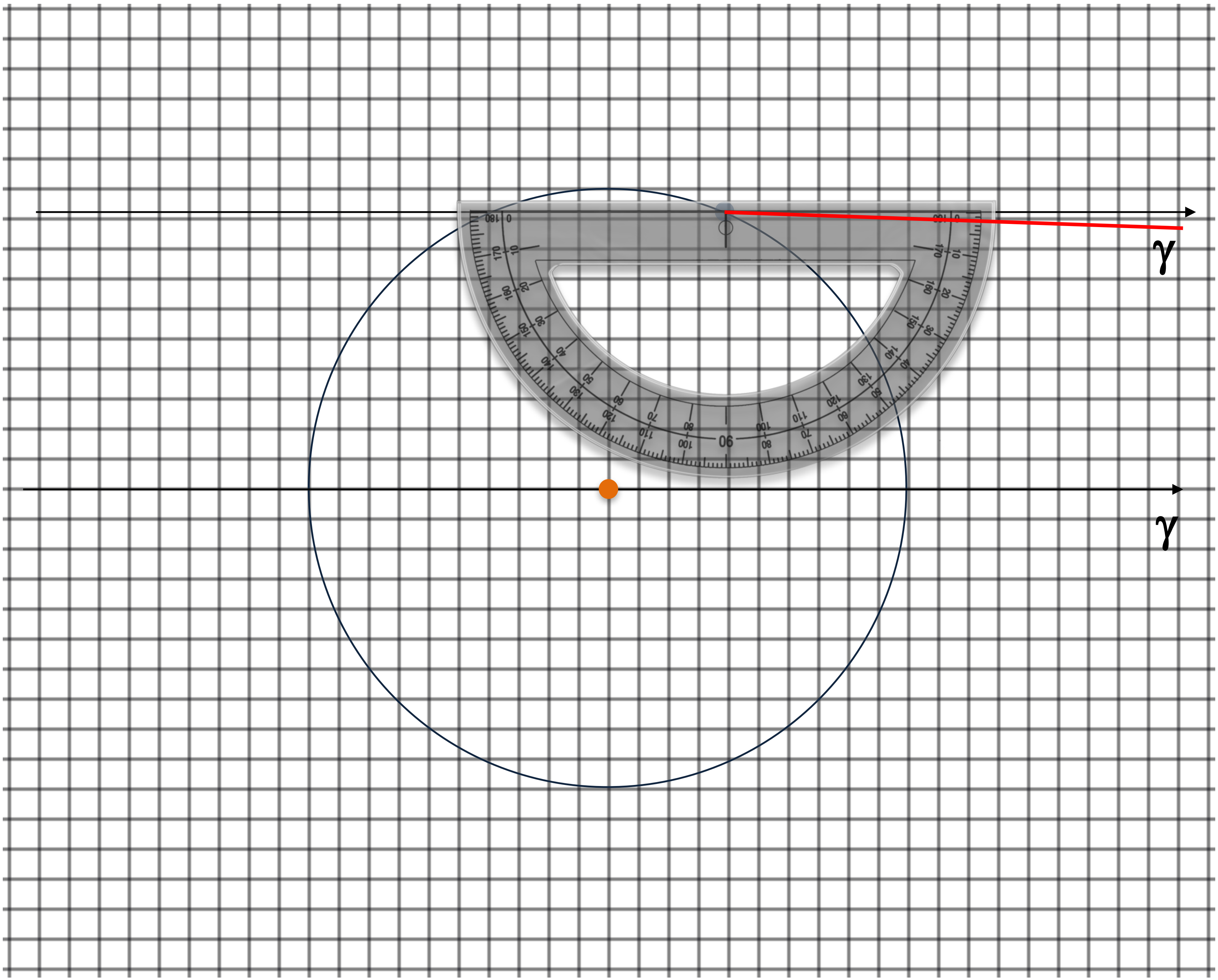
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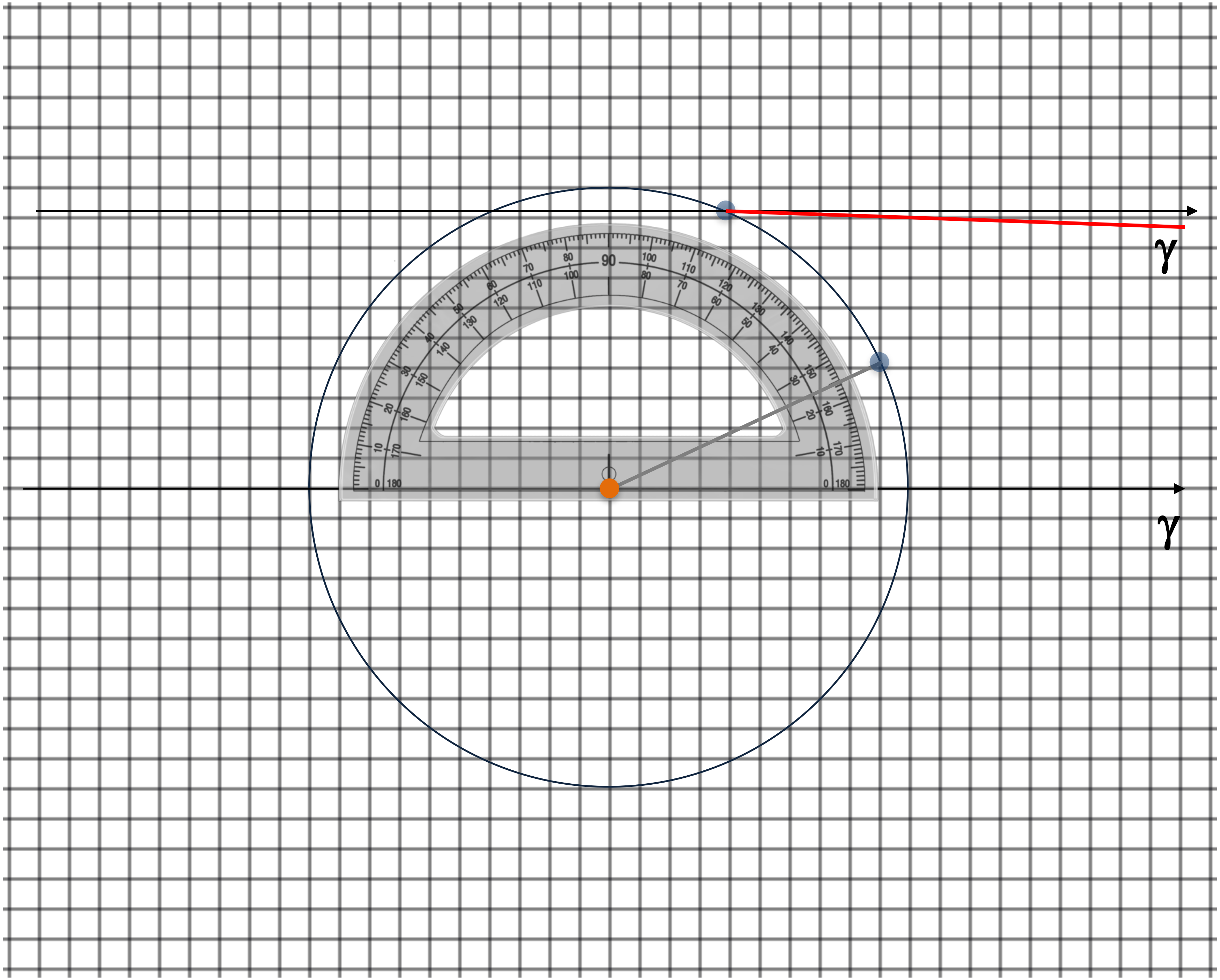

γ
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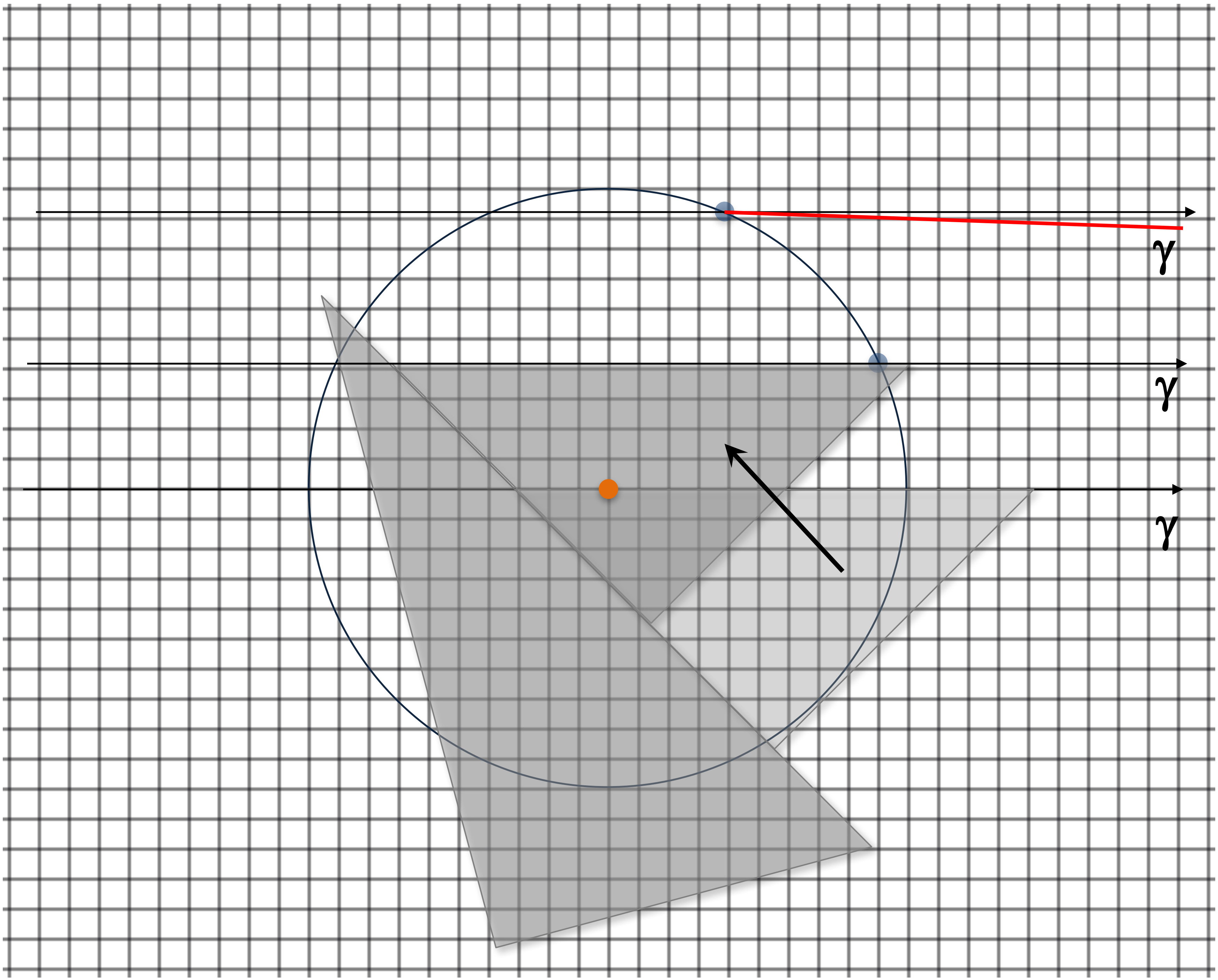
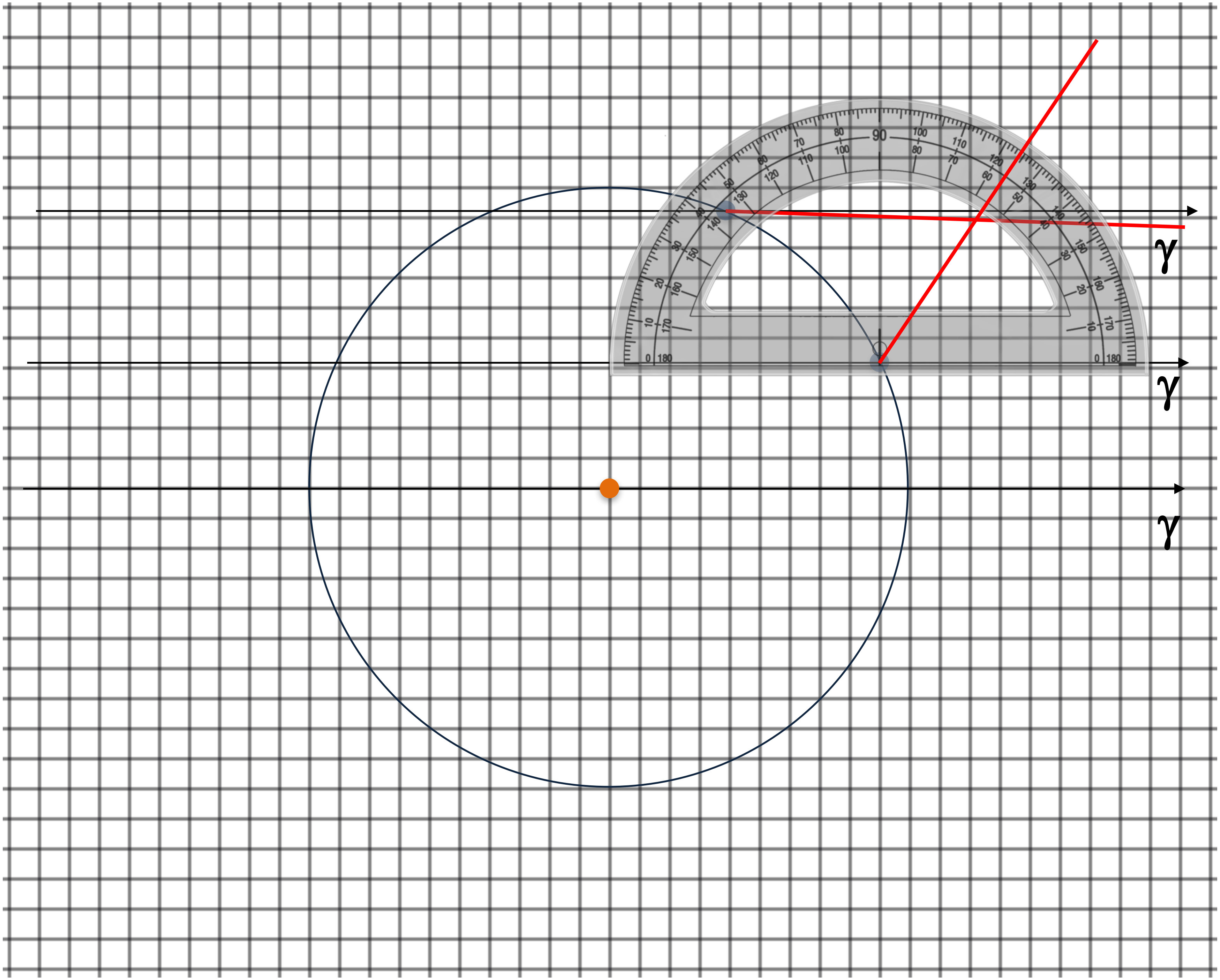


γ
γ
γ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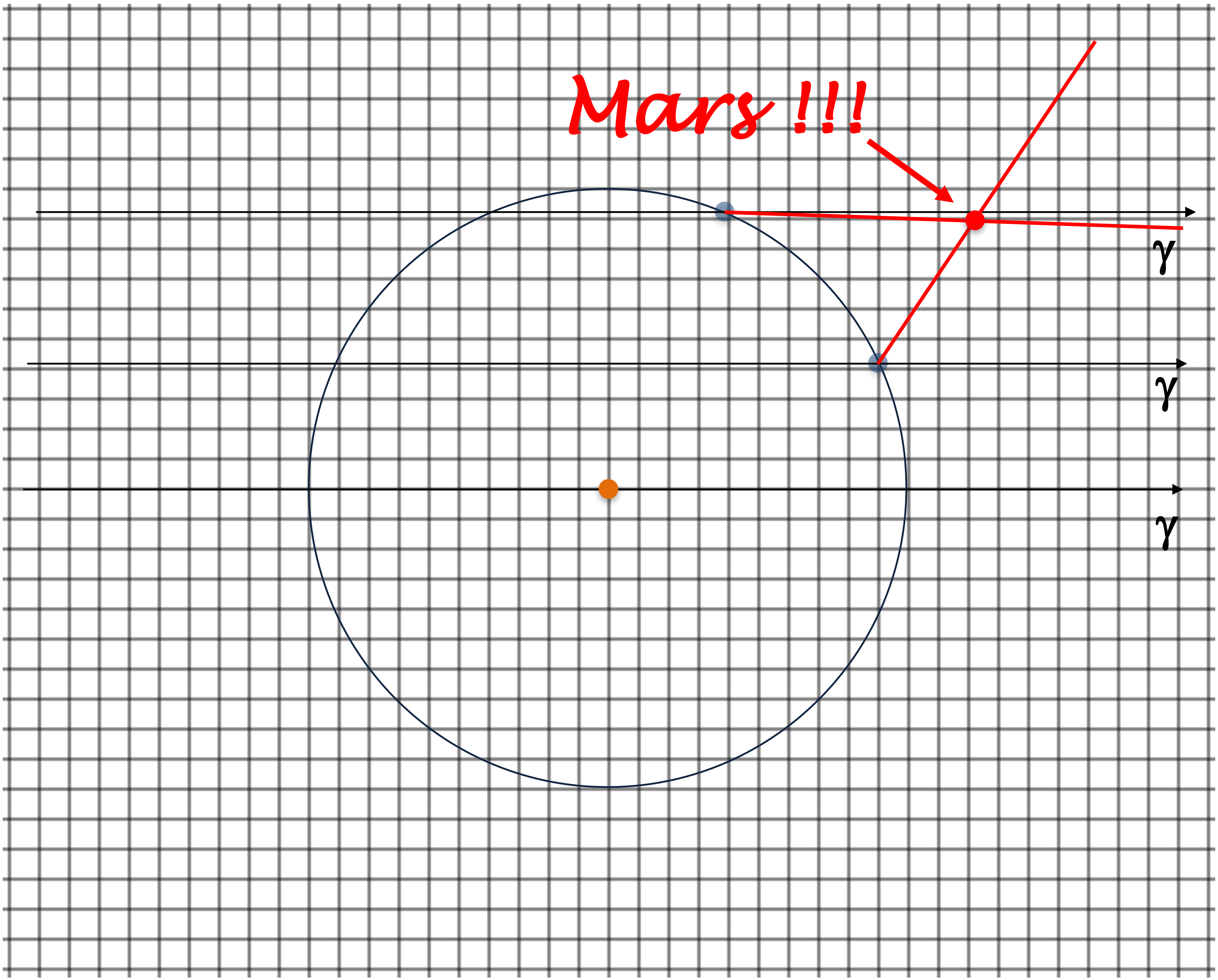
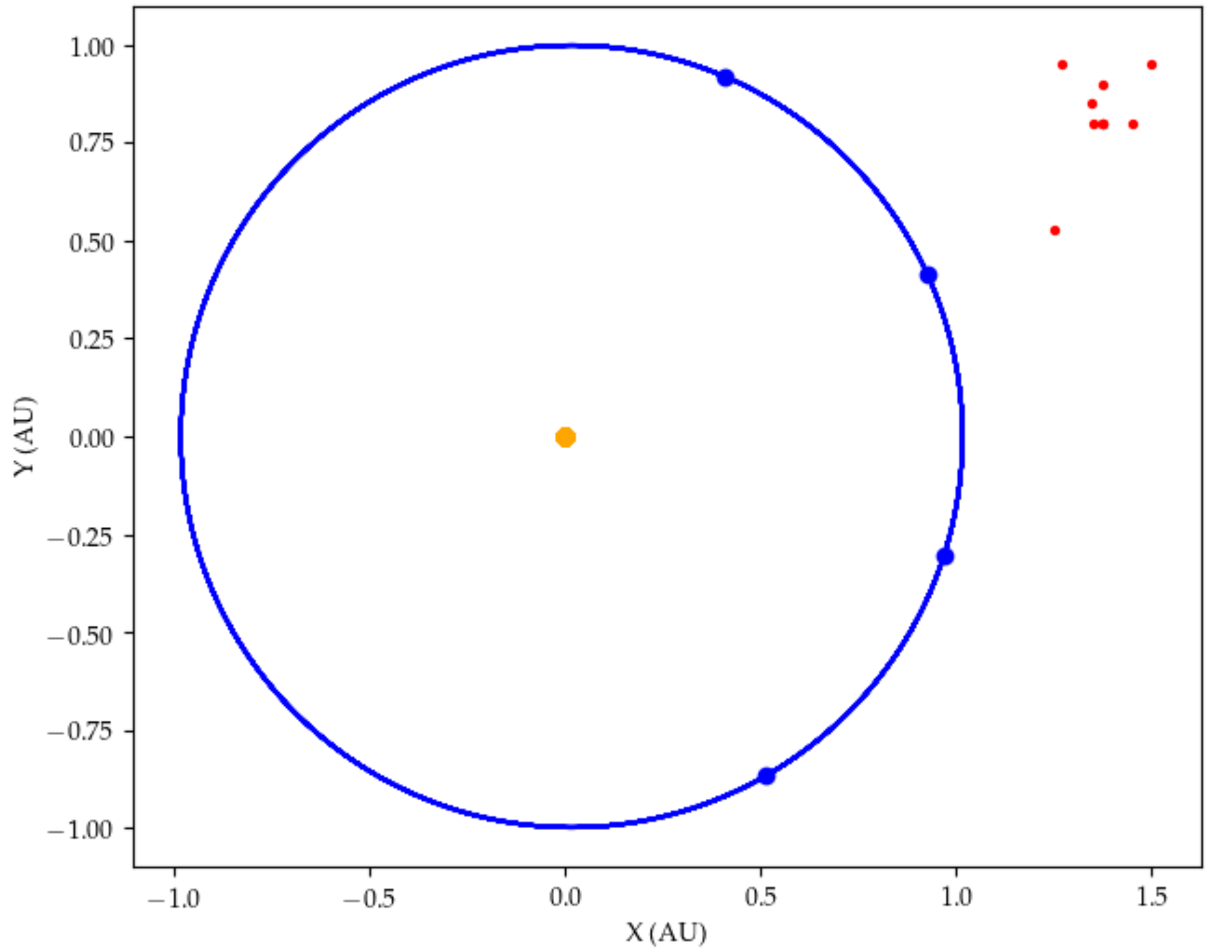

Mars !!!
γ
γ
γ



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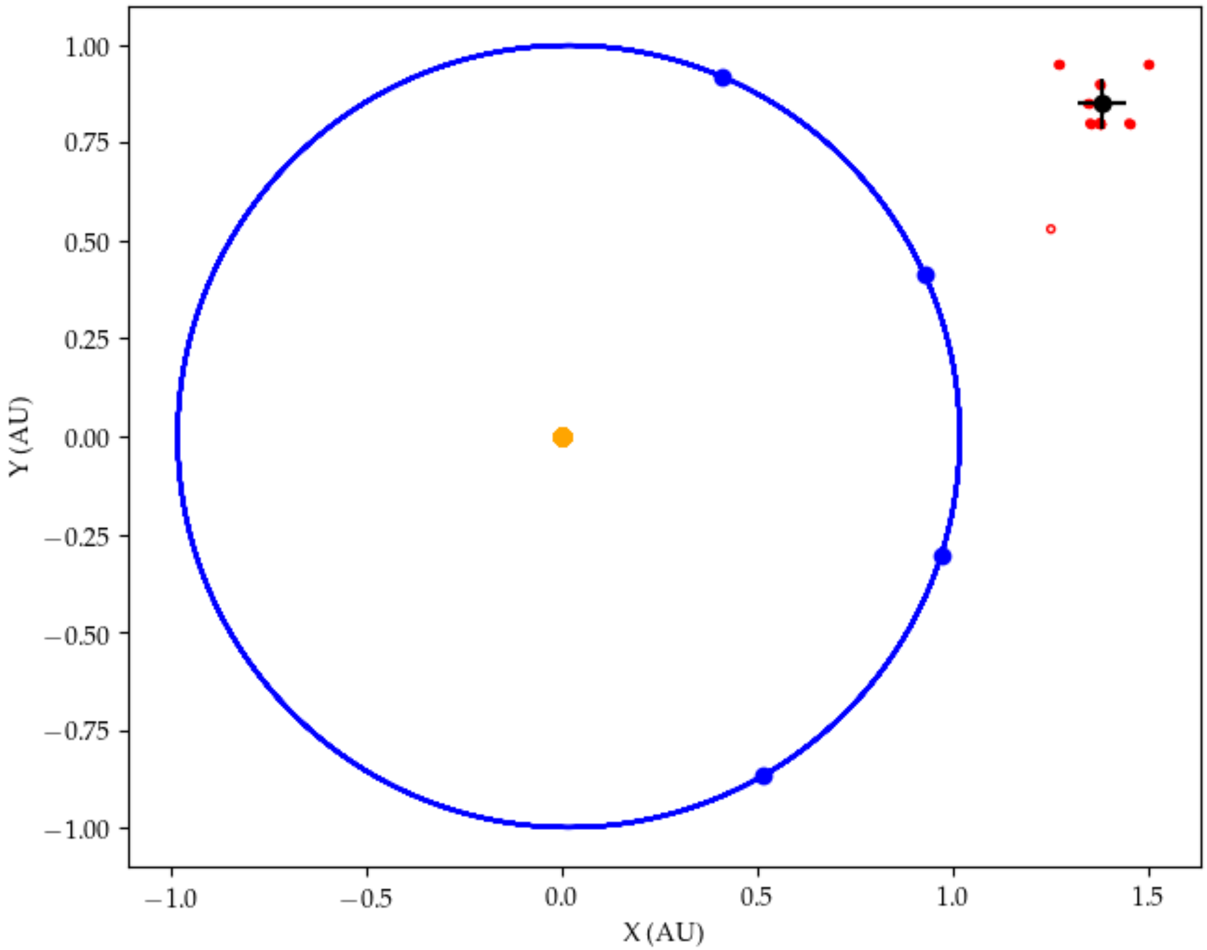

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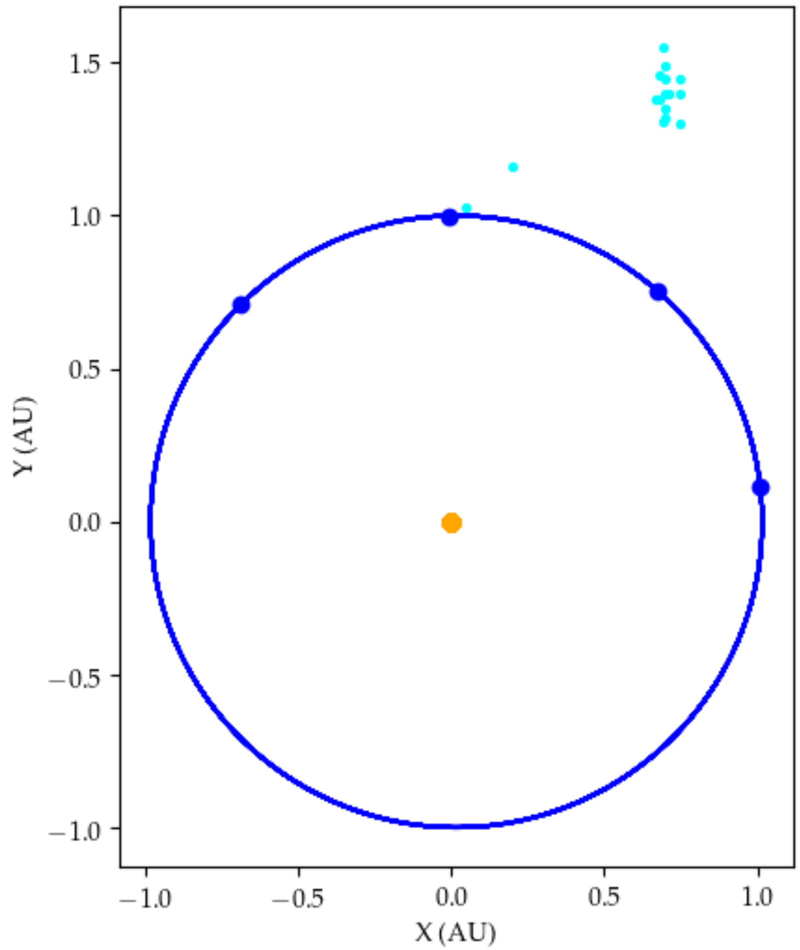

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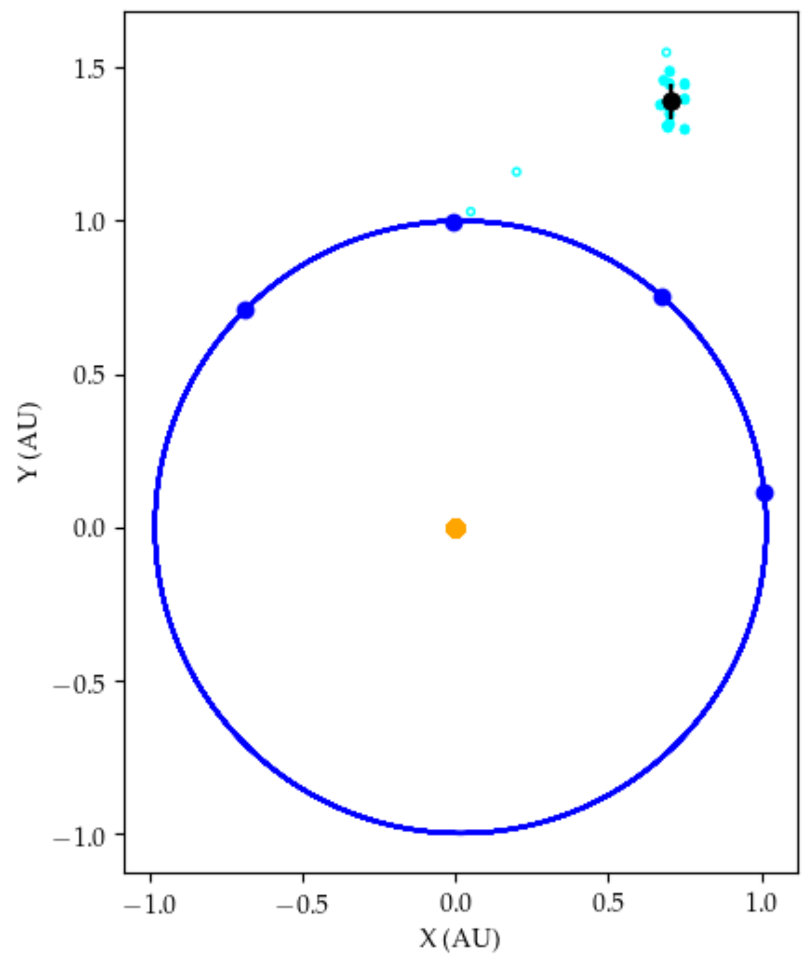

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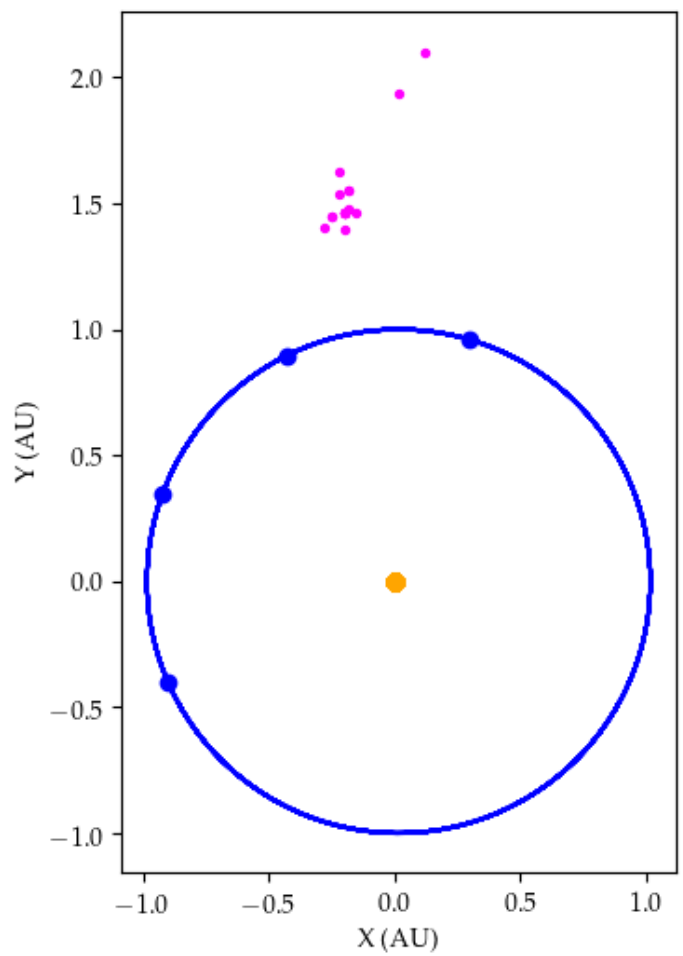

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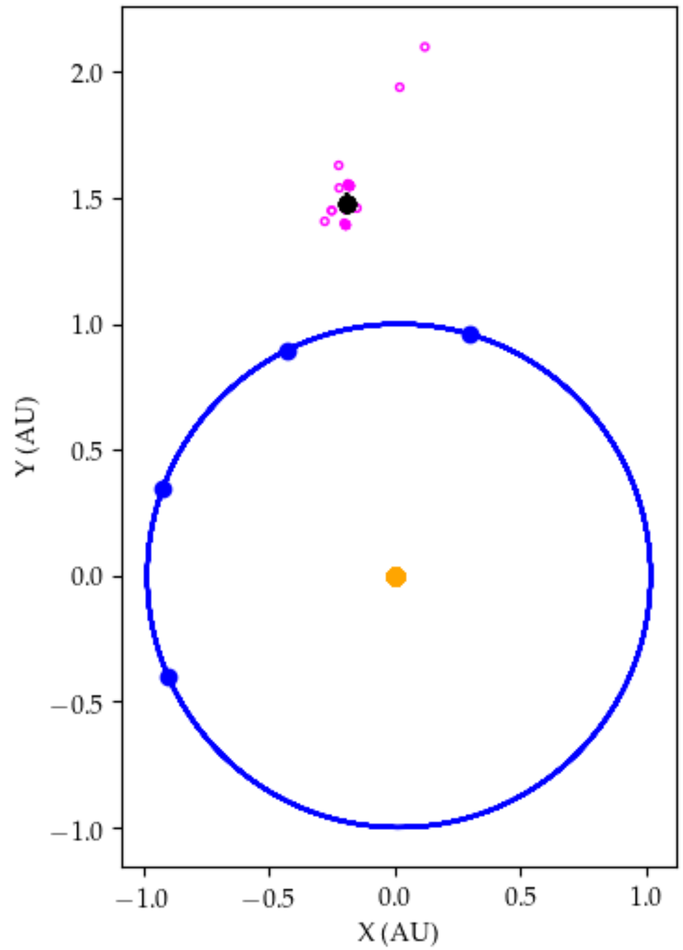

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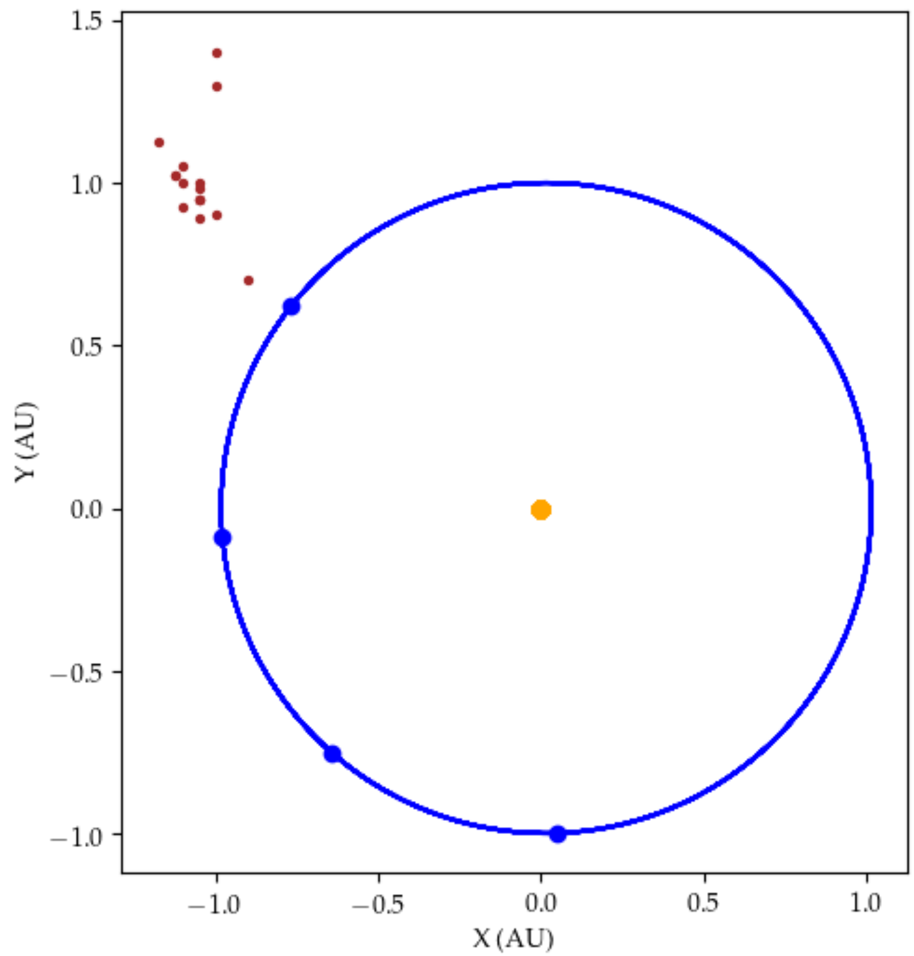
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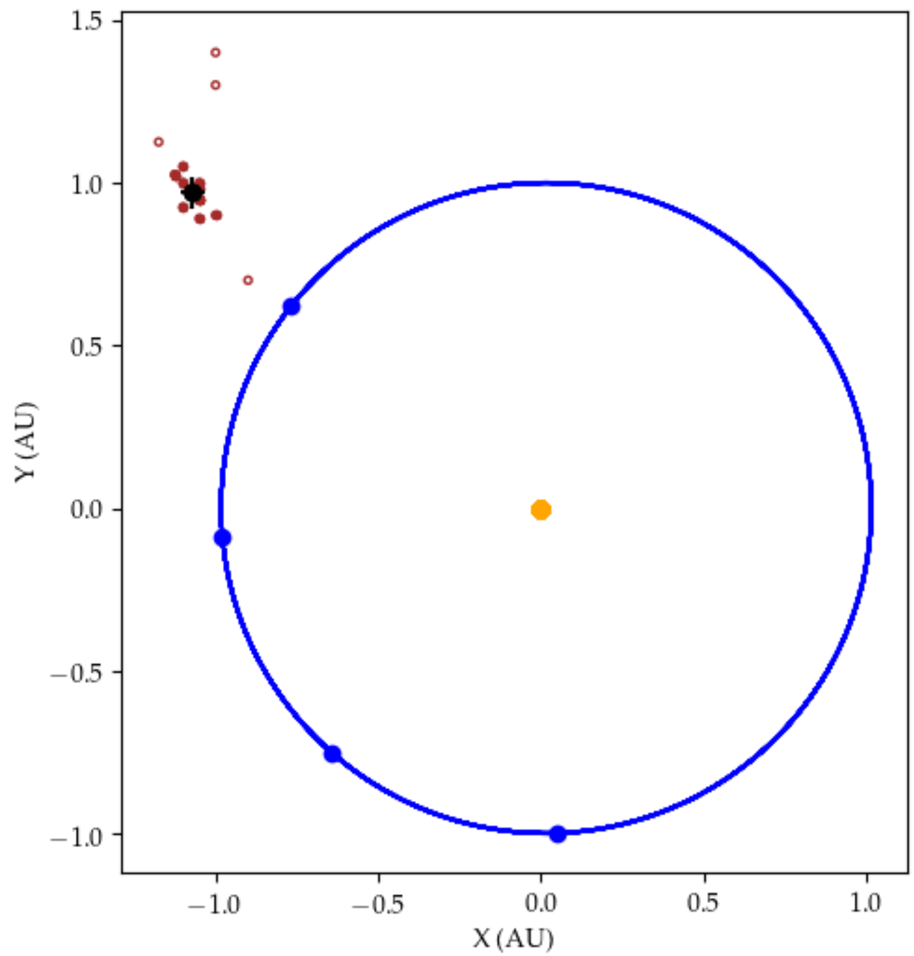

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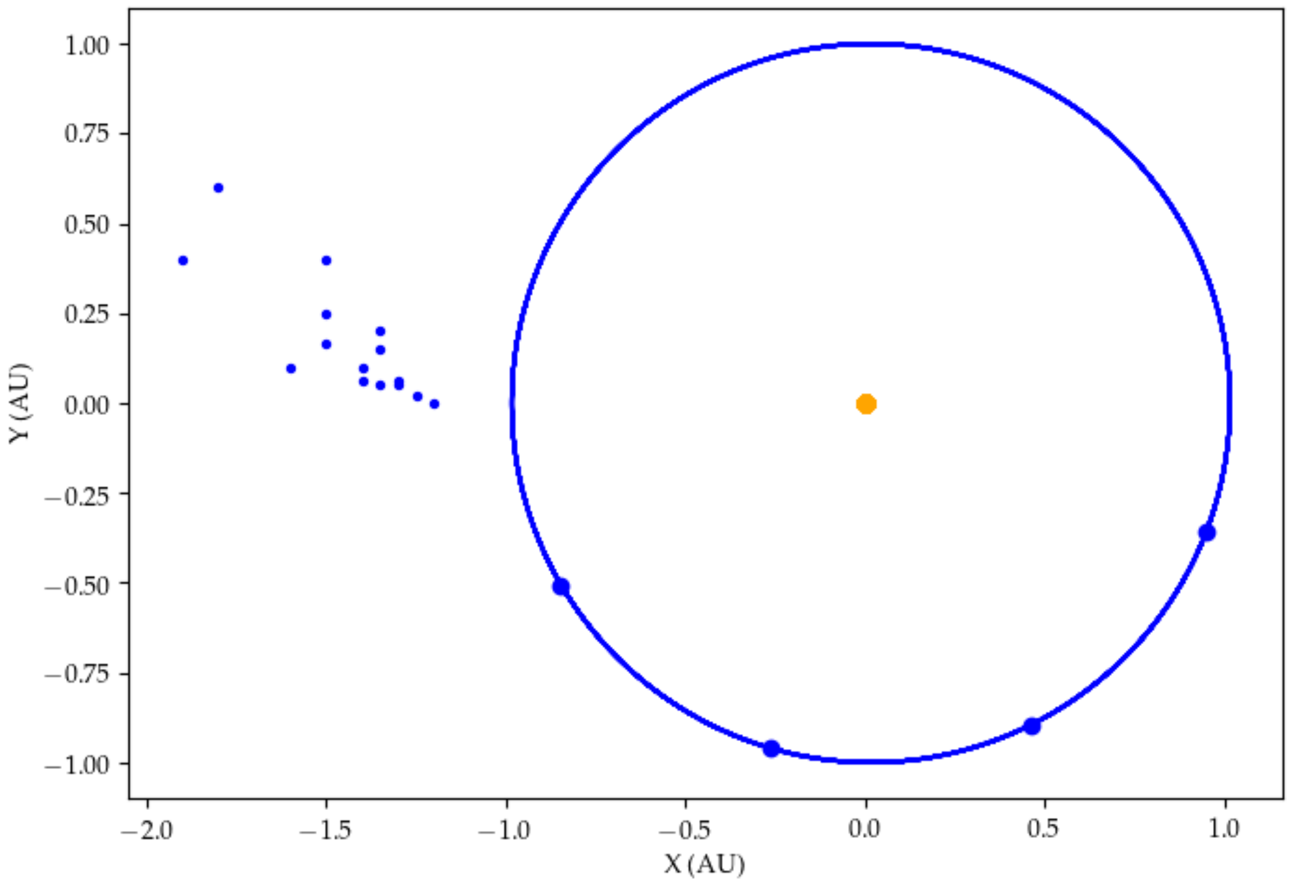

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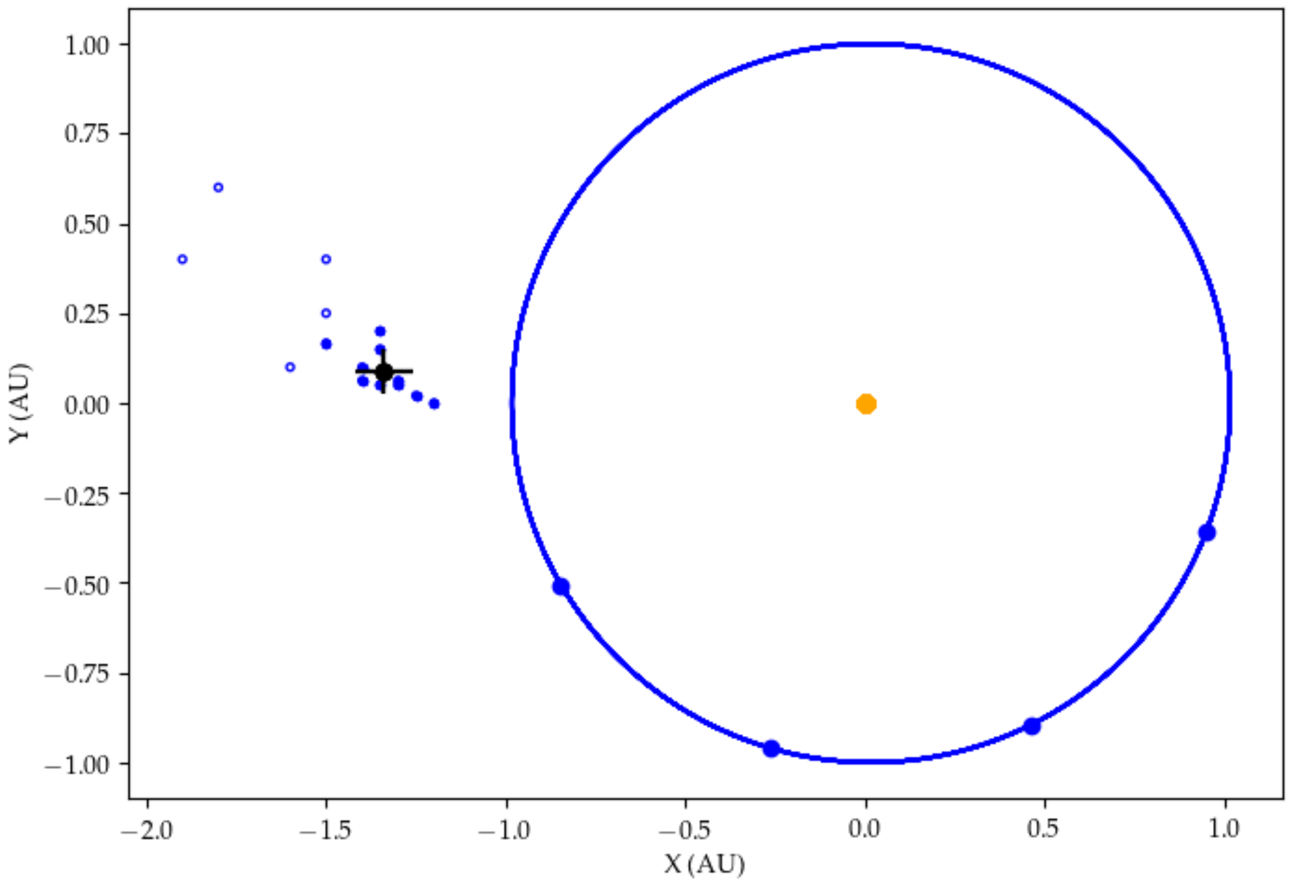

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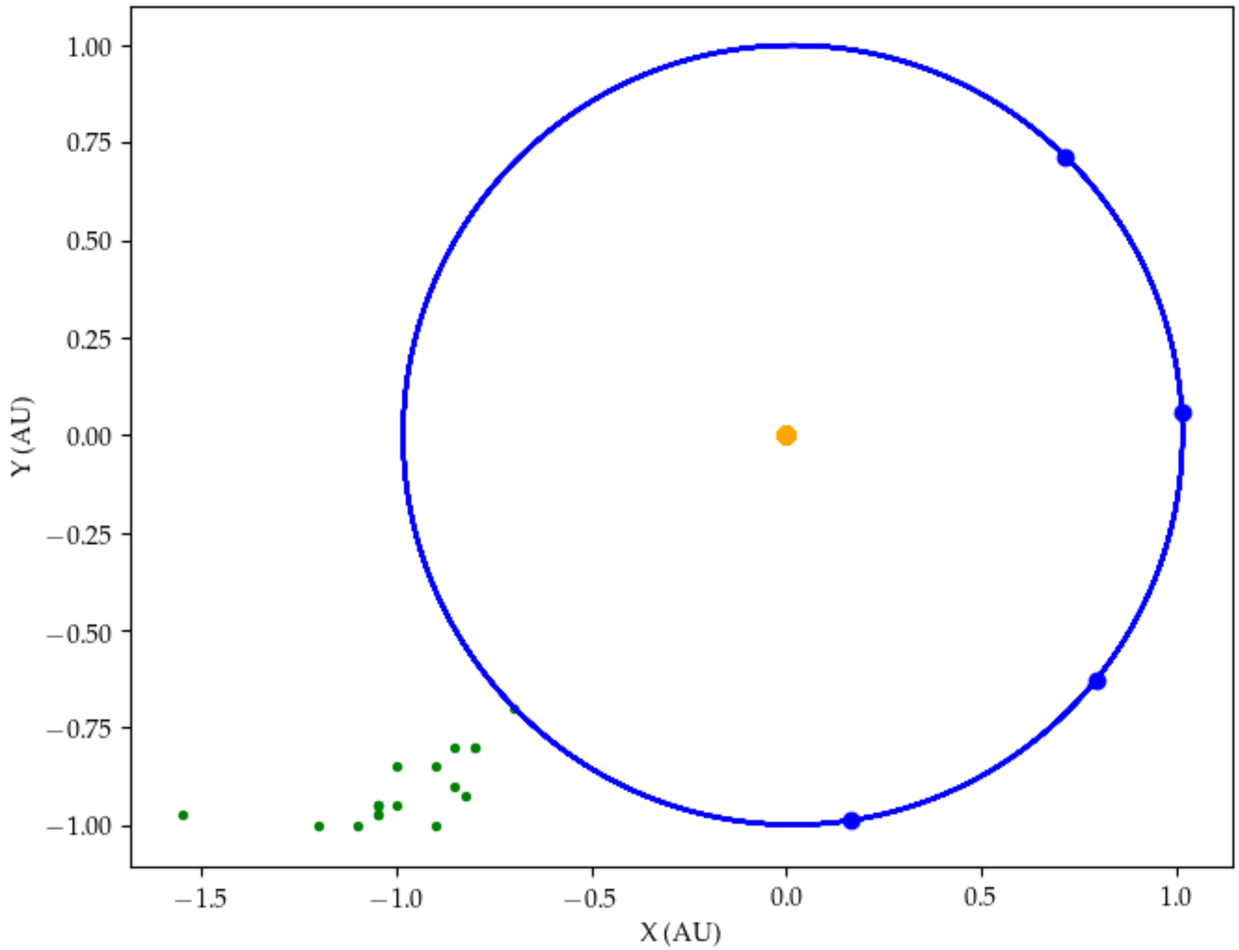

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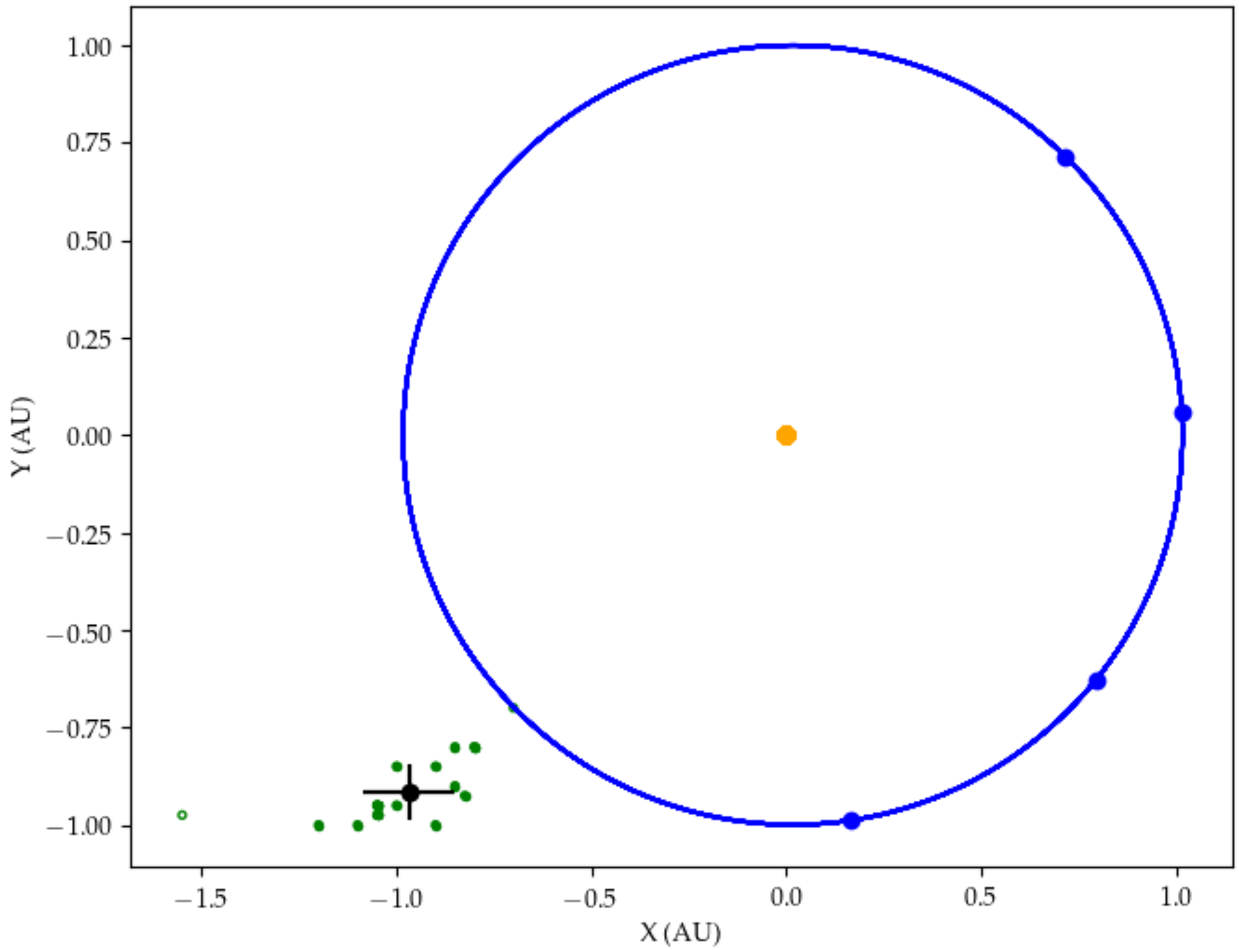

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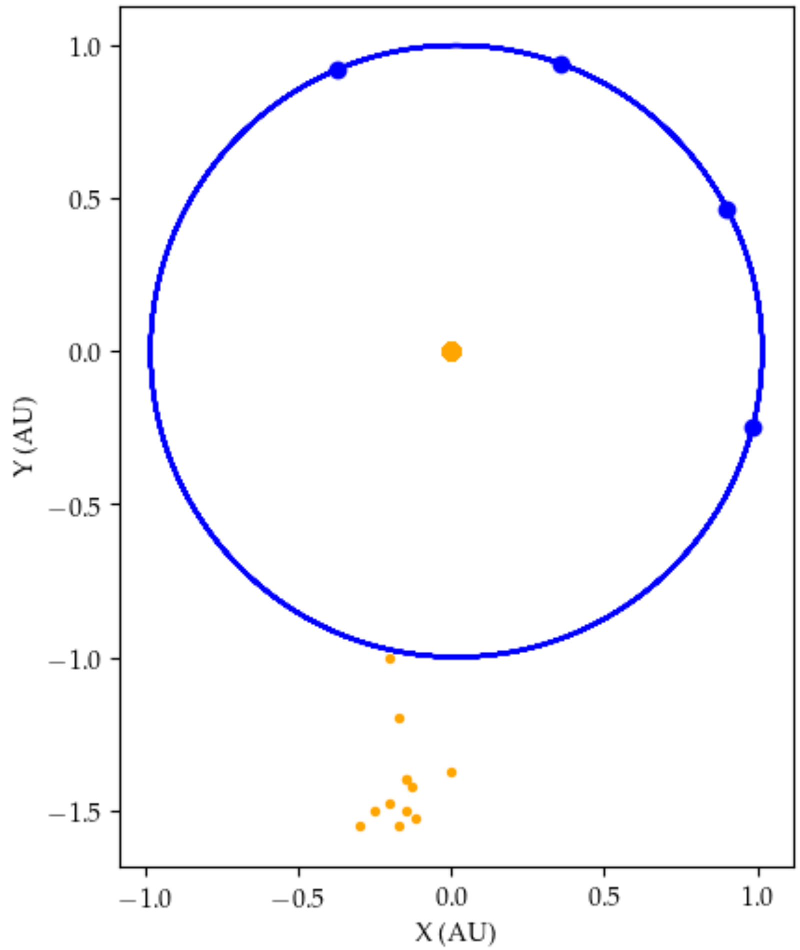

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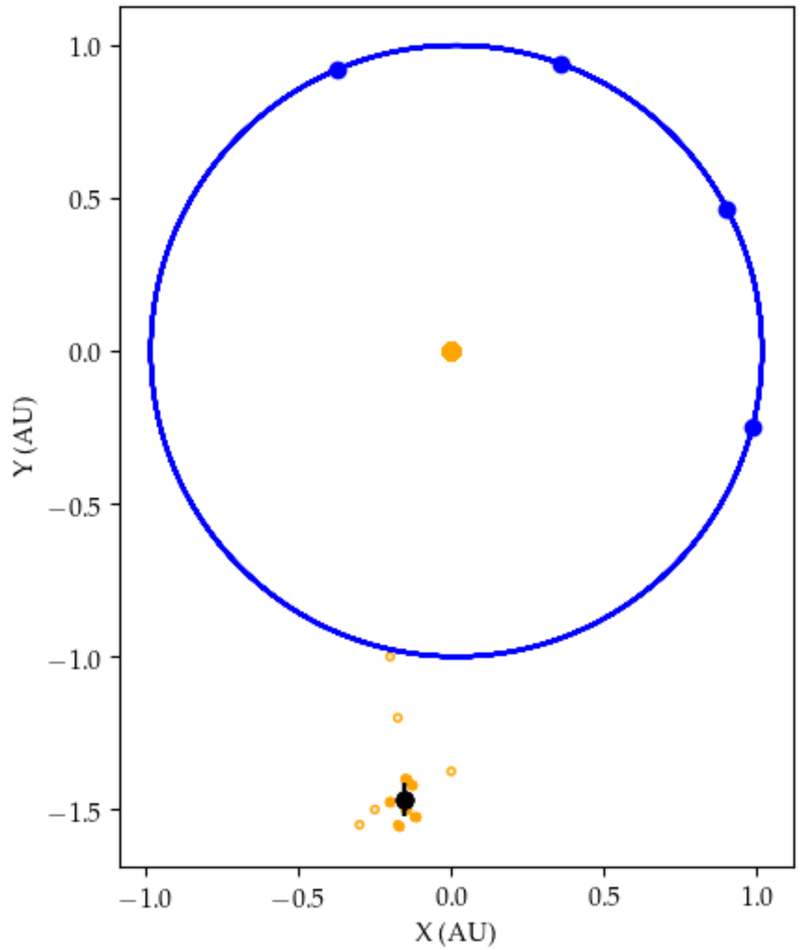

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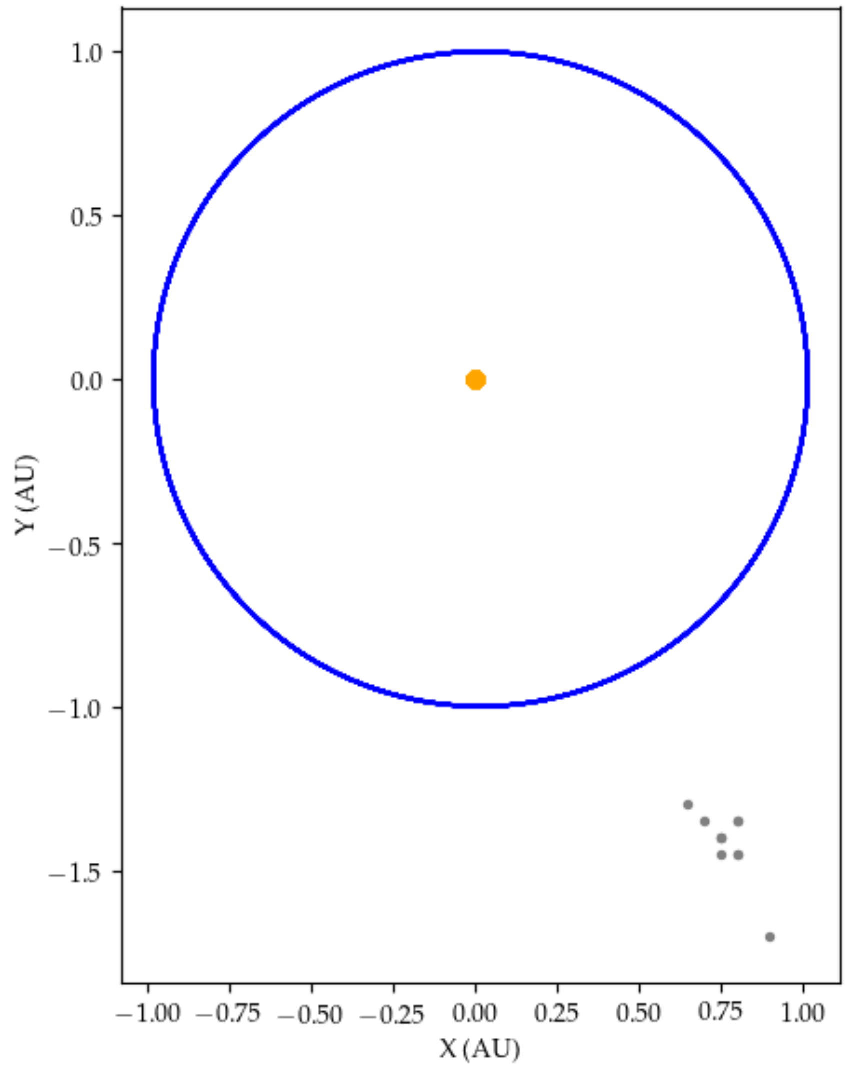

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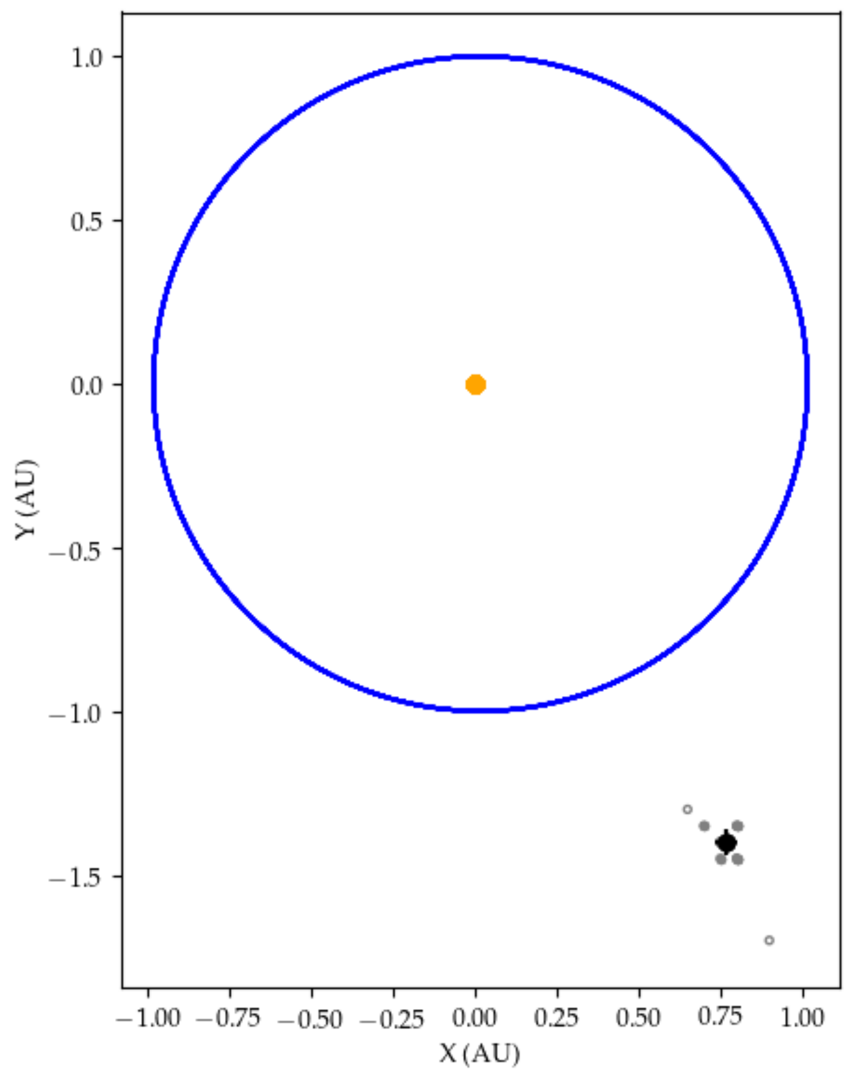

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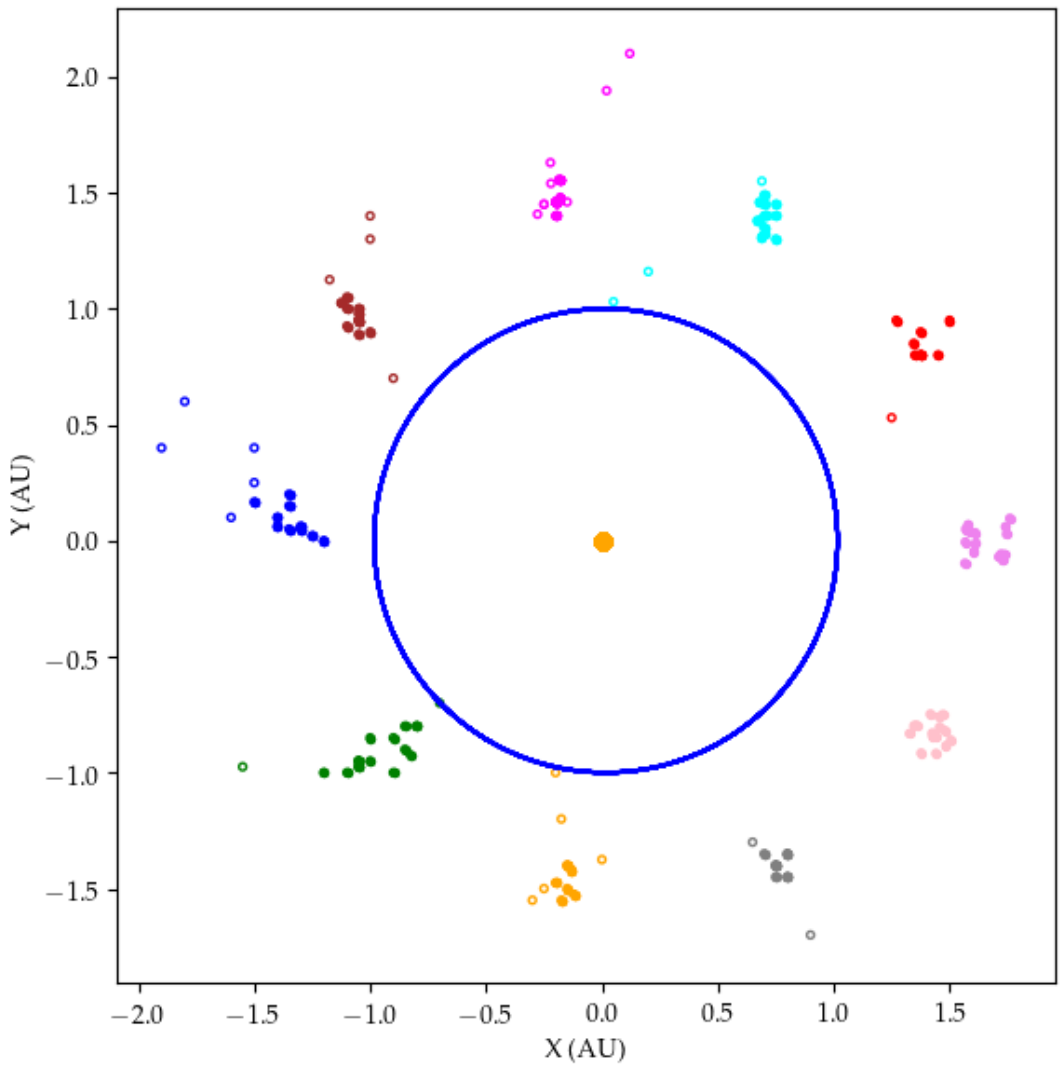

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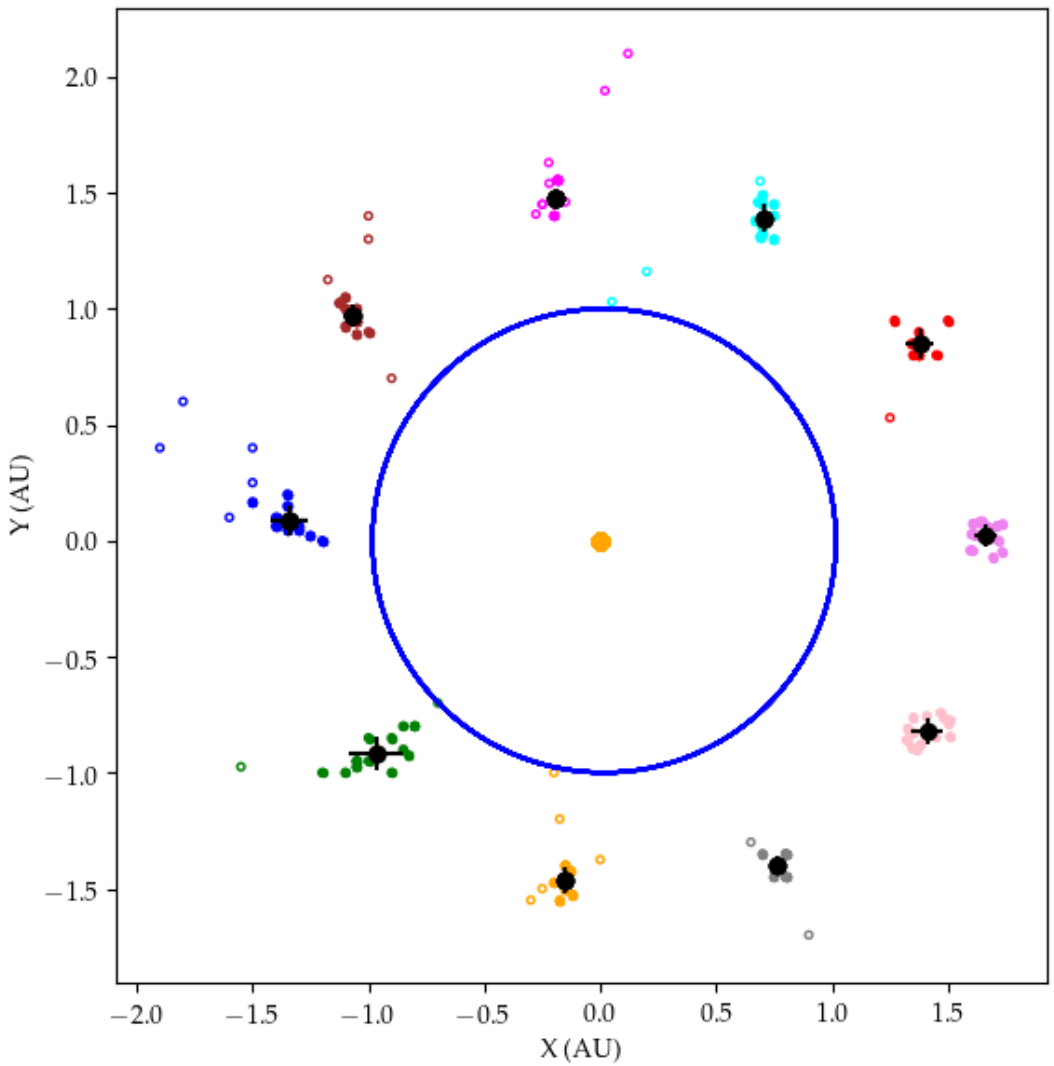

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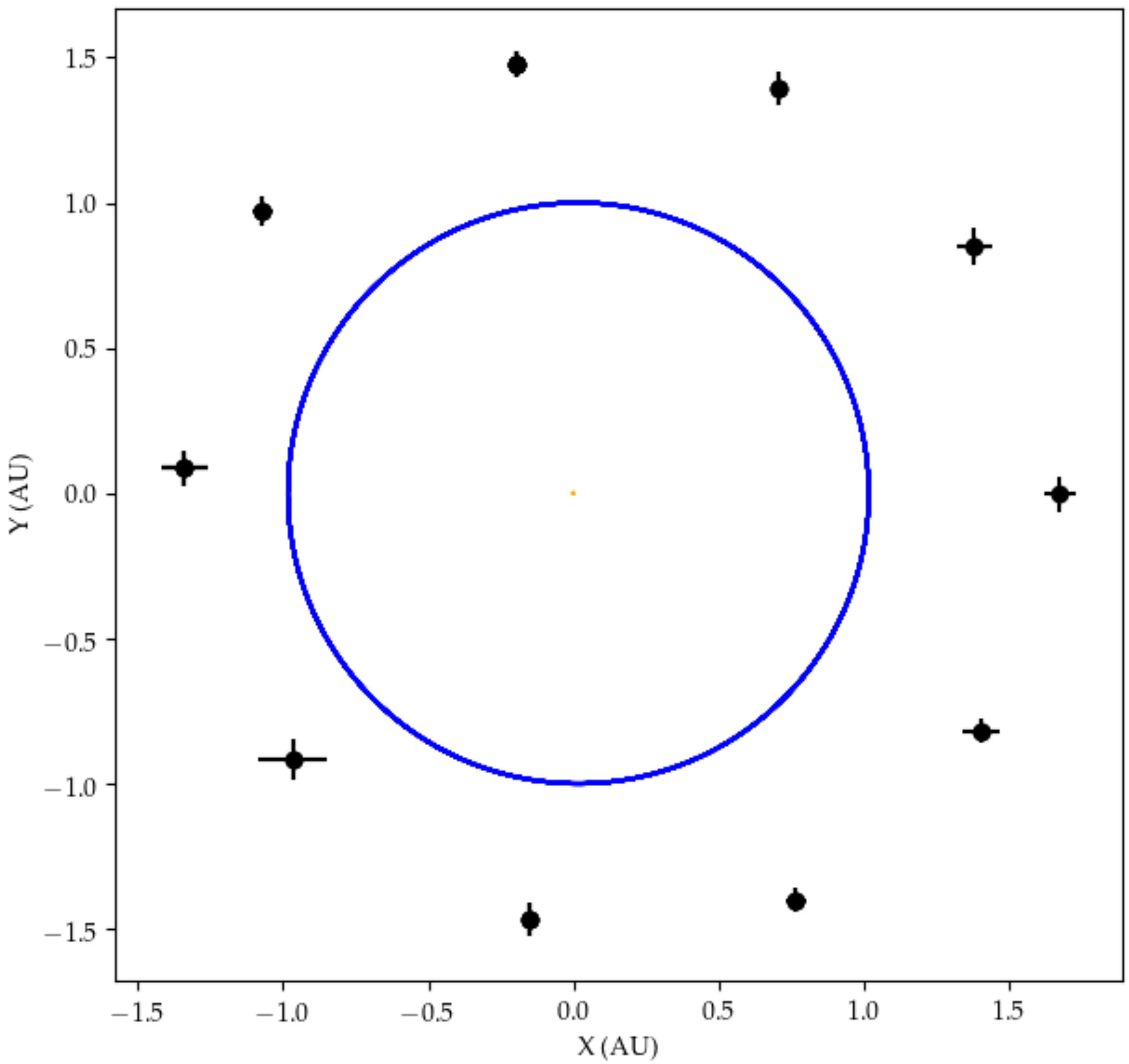

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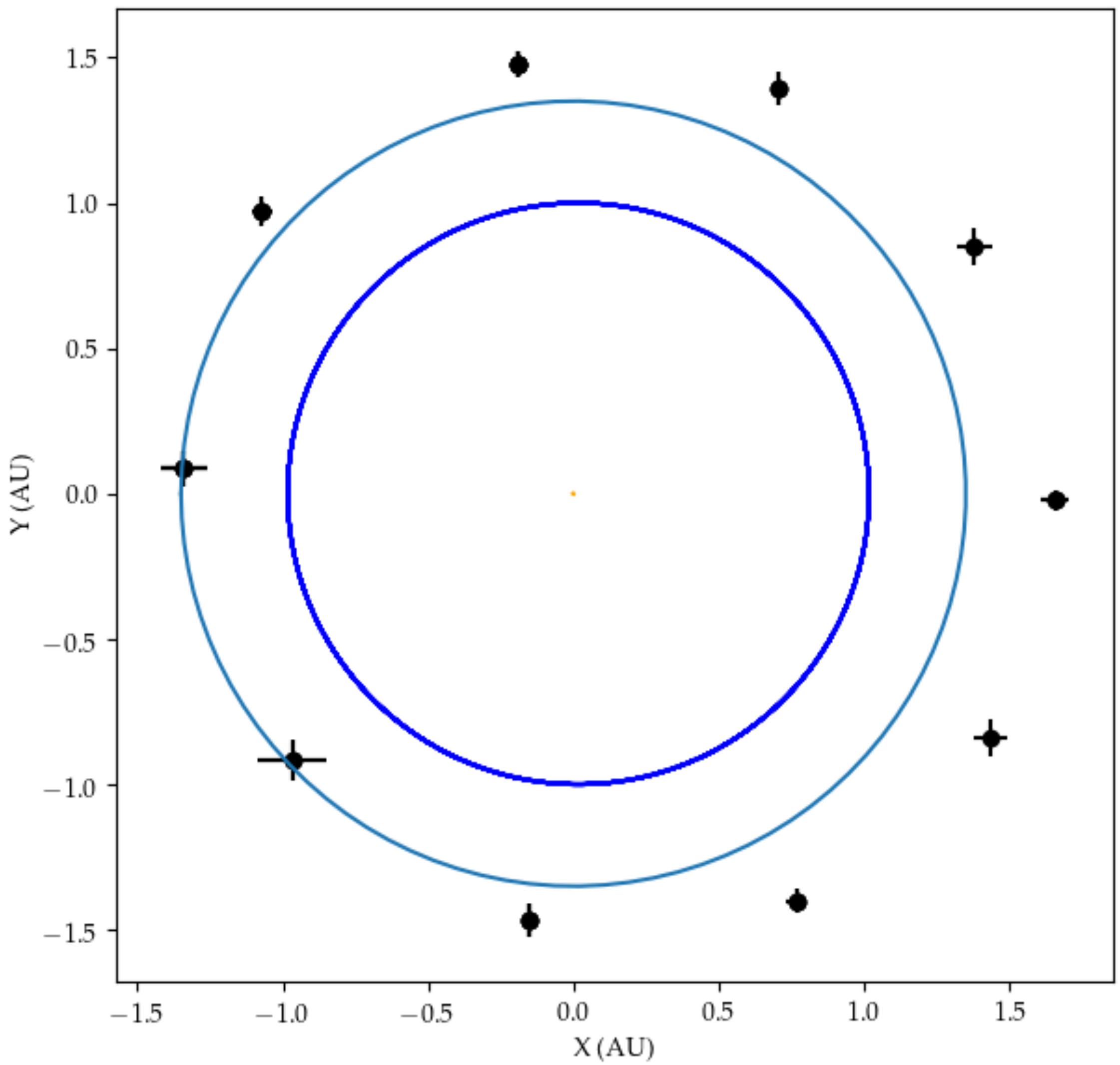
X (AU)



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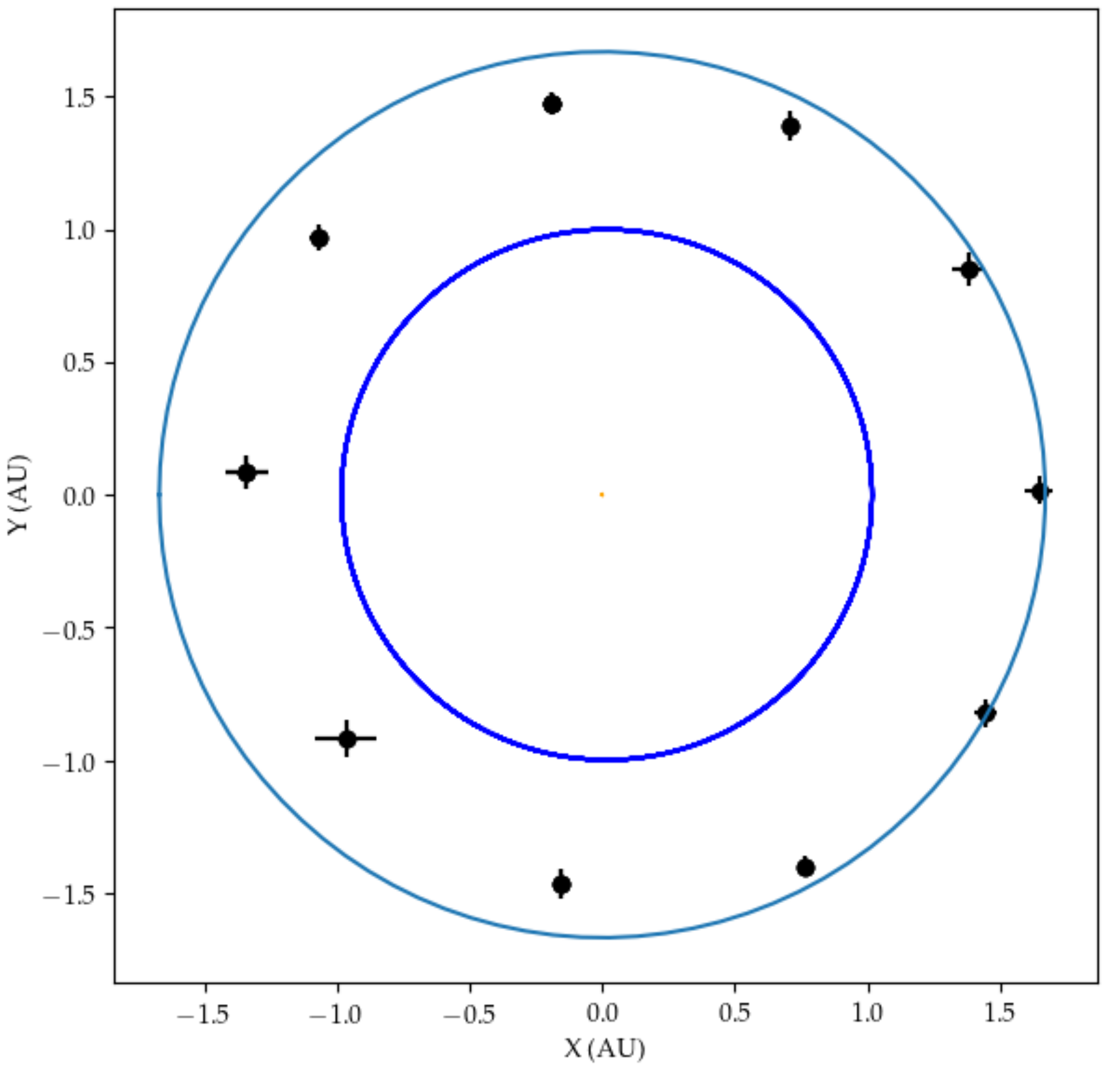

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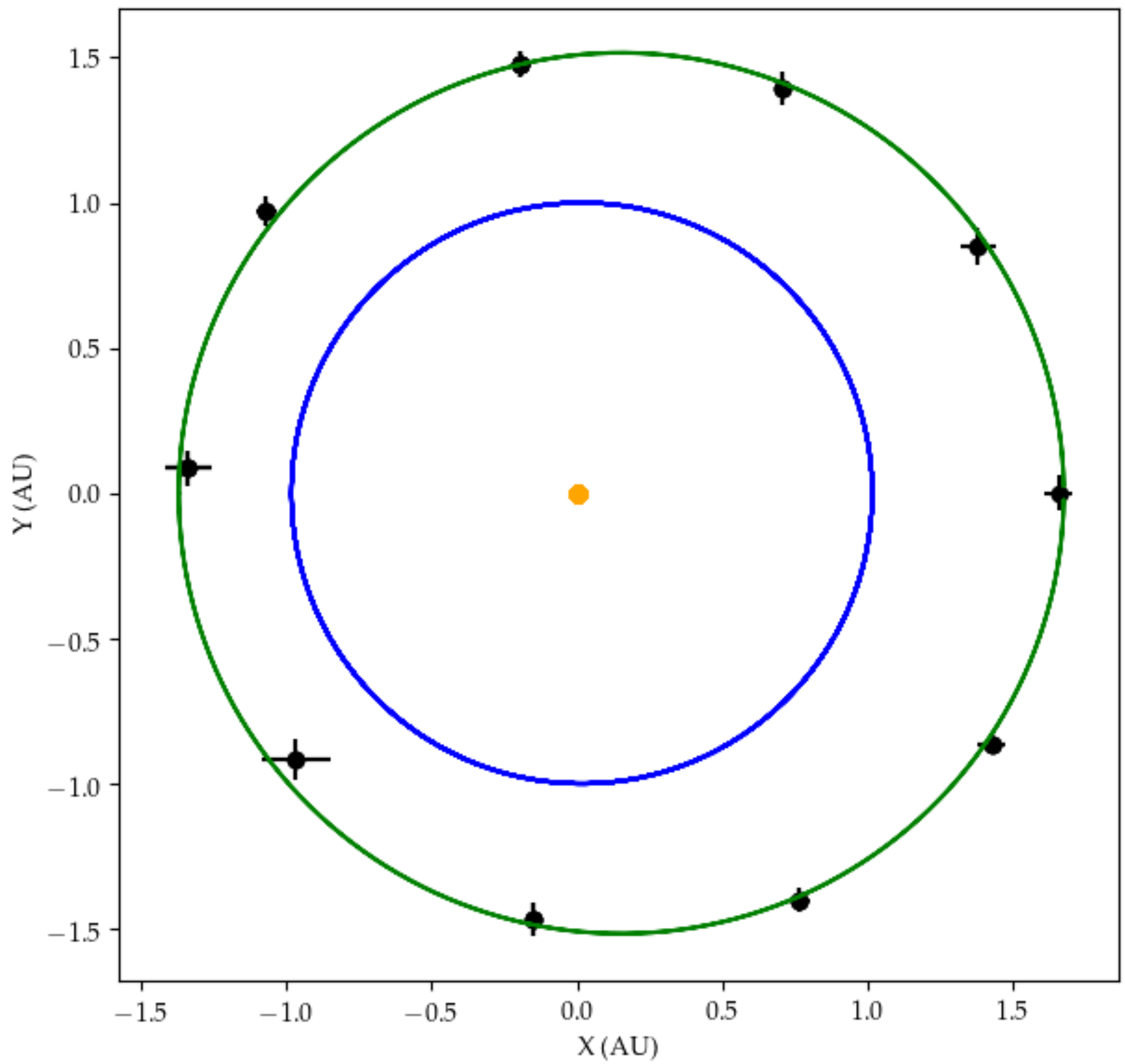
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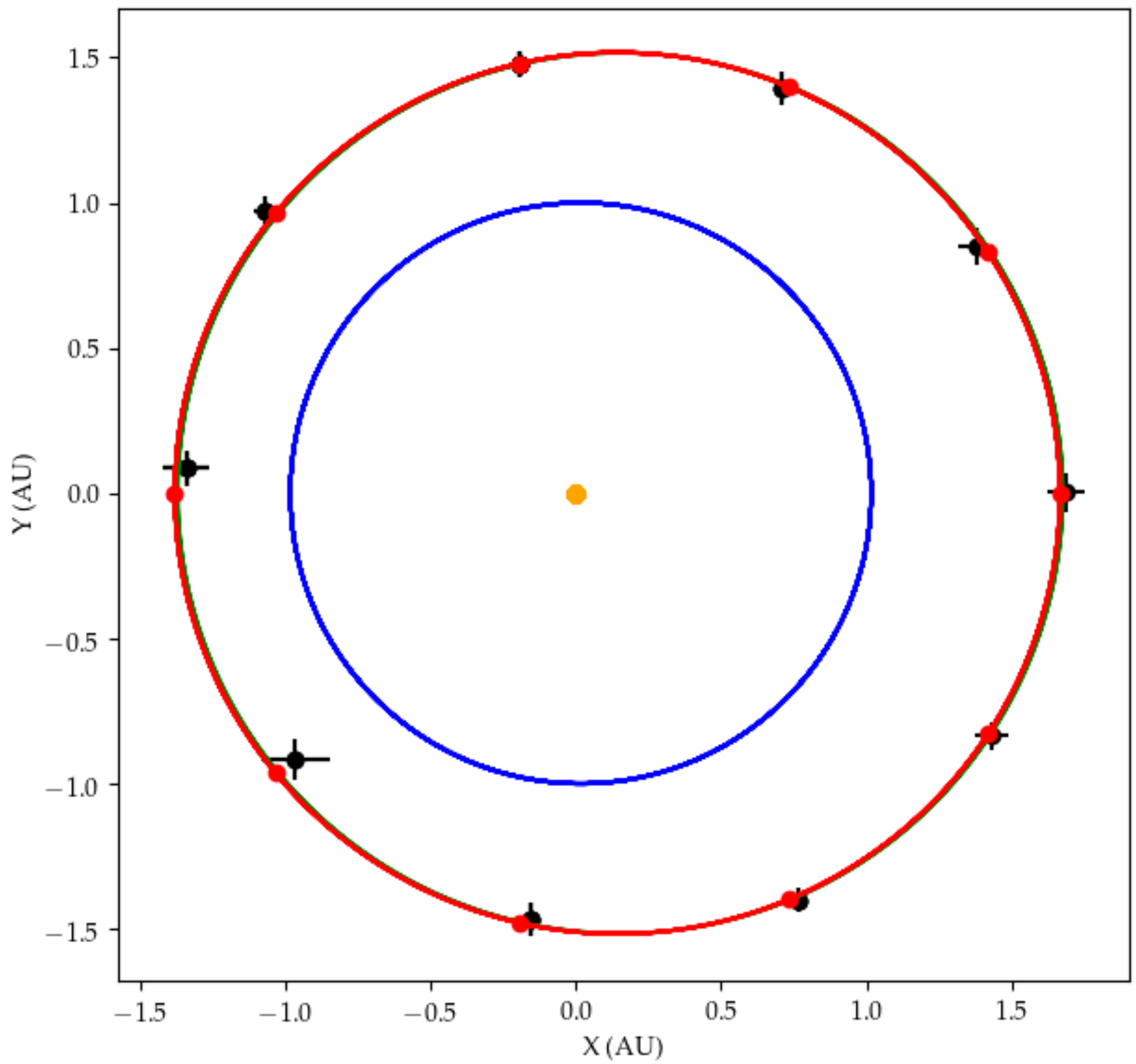

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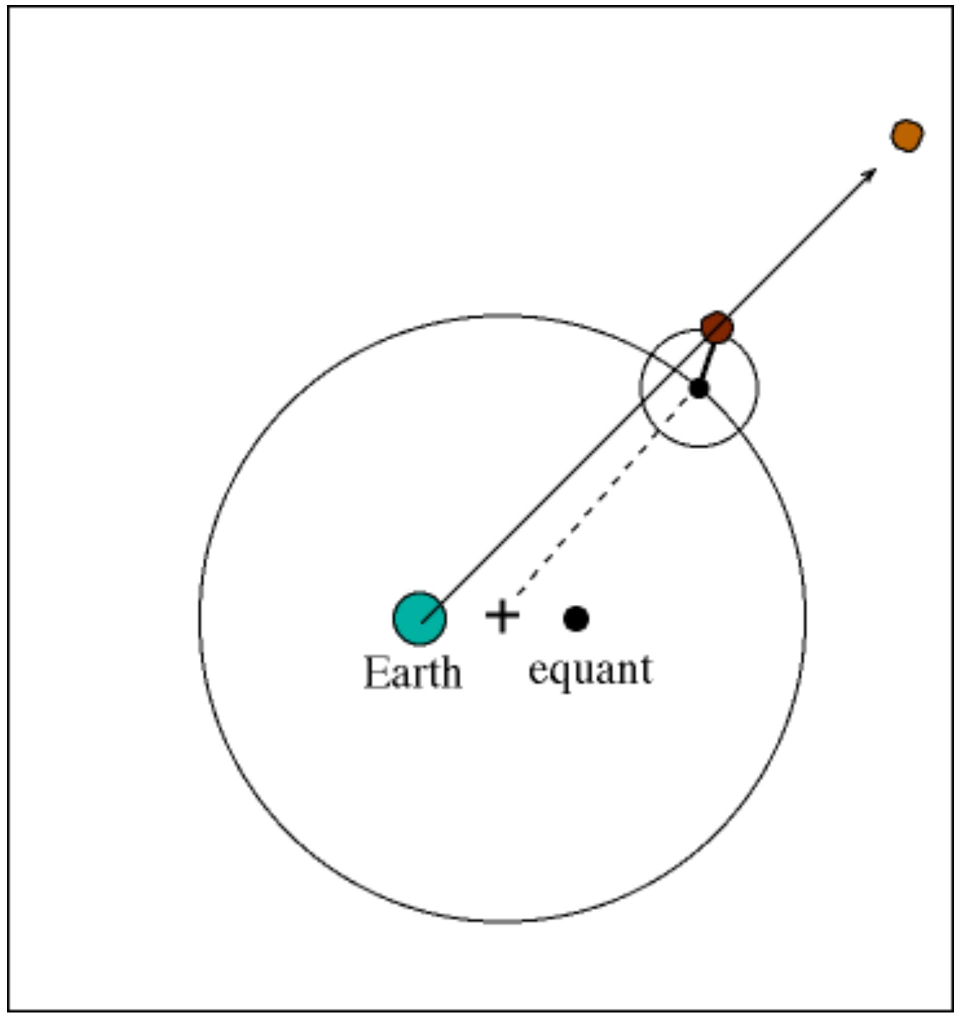
X (AU)


TYCHO BRAHE
JOHANNES KEPLER


Earth
equant

① inclination of planet
② heliacal/synodic anomaly
→ epicycle
③ zodiacal/ecliptic
→ eccentric
④ precession,
- the movement of the
fixed stars, planets
(ADK) 1°/100 years
⑤ equant

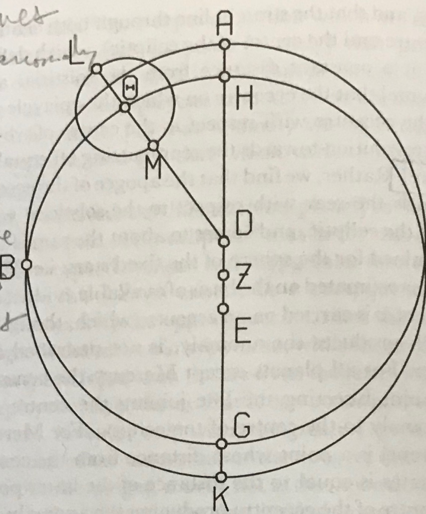


Fig. 9.1

planets. Next, we say that the whole plane [of the eccentre] moves uniformly about centre E towards the rear [i.e. in the order] of the signs, shifting the position of apogee and perigee 1° in 100 years, and that diameter LΘM of the epicycle rotates uniformly about centre D, again towards the rear [i.e. in the
H255 order] of the signs, with a speed corresponding to the planet's return in longitude, and that it carries with it points L and M of the epicycle, and centre Θ of the epicycle (which always moves on the eccentre HΘK), and also carrie with it the planet; the planet, for its part, moves with uniform motion on th epicycle LM and performs its return always with respect to that diameter [of th epicycle] which points towards centre D, with a speed corresponding to th mean period of the synodic anomaly, and [a sense of rotation] such that it motion at the apogee L takes place towards the rear.

We can visualise the peculiar features of the hypothesis for Mercury a follows. Let [Fig. 9.2] the eccentre producing the anomaly be ABG about centr D, and let the diameter through D and centre E of the ecliptic be ADEC [passing] through the apogee at A. On AG take DZ towards the apogee A, equa to DE. Then everything else remains the same, namely the whole plan [revolving] about centre E, shifts the apogee towards the rear by the sam amount as for the other planets, the epicycle is revolved uniformly about centr D towards the rear, as [here] by the line DB, and furthermore the planet mov on the epicycle in the same way as the others. But in this case the centre of th other eccentre, which is, again, equal in size to the first eccentre, and on whic
H256 the epicycle centre is always located, is carried around point Z in the opposi sense to the motion of the epicycle, namely in advance [i.e. in the reverse orde of the signs, but uniformly and with the same speed as the epicycle, as [here] b the line ZHΘ. Thus in one year each of the lines DB and ZHΘ performs o

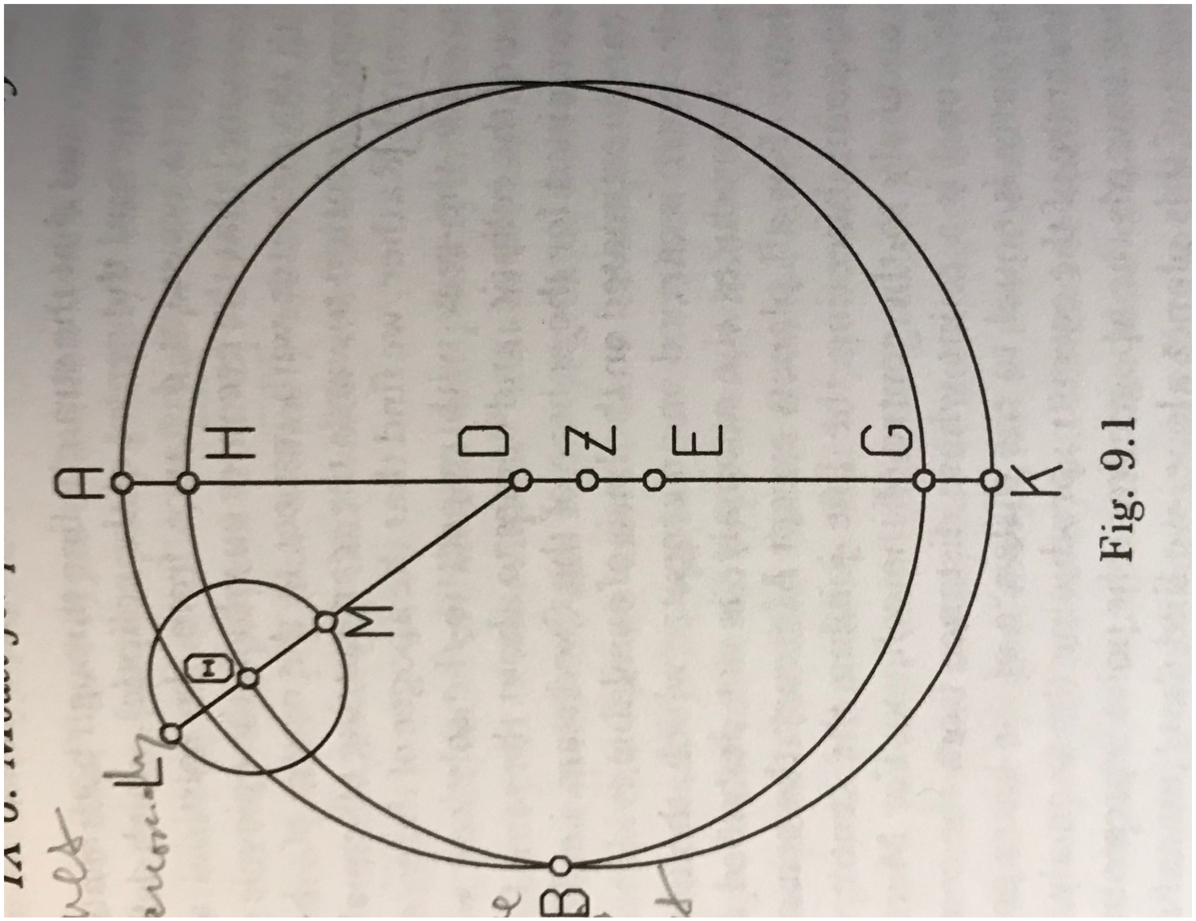
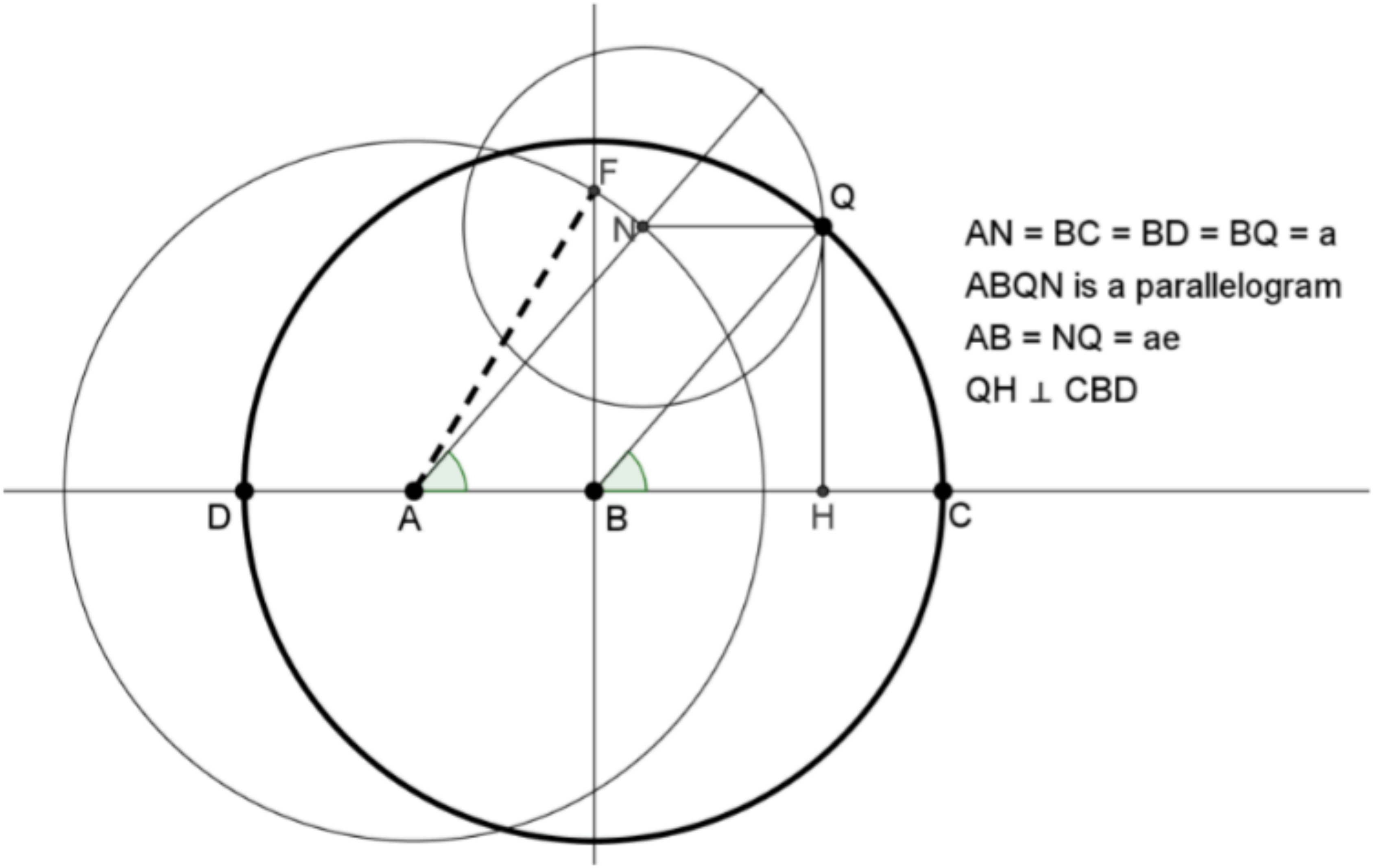


Fig. 9.1

D – Equant
E – Centre of ecliptic (Earth)

A – apogee
G – perigee

HΘK – deferent
ABG – eccentre



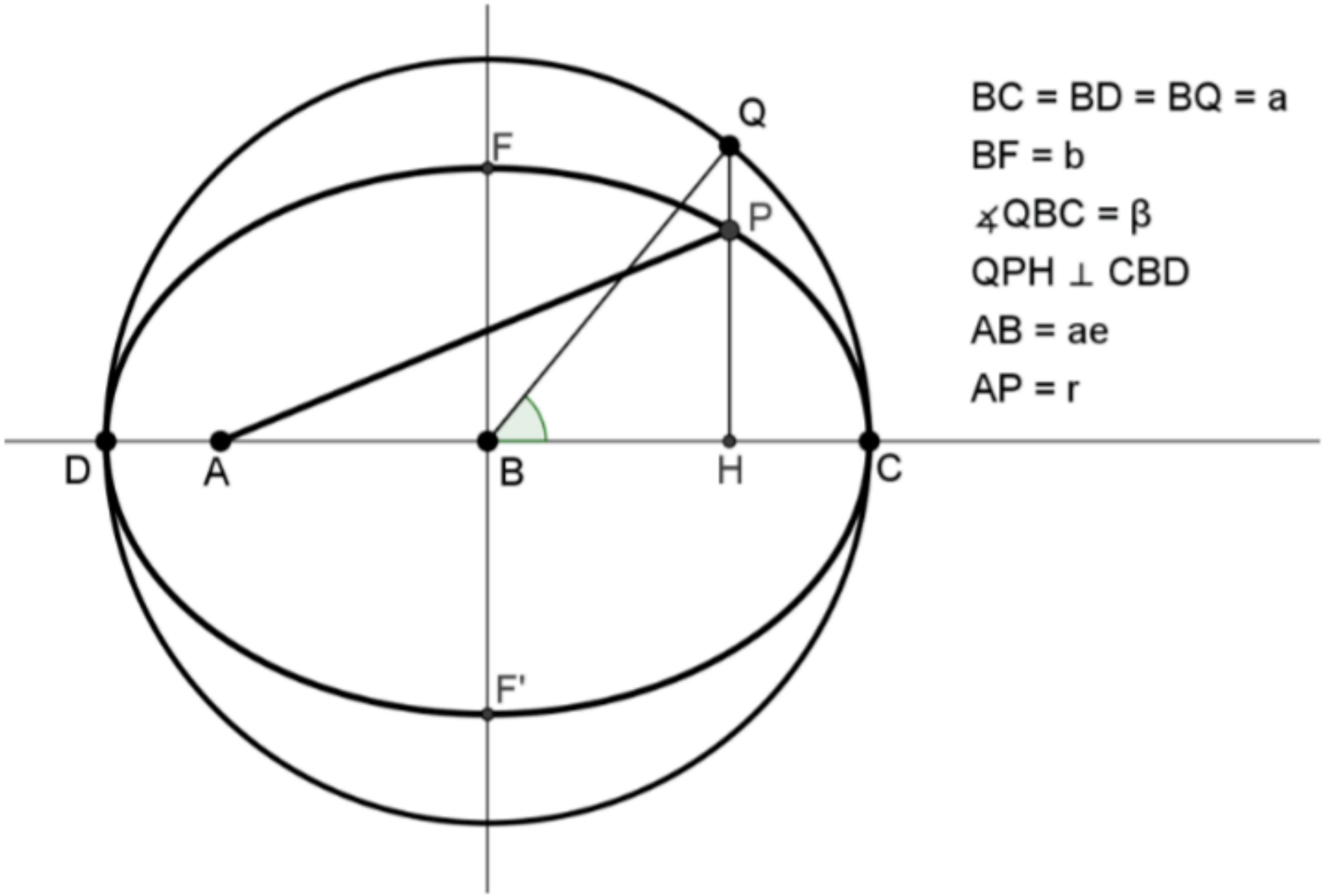
AN = BC = BD = BQ = a

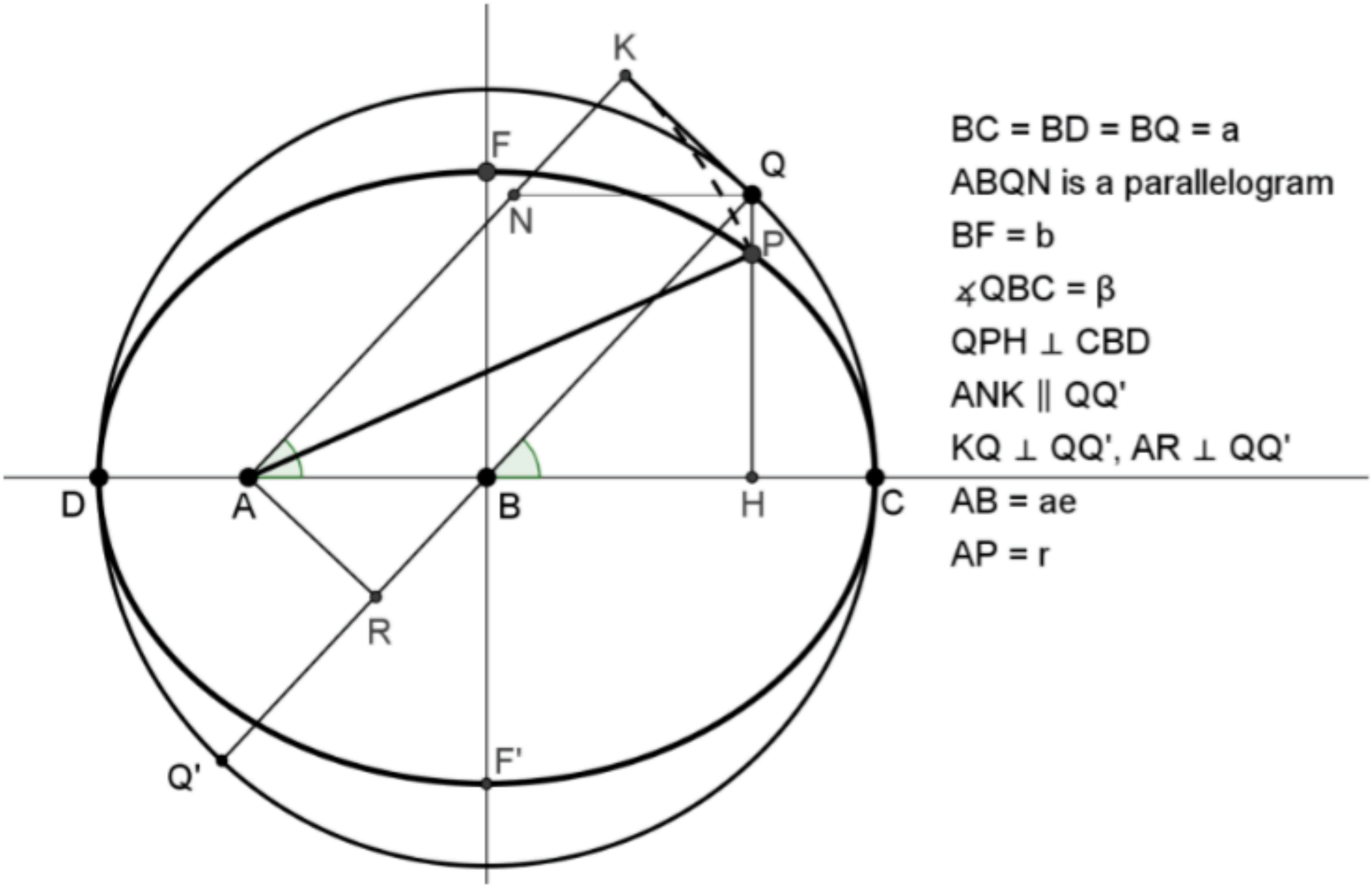
ABQN is a parallelogram

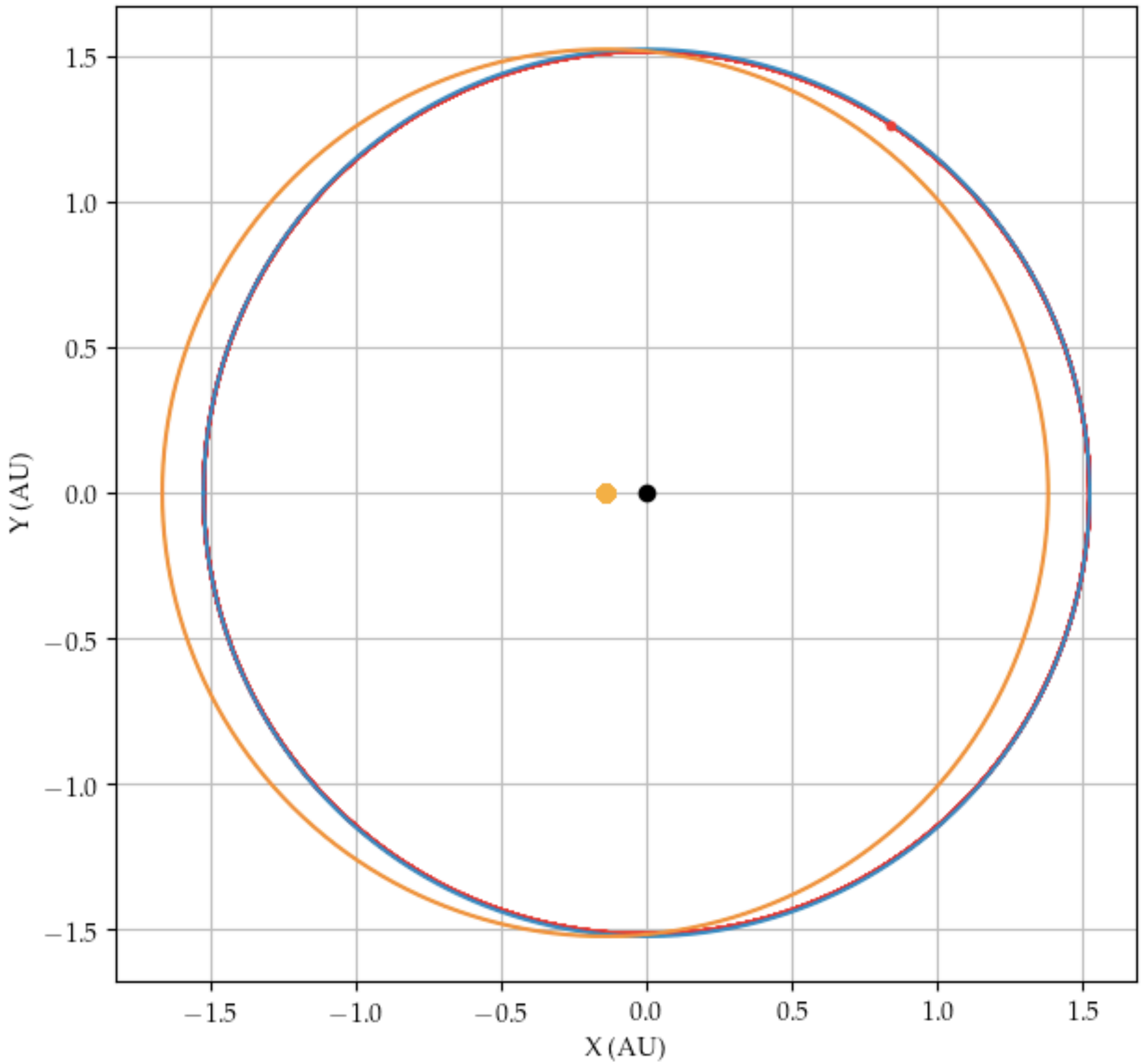
AB = NQ = ae

QH ⊥ CBD

$$AB = ae = \tfrac{1}{2}(CA - DA).$$




K
F
Q
N
P
D
A
B
H
C
R
F'
Q'
BC = BD = BQ = a
ABQN is a parallelogram
BF = b
∡QBC = β
QPH ⊥ CBD
ANK ∥ QQ'
KQ ⊥ QQ', AR ⊥ QQ'
AB = ae
AP = r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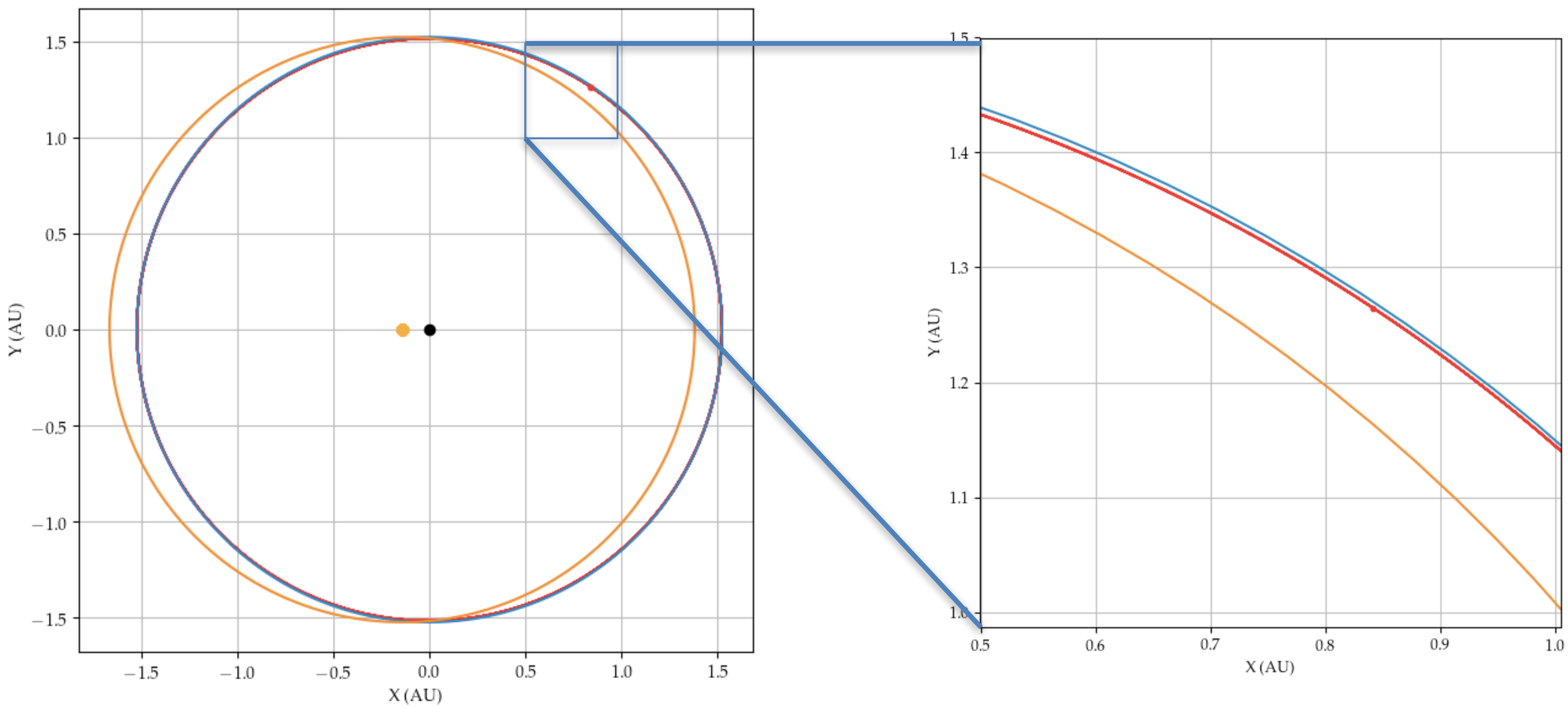

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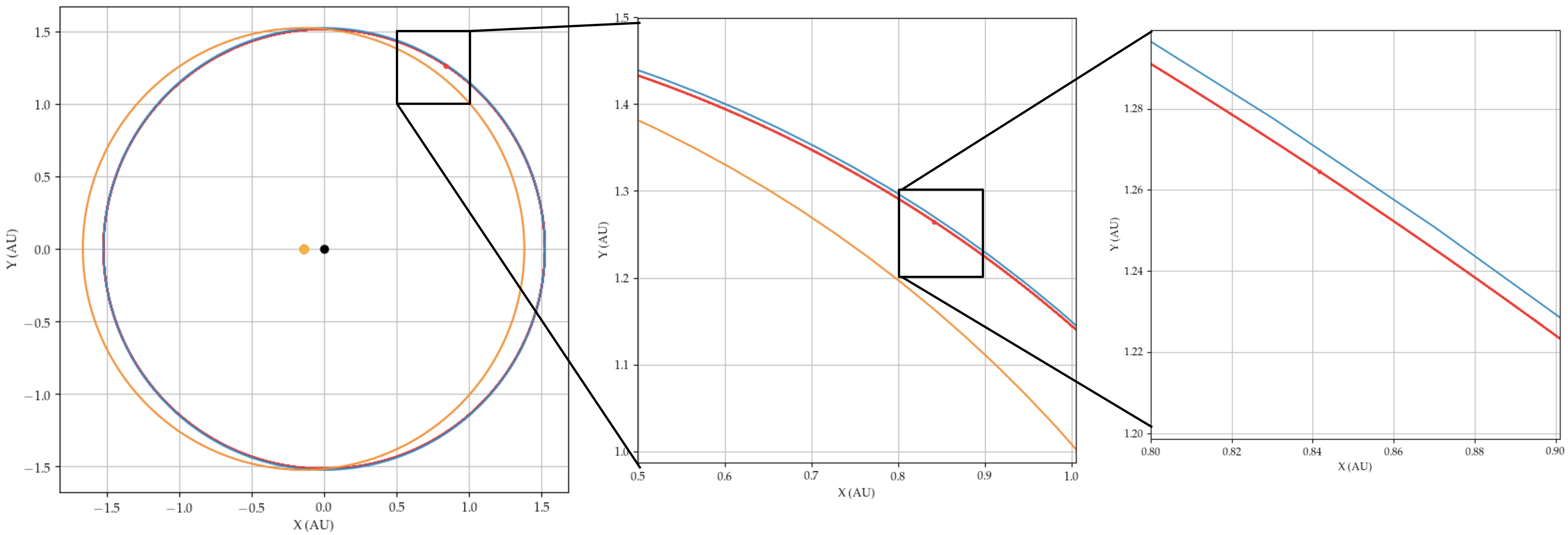
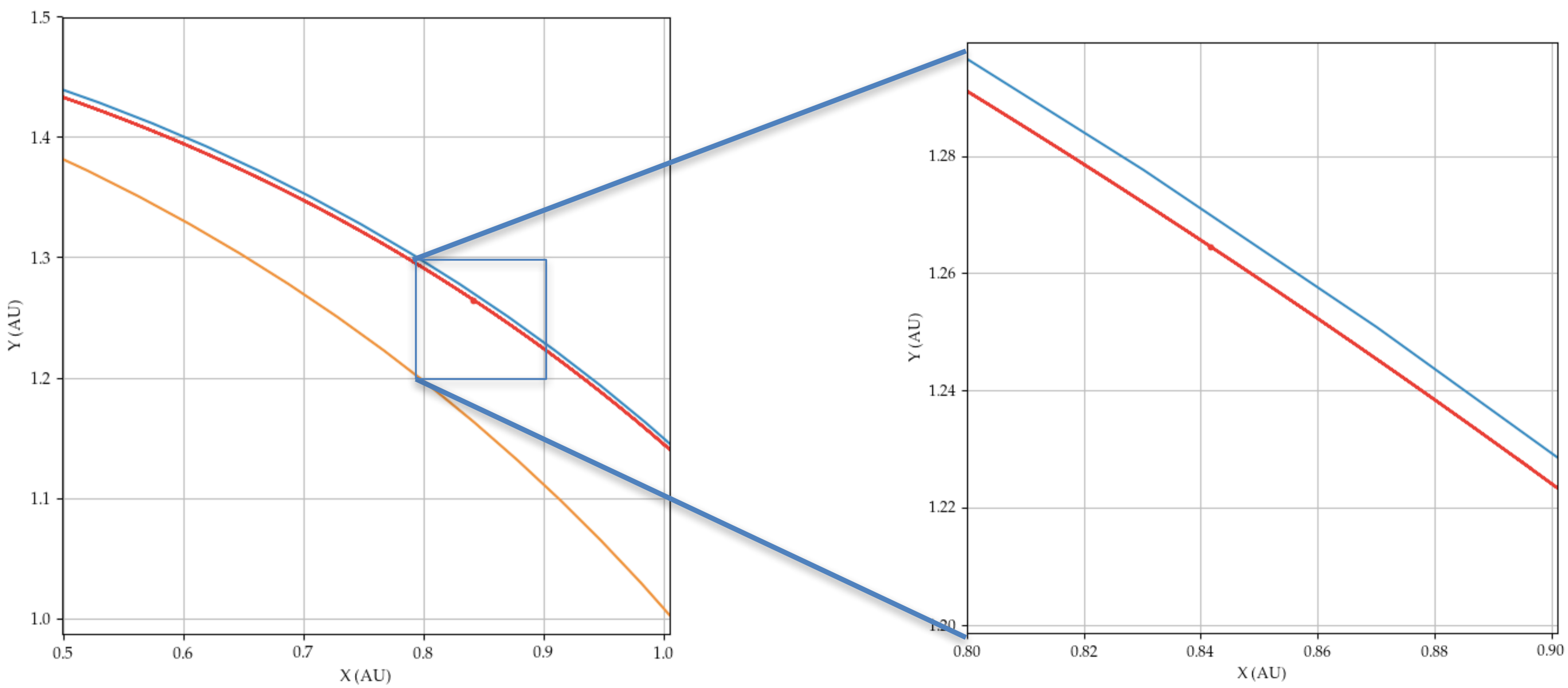
X (AU)



Y (AU)
X (AU)
Y (AU)
X (AU)
Y (AU)
X (AU)



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1.0
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0.6
0.7
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0.9
1.0
X (AU)
1.28
1.26
1.24
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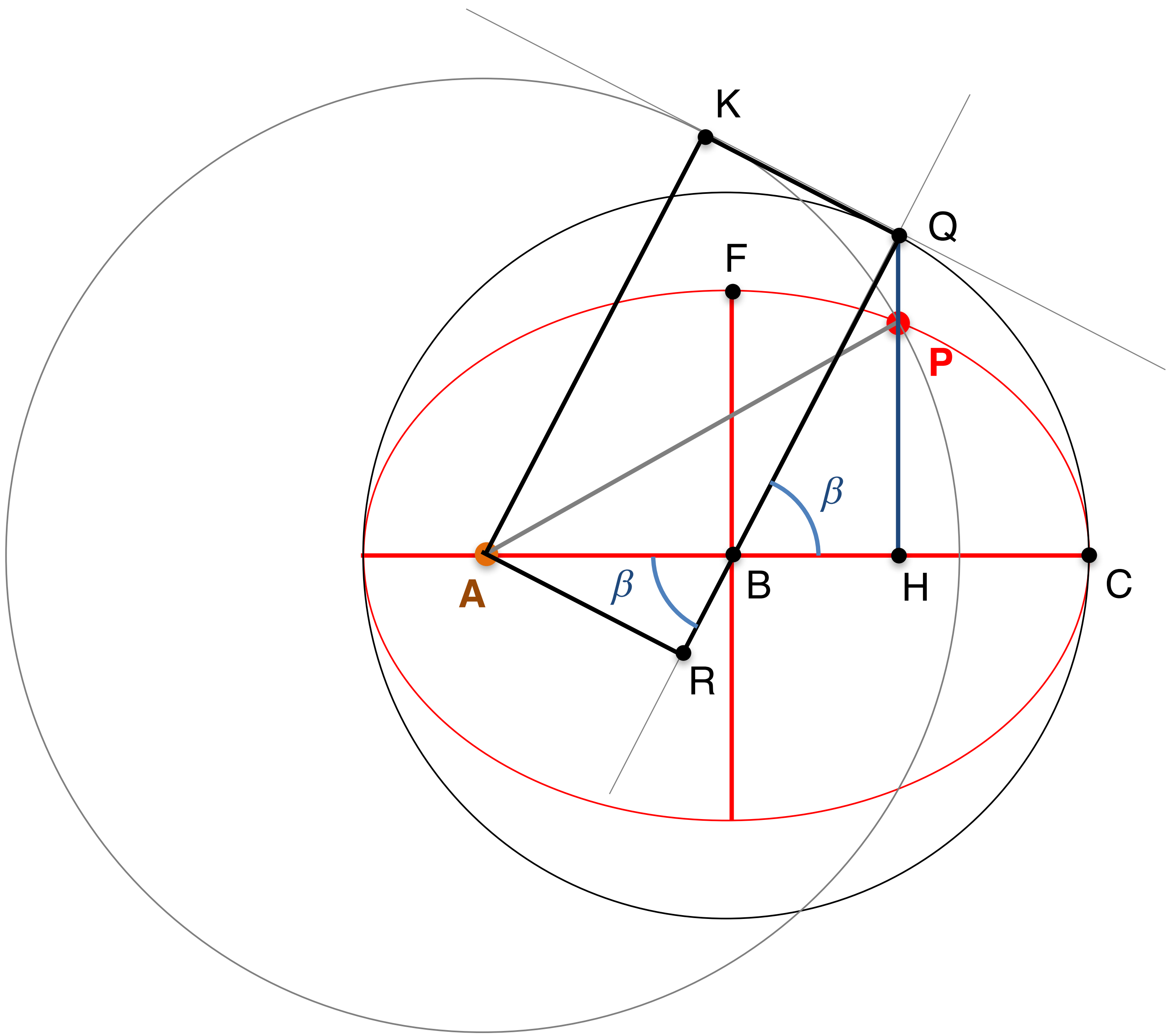
1.20
Y (AU)
0.80
0.82
0.84
0.86
0.88
0.90
X (AU)



K
Q
F
P
β
A
β
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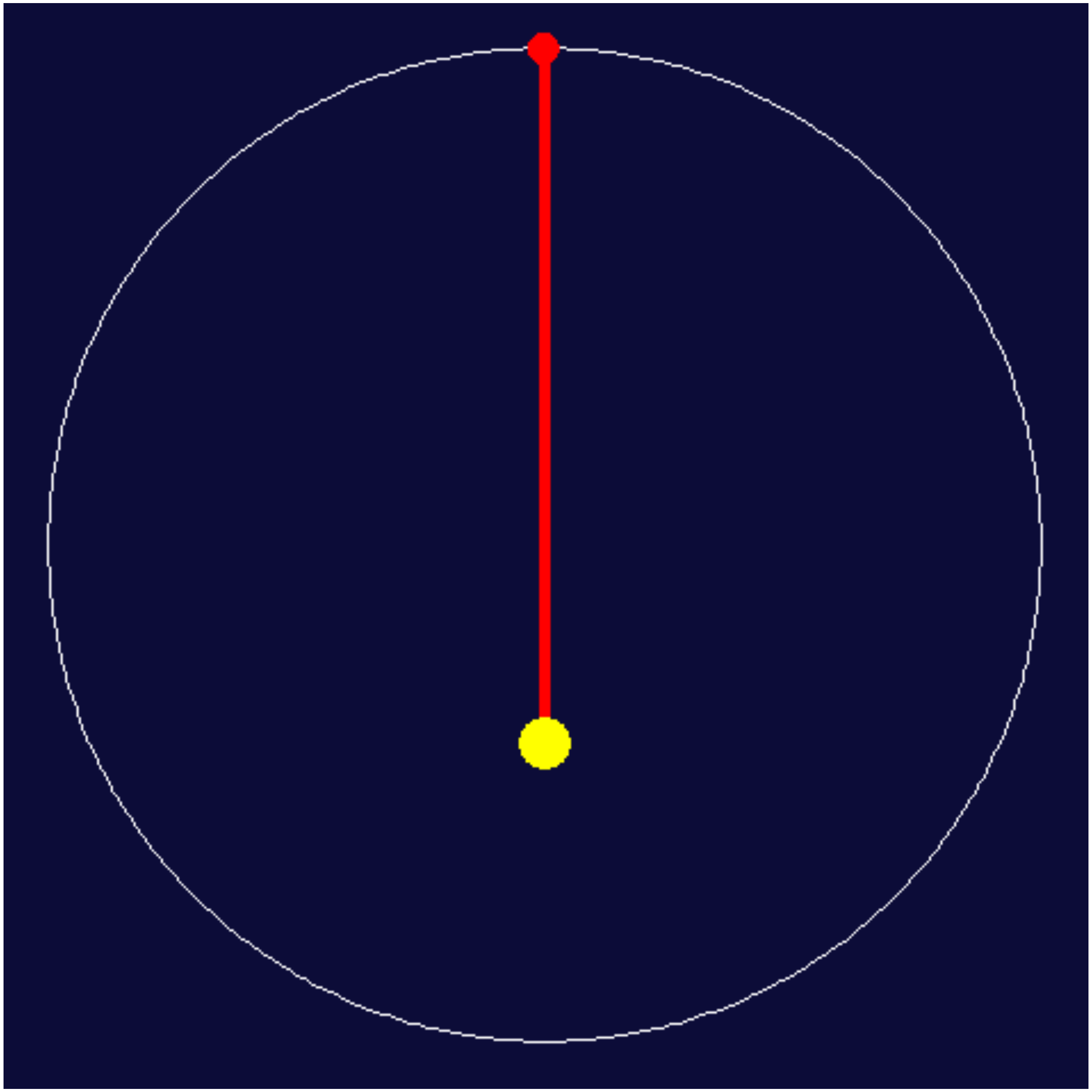
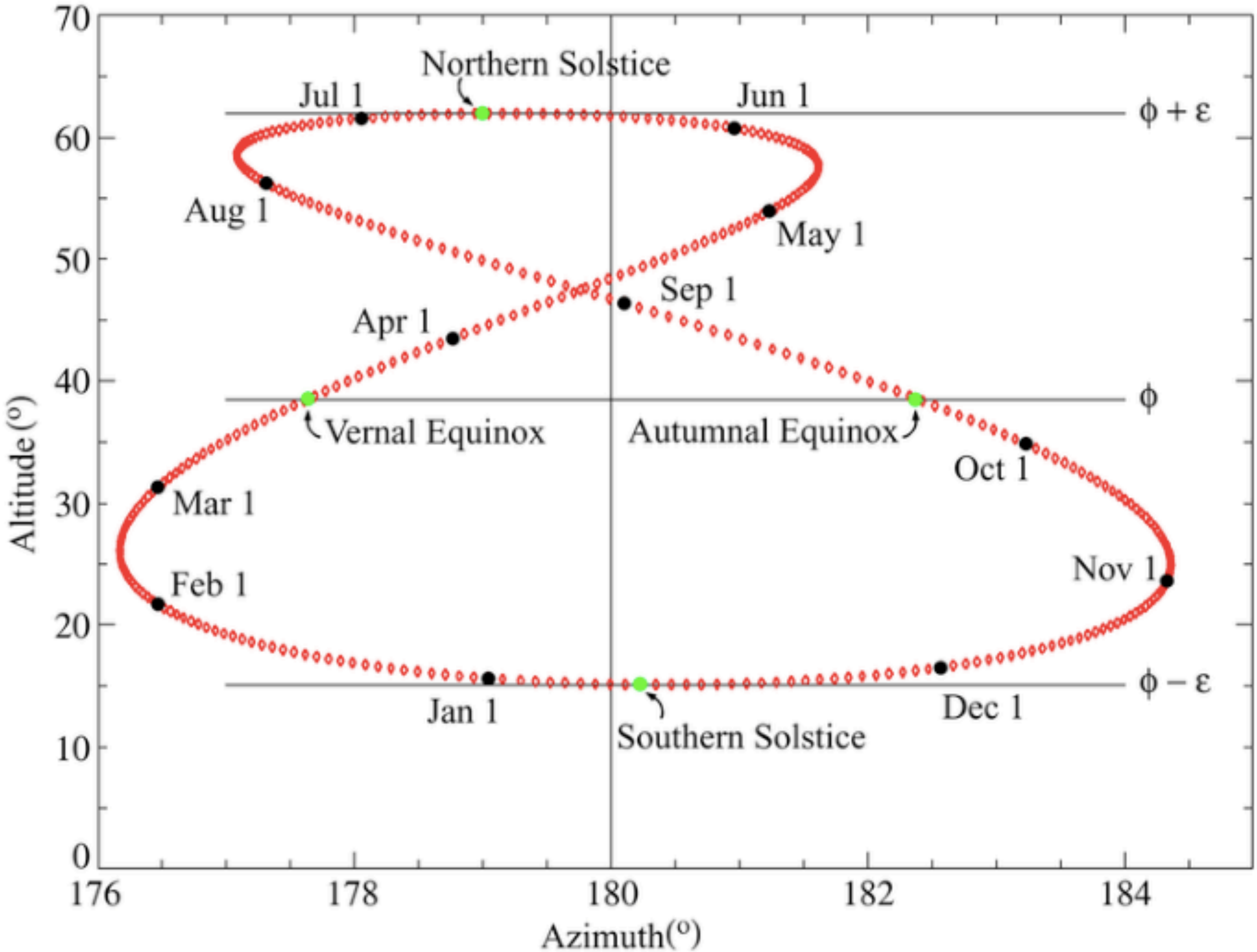
H
C
R

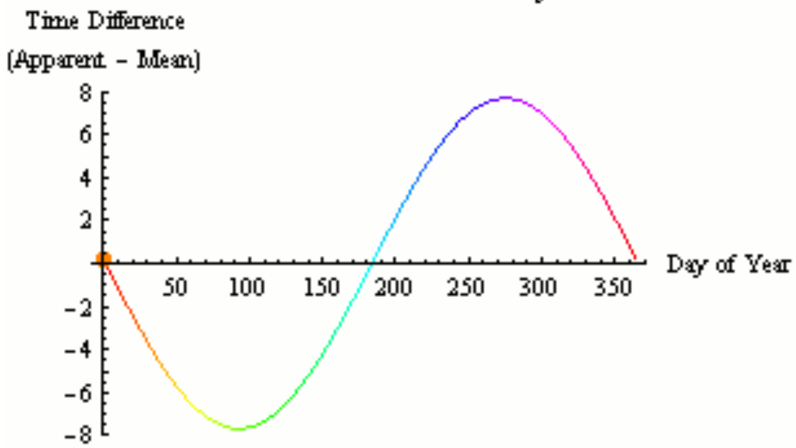


Analemma

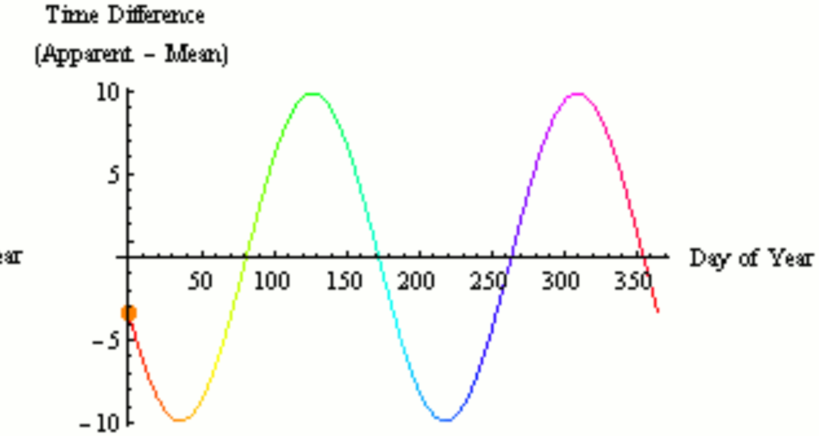


Northern Solstice
Jul 1
Jun 1
ϕ + ε
Aug 1
May 1
Sep 1
Apr 1
ϕ
Vernal Equinox
Autumnal Equinox
Oct 1
Mar 1
Feb 1
Nov 1
ϕ − ε
Jan 1
Dec 1
Southern Solstice
Altitude (°)
Azimuth(°)
70
60
50
40
30
20
10
0
176
178
180
182
184

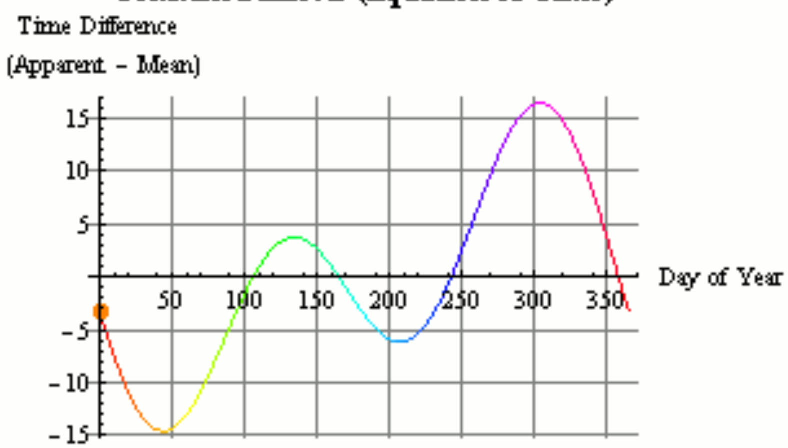
Effect of Orbit Eccentricity



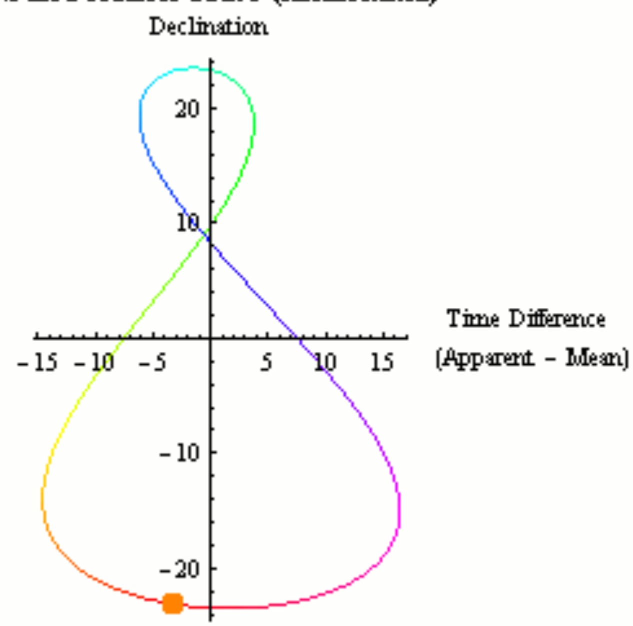
Effect of Obliquity



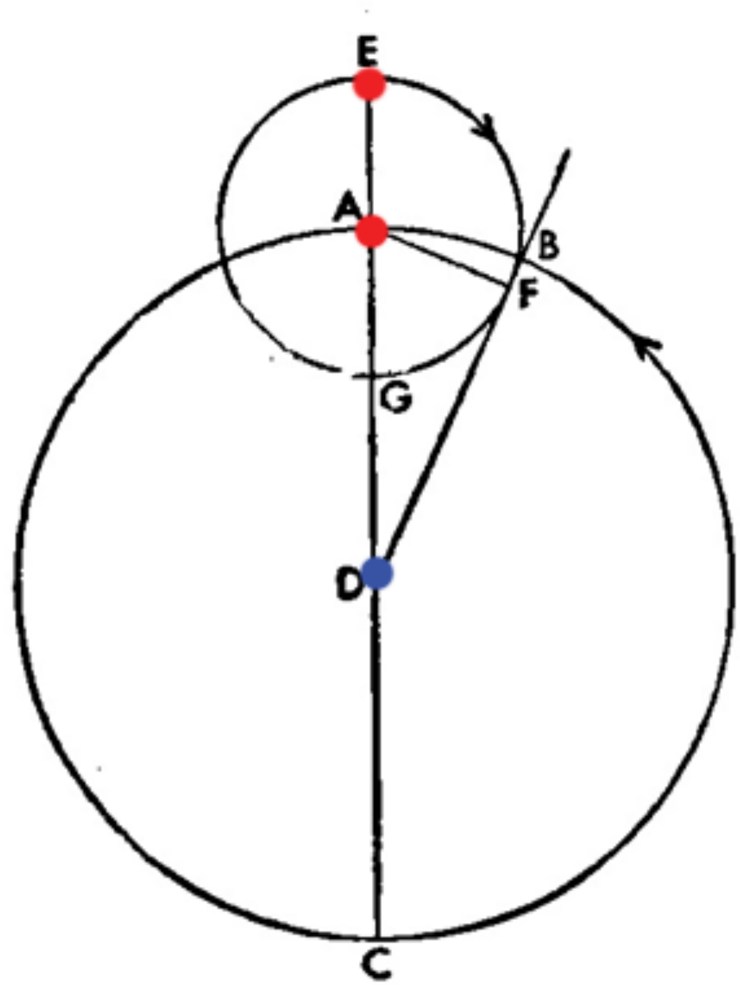
Combined Effects (Equation of Time)



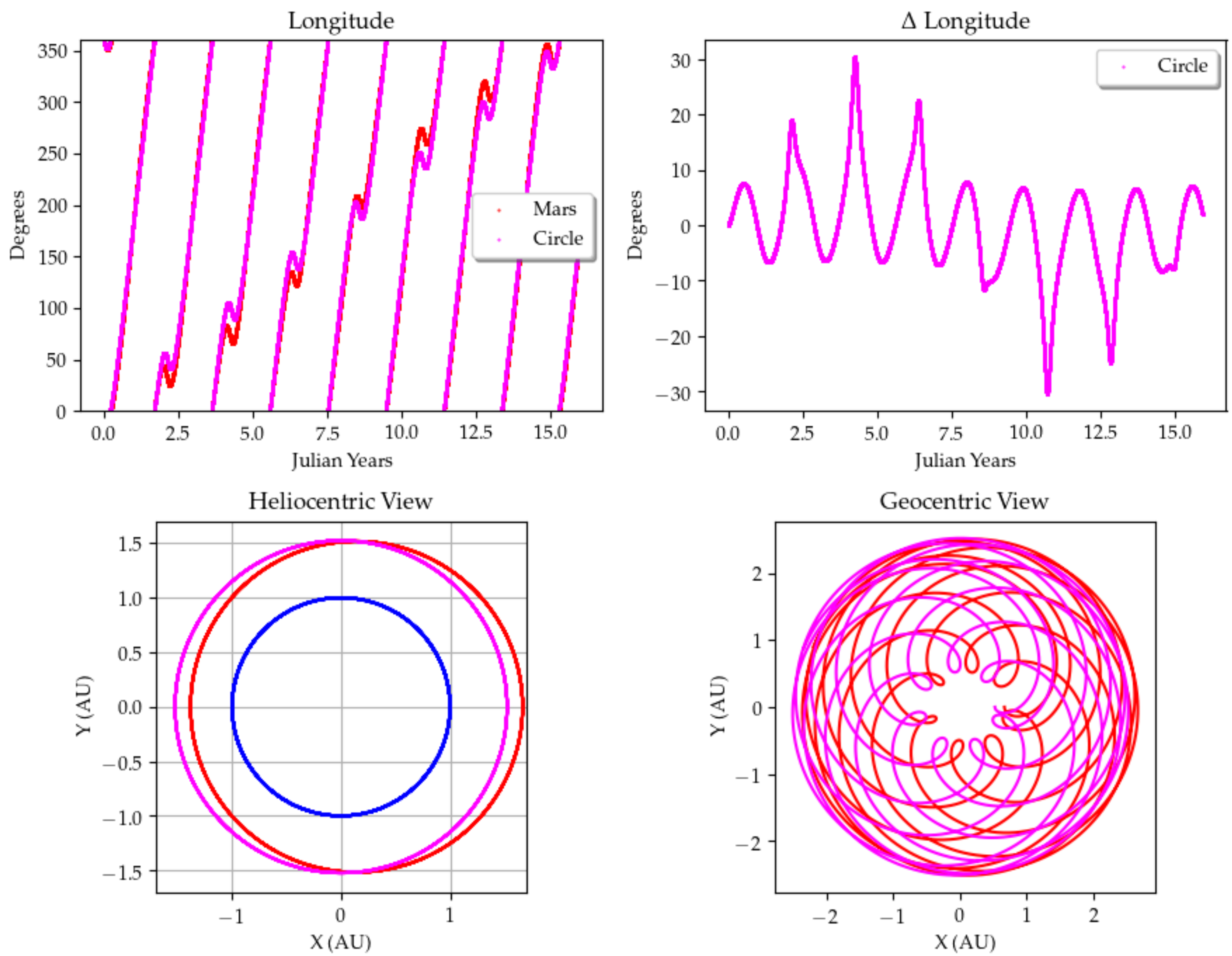
Sun Position Trace (Analemma)



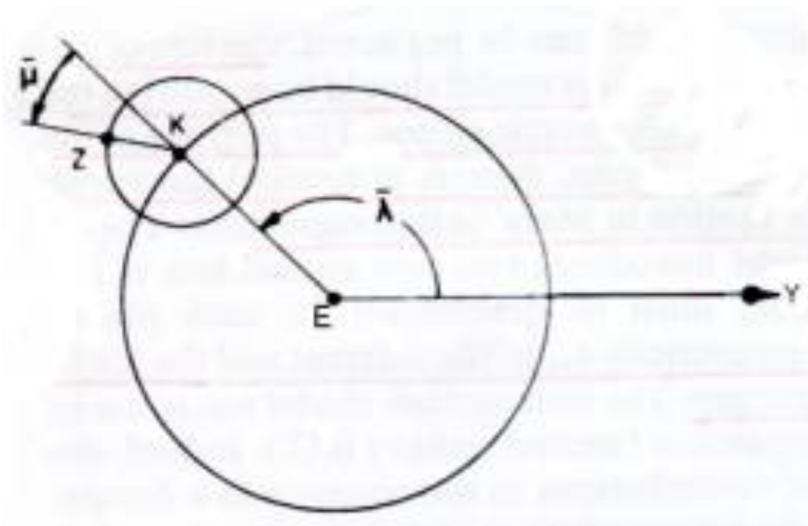
Ptolemy – The Sun had a small epicycle (~1/25 of deferent)



Circular and Centered Orbit

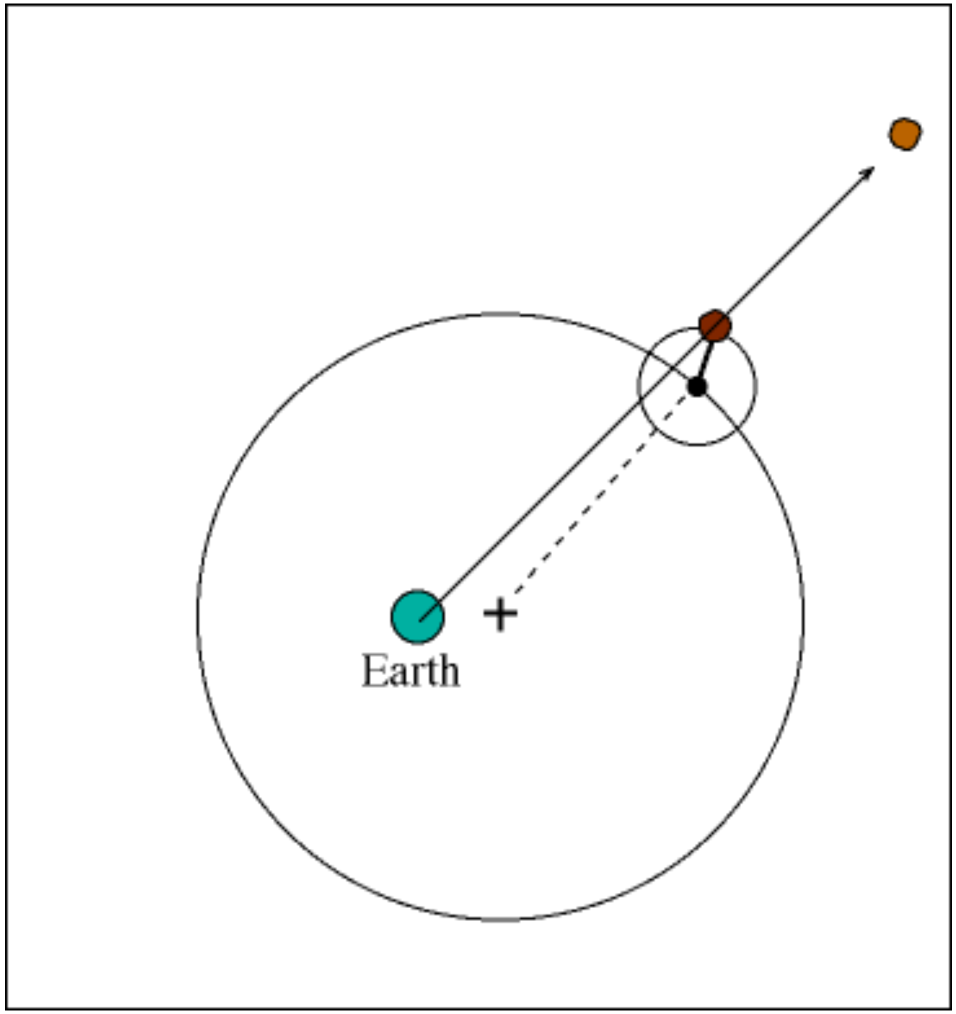


Regular Epicycles produce regular retrogradations

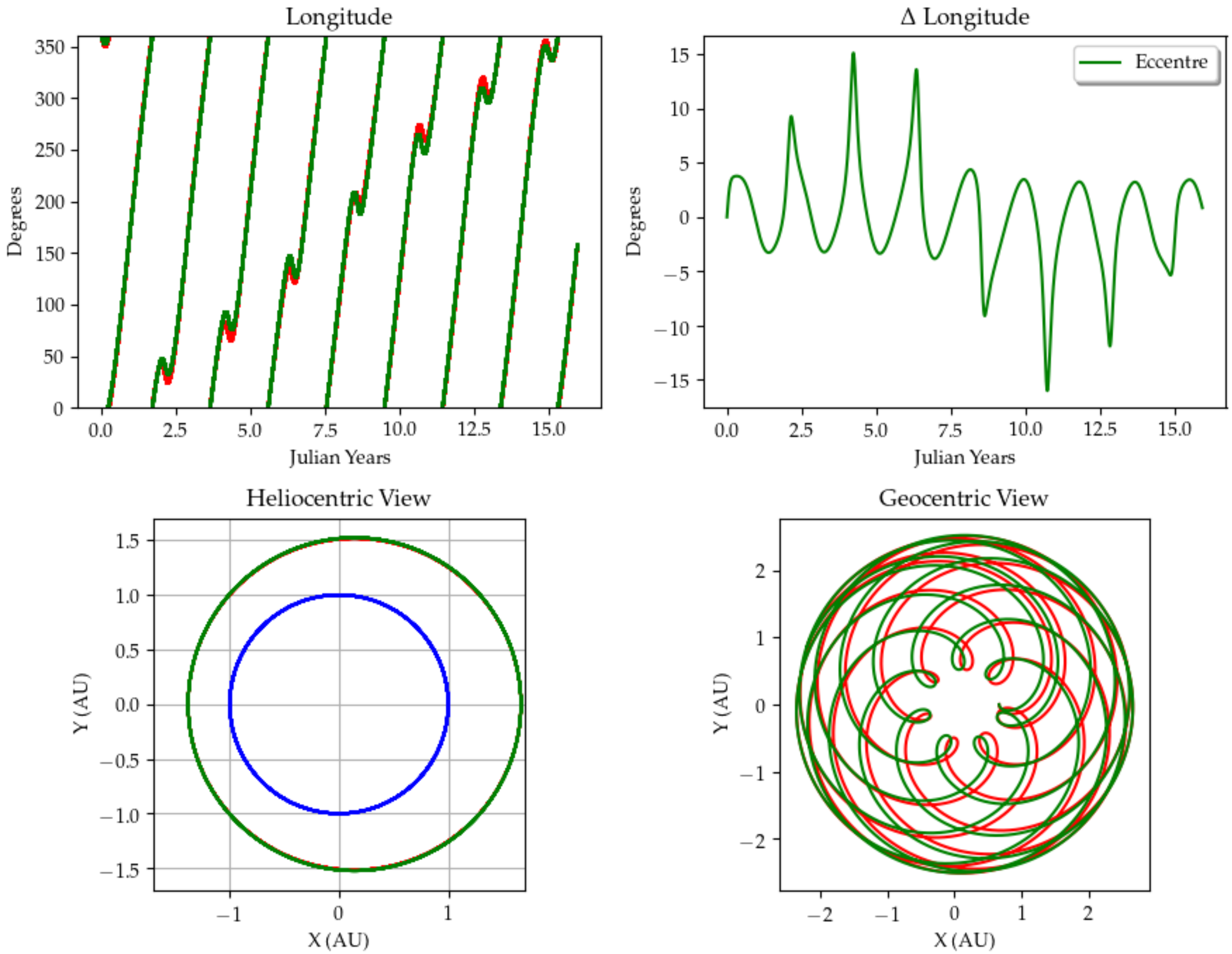


In reality the retrogradations vary both in position and duration.

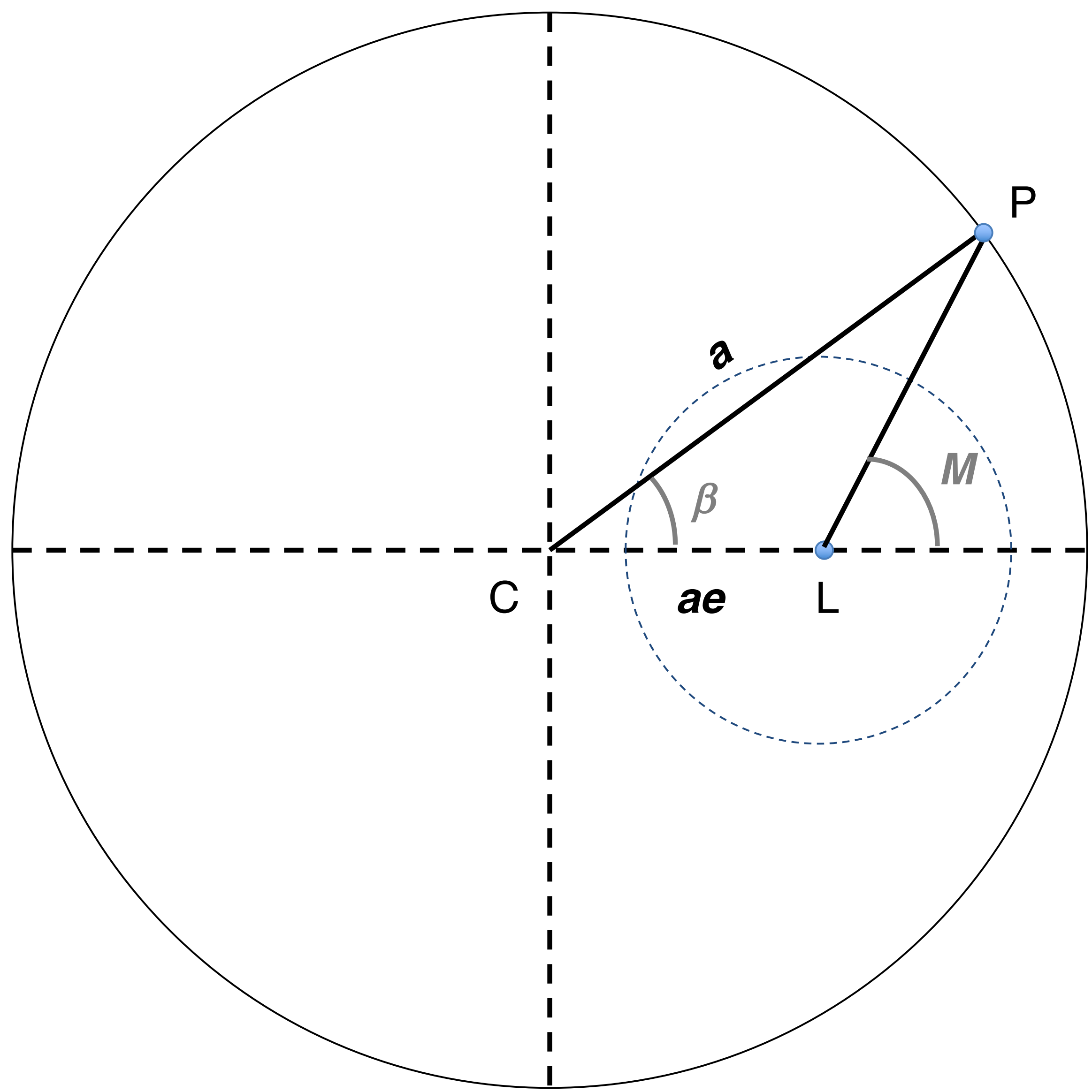
Move the Earth from the Center



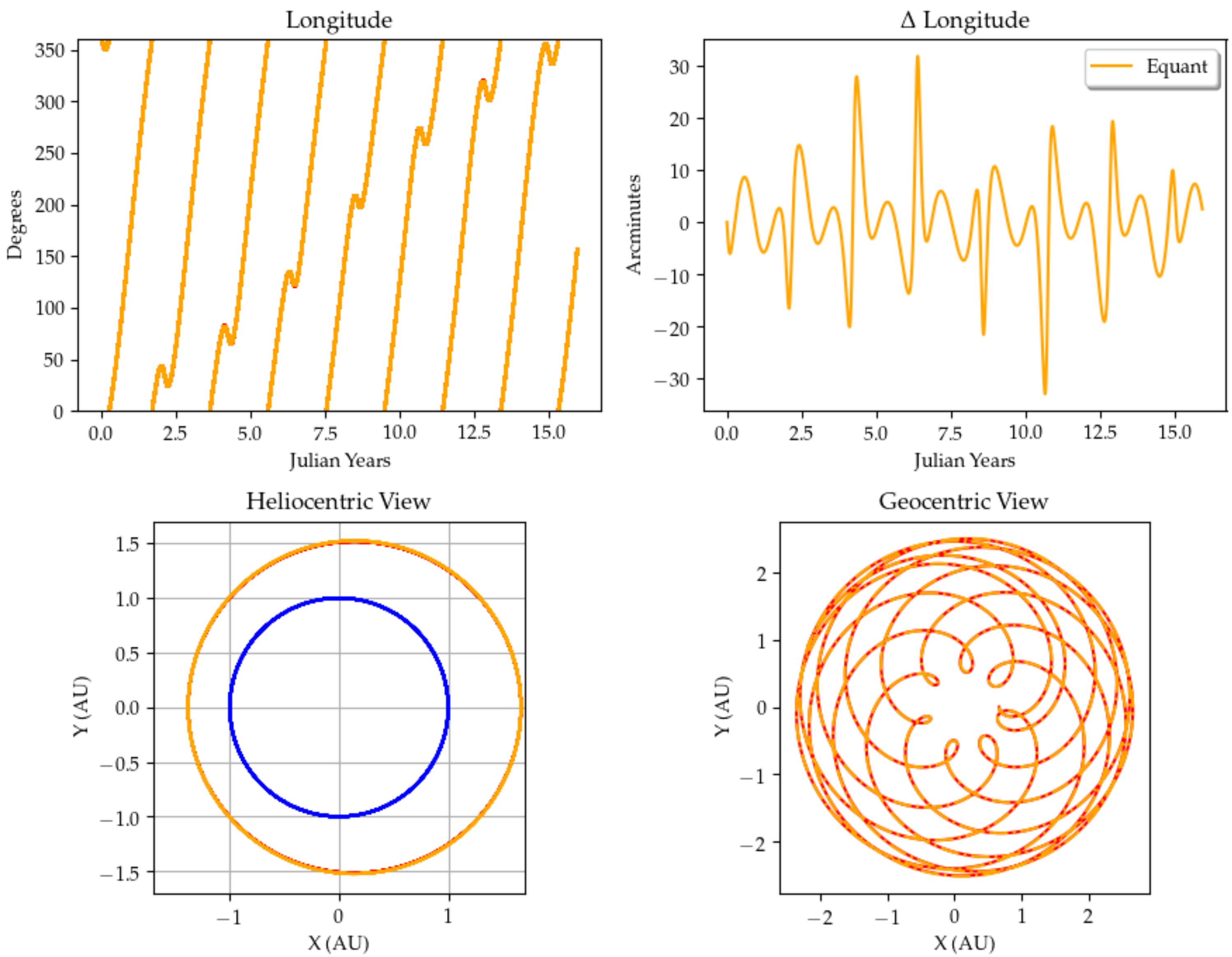
Circular Off-Centered Orbit (the Eccentre)



The Equant

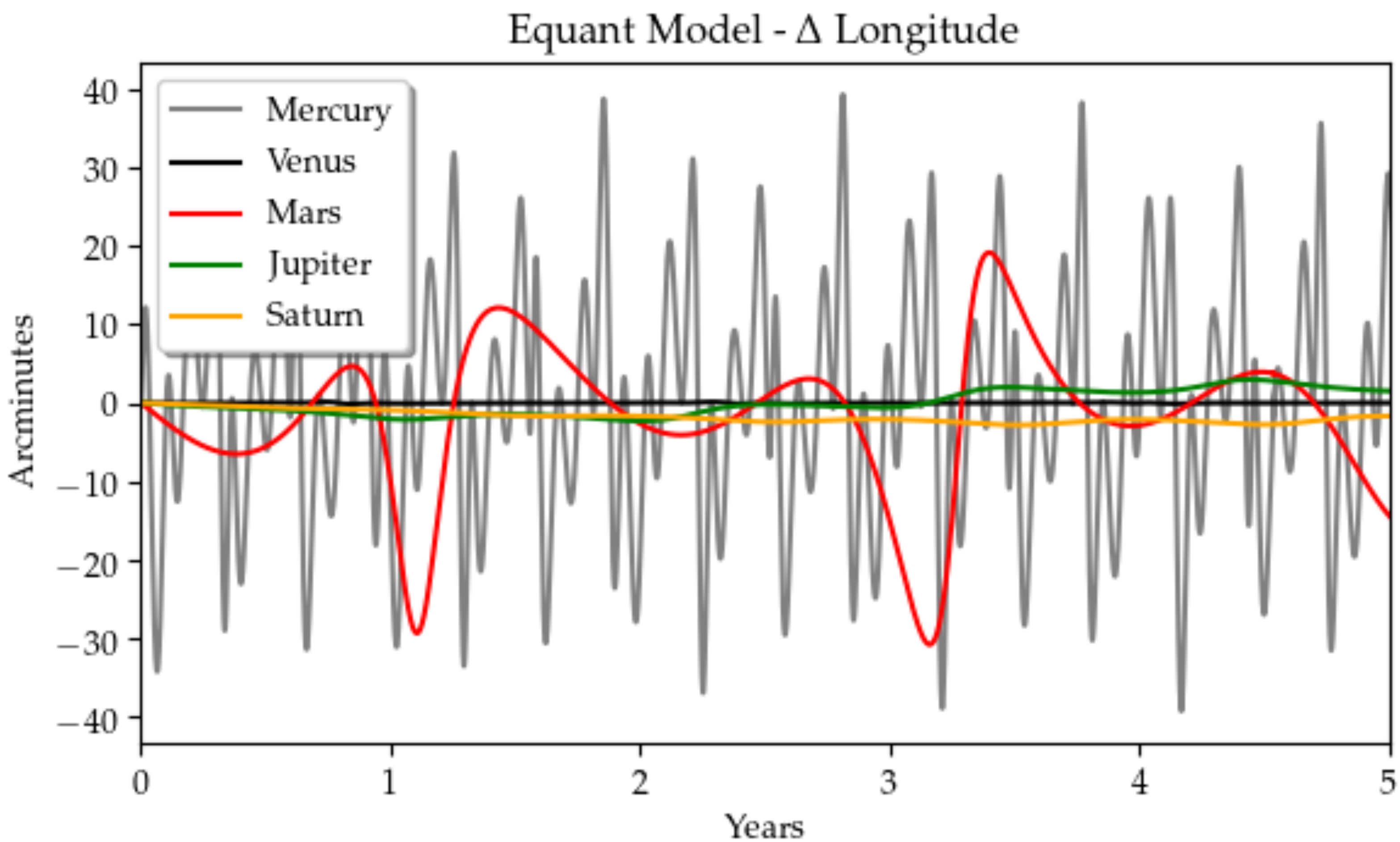


The Equant



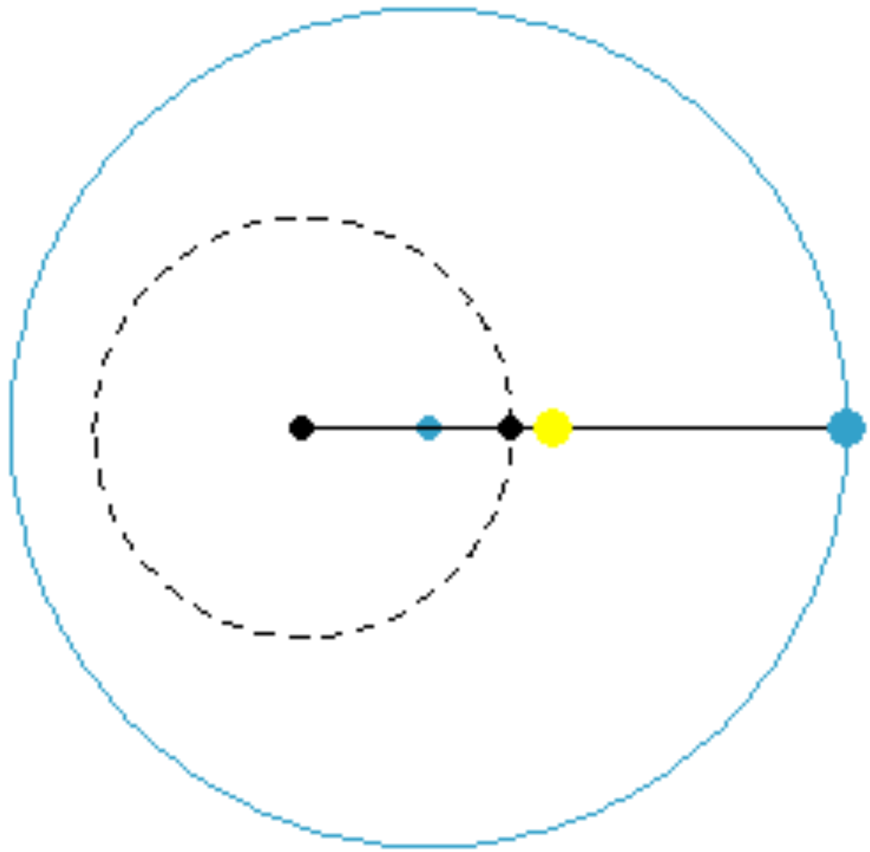
Longitude
Degrees
Julian Years
Δ Longitude
Equant
Arcminutes
Julian Years
Heliocentric View
Y (AU)
X (AU)
Geocentric View
Y (AU)
X (AU)

The Equant

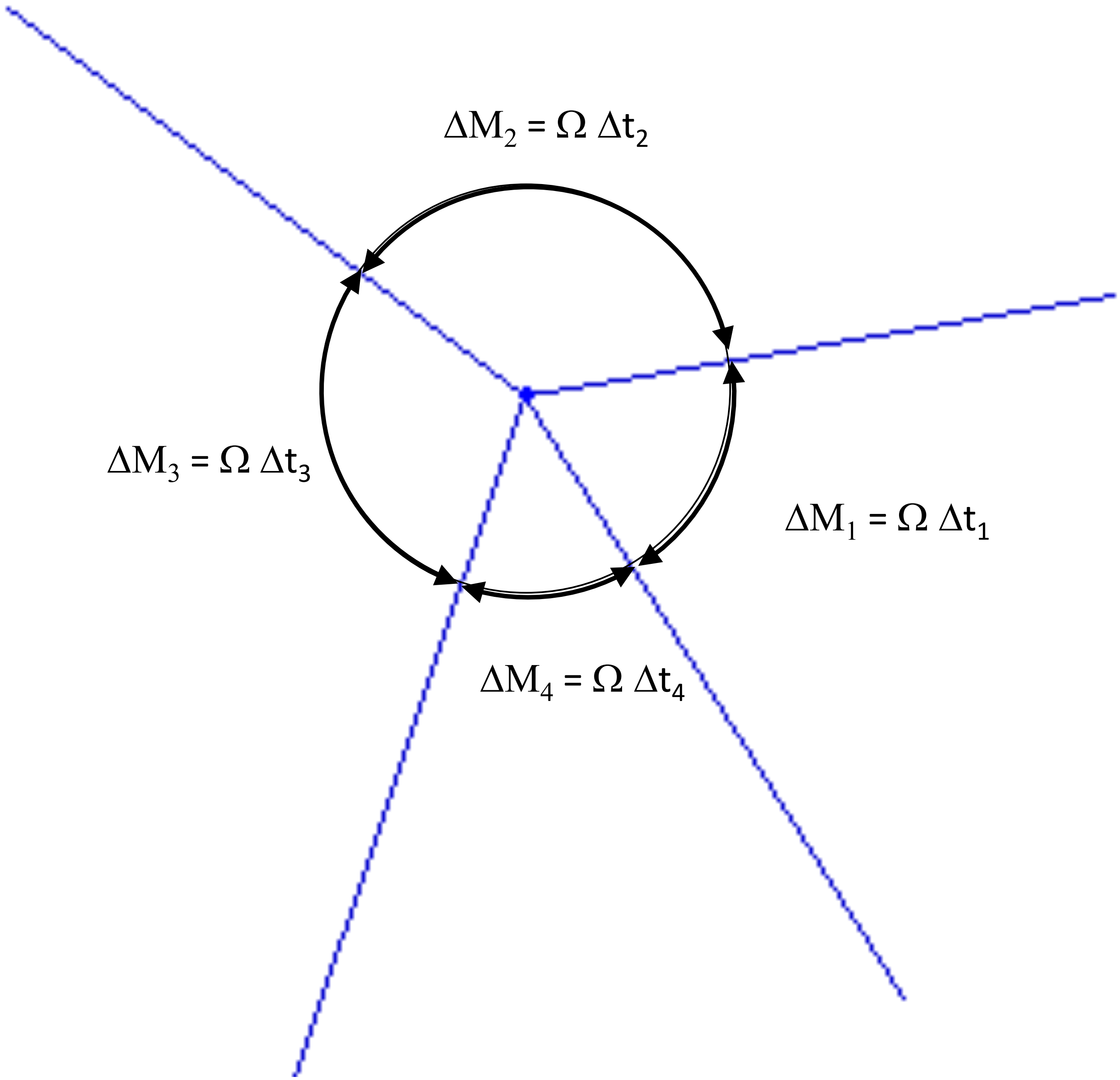


Even for the highest eccentricity (Mercury),
the equant reproduces the observations to the degree.

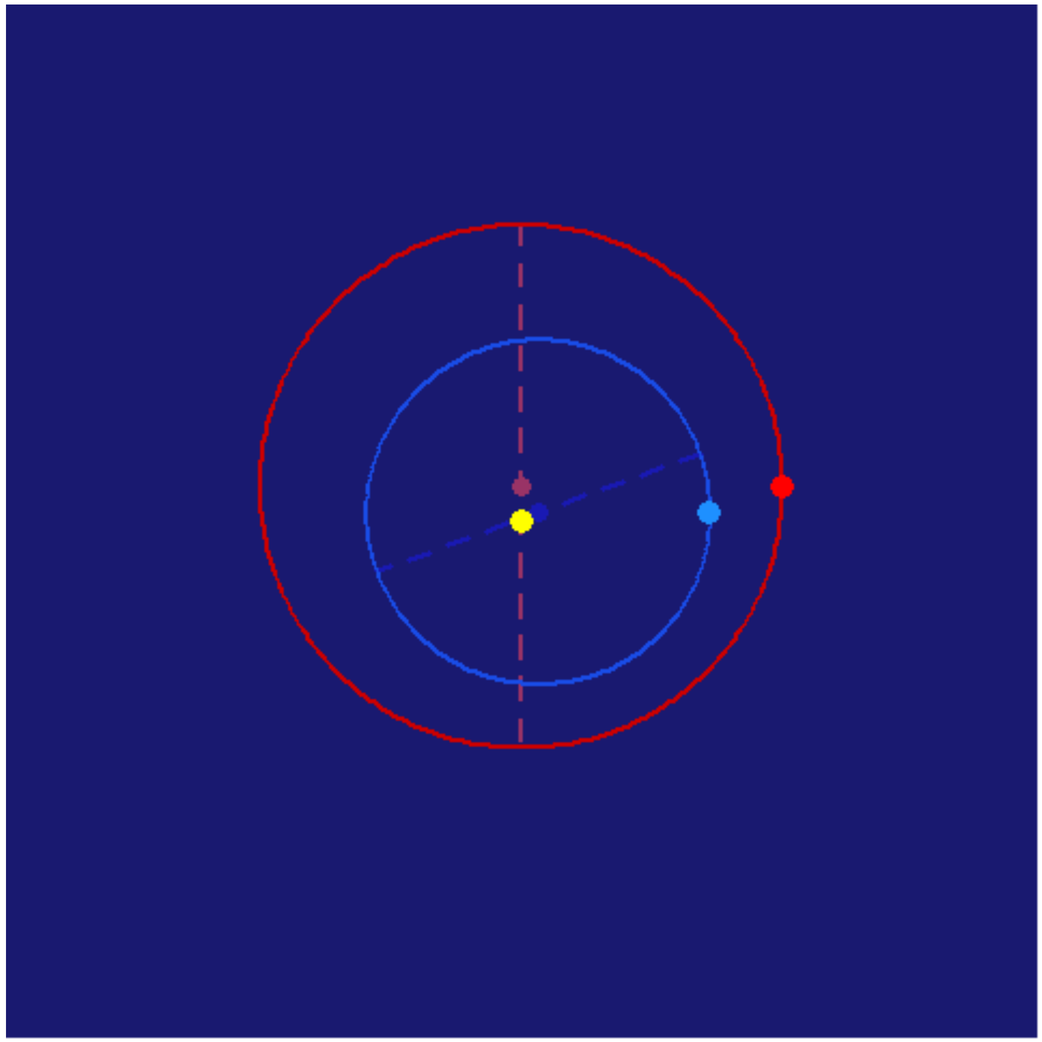
The equant: Equal angles at equal time



Equant Point of View



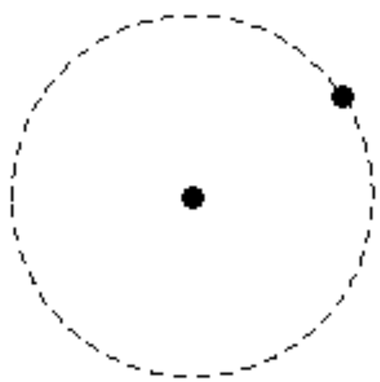
Changing to the Sun's Reference Frame: Observations at Opposition



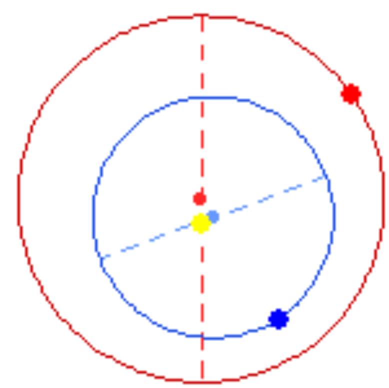
Locating the Equant

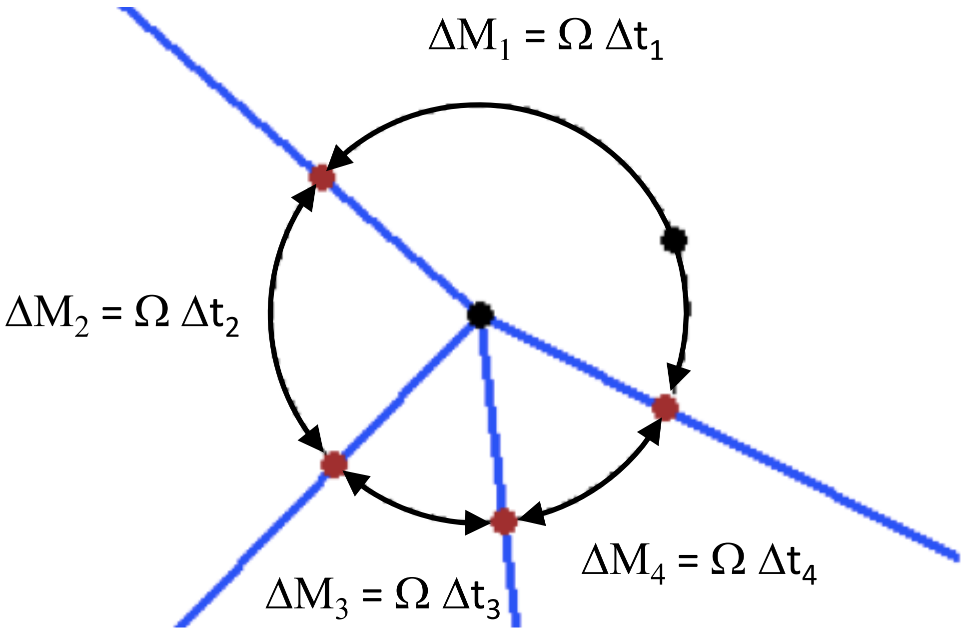
Equant (Mean)

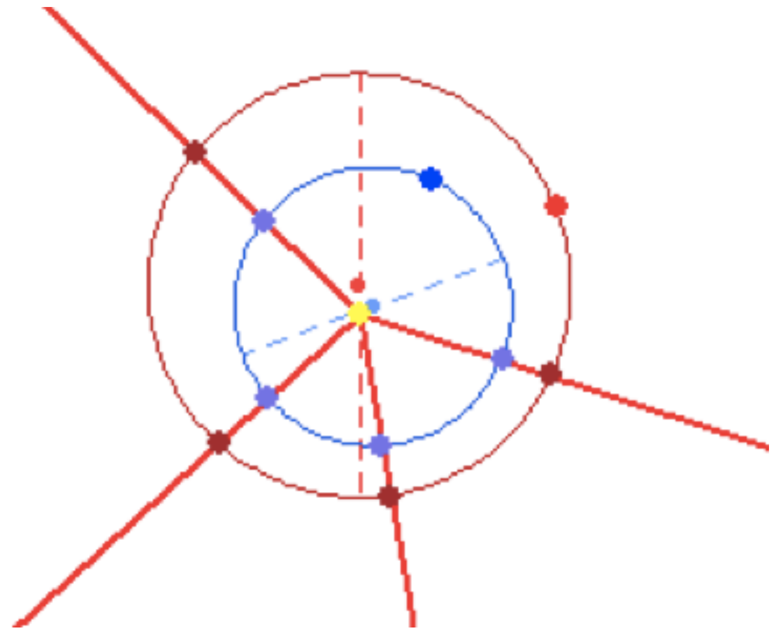
Time between Oppositions



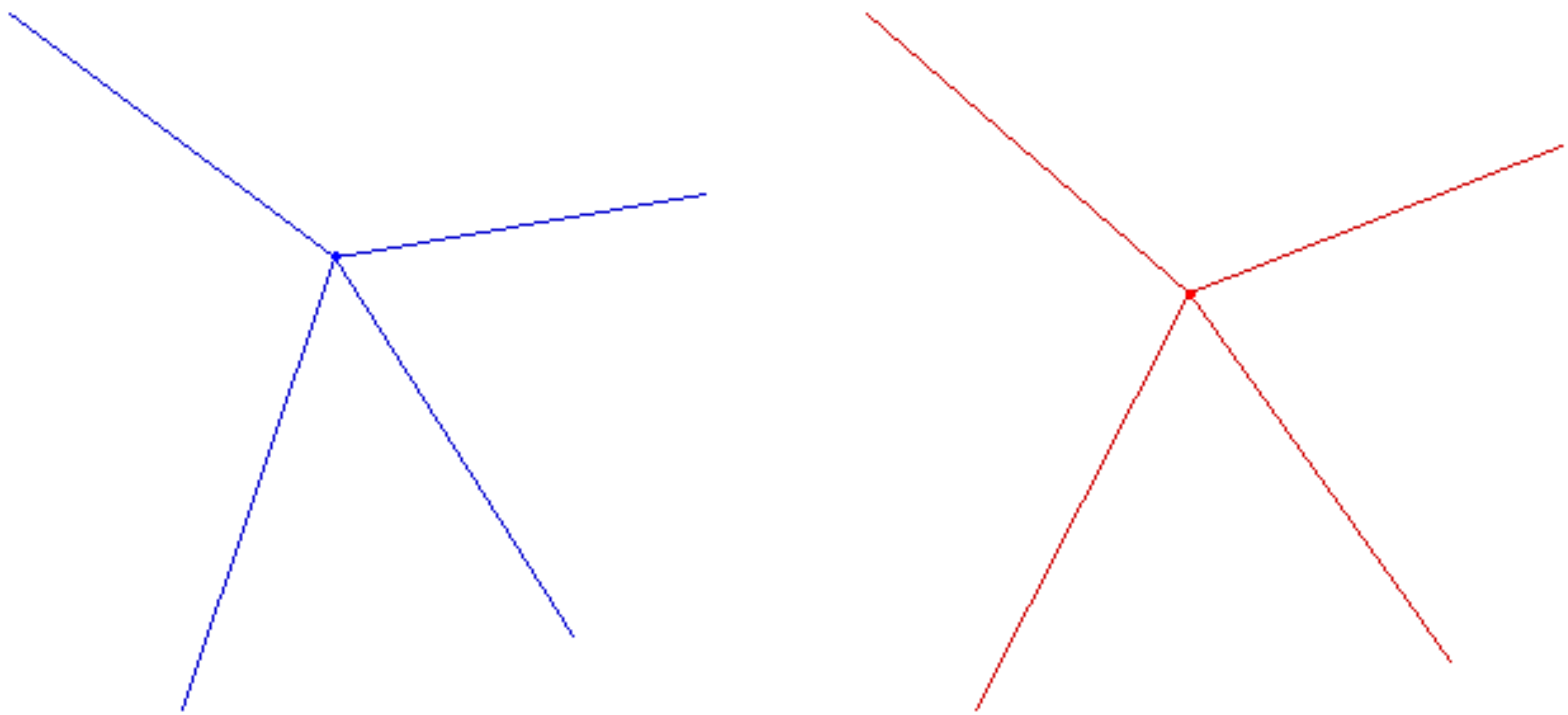
Observed (Apparent)



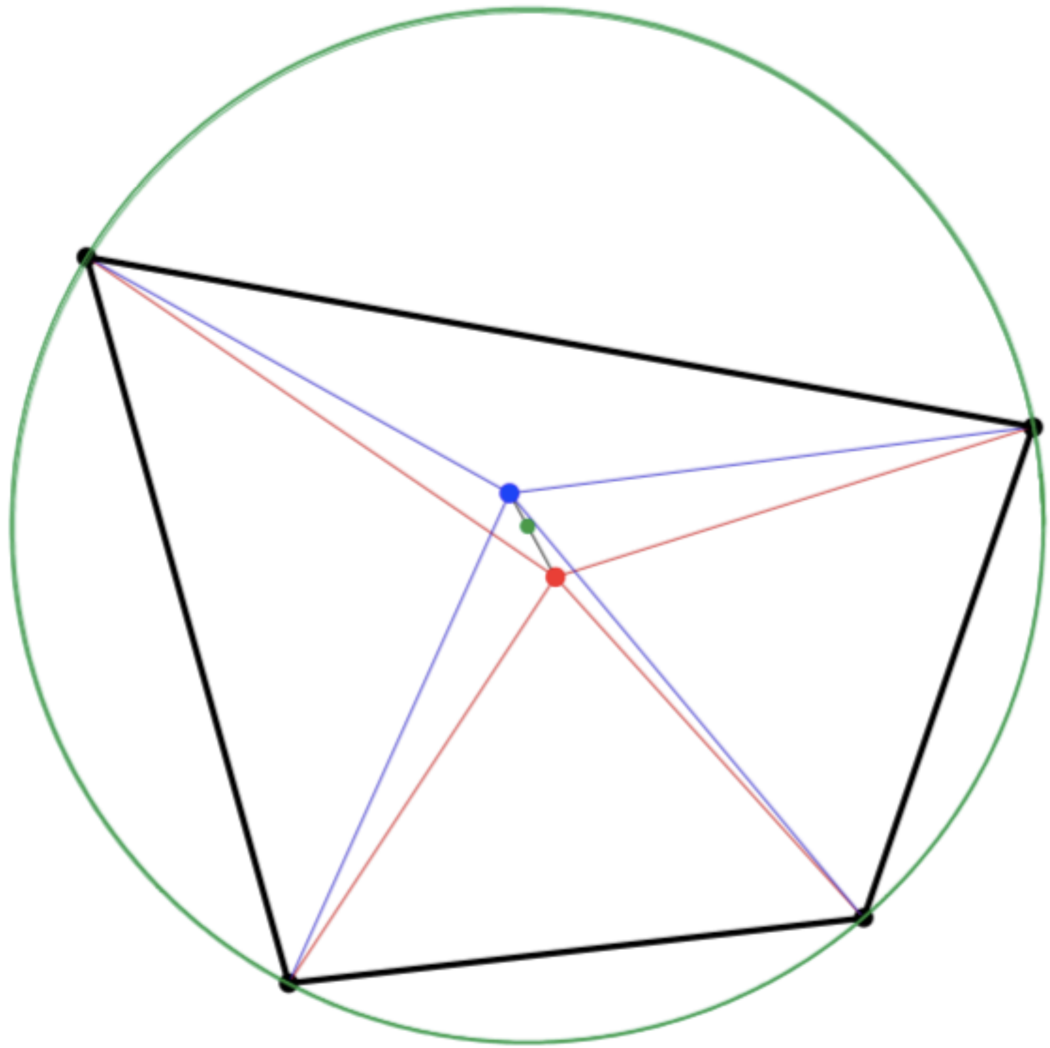

$\Delta M_1 = \Omega\ \Delta t_1$
$\Delta M_2 = \Omega\ \Delta t_2$
$\Delta M_3 = \Omega\ \Delta t_3$
$\Delta M_4 = \Omega\ \Delta t_4$

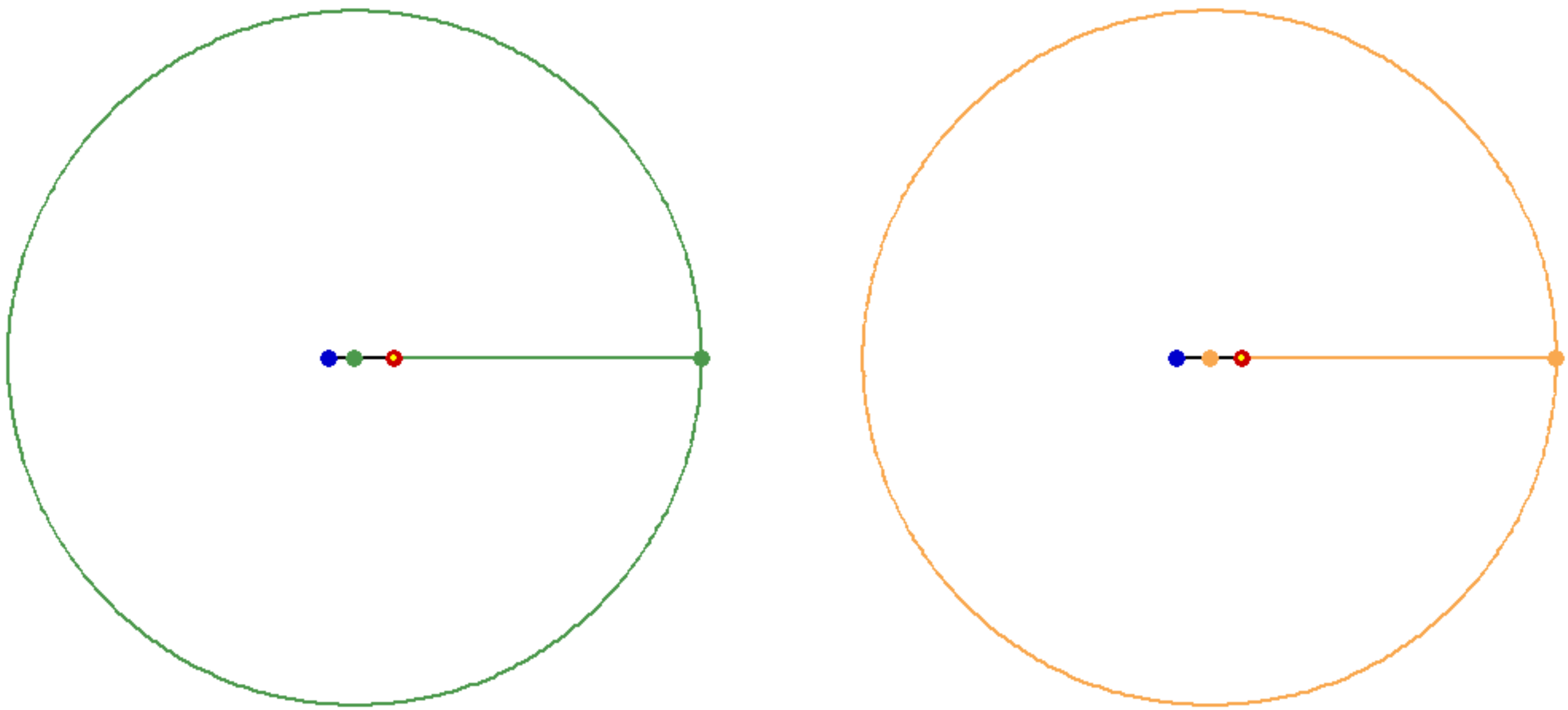


Locating the Equant

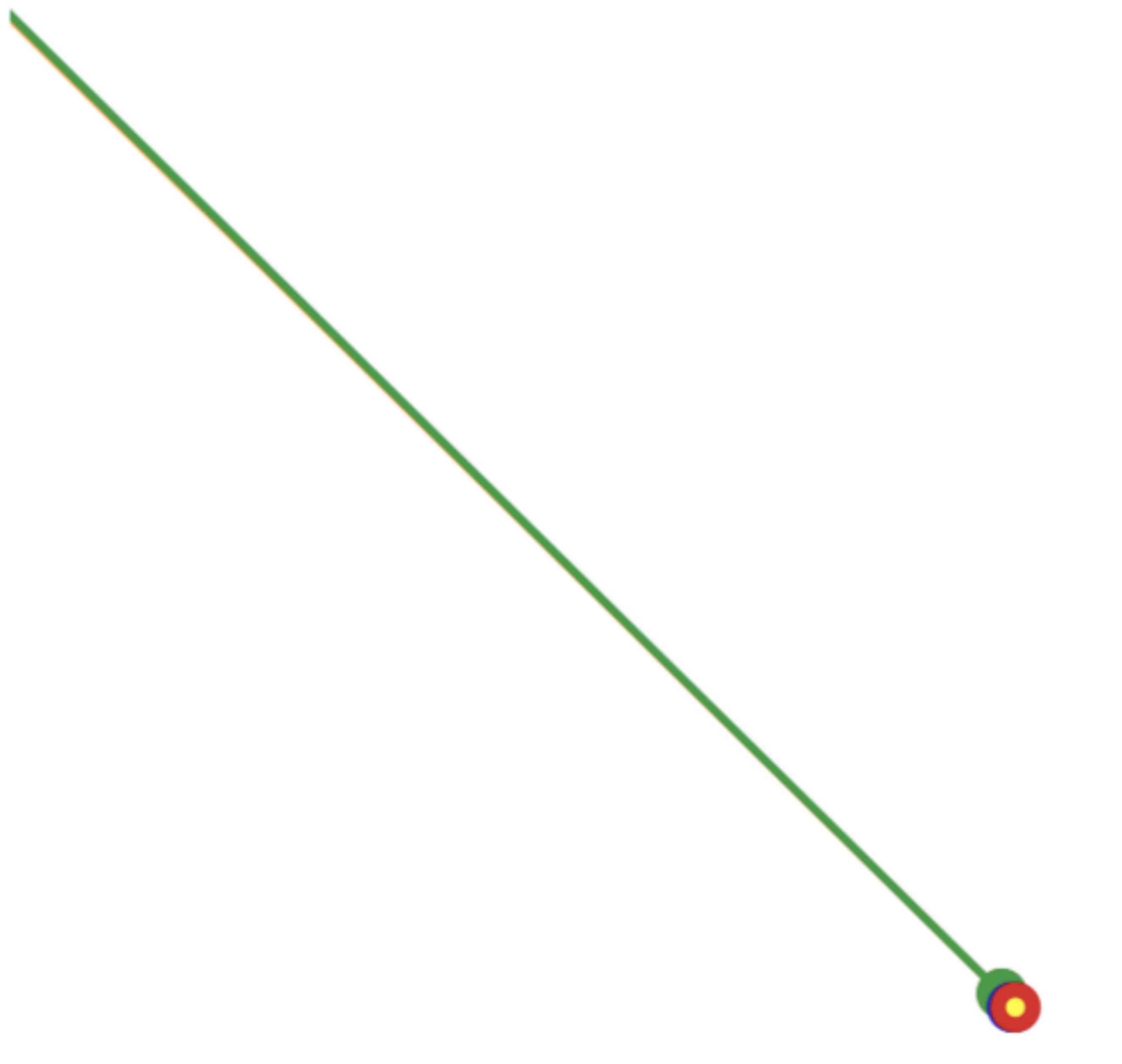


Kepler's solution

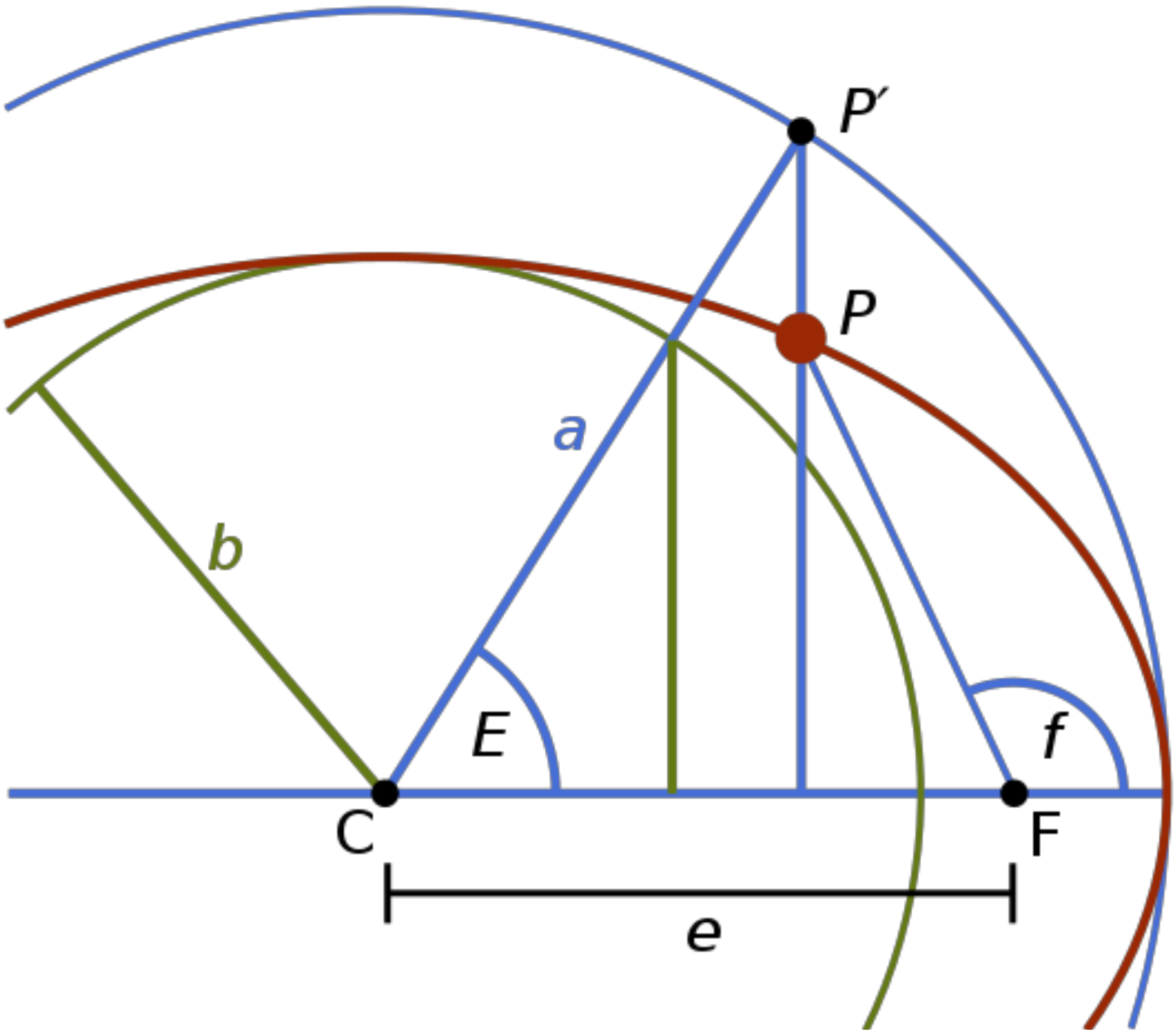


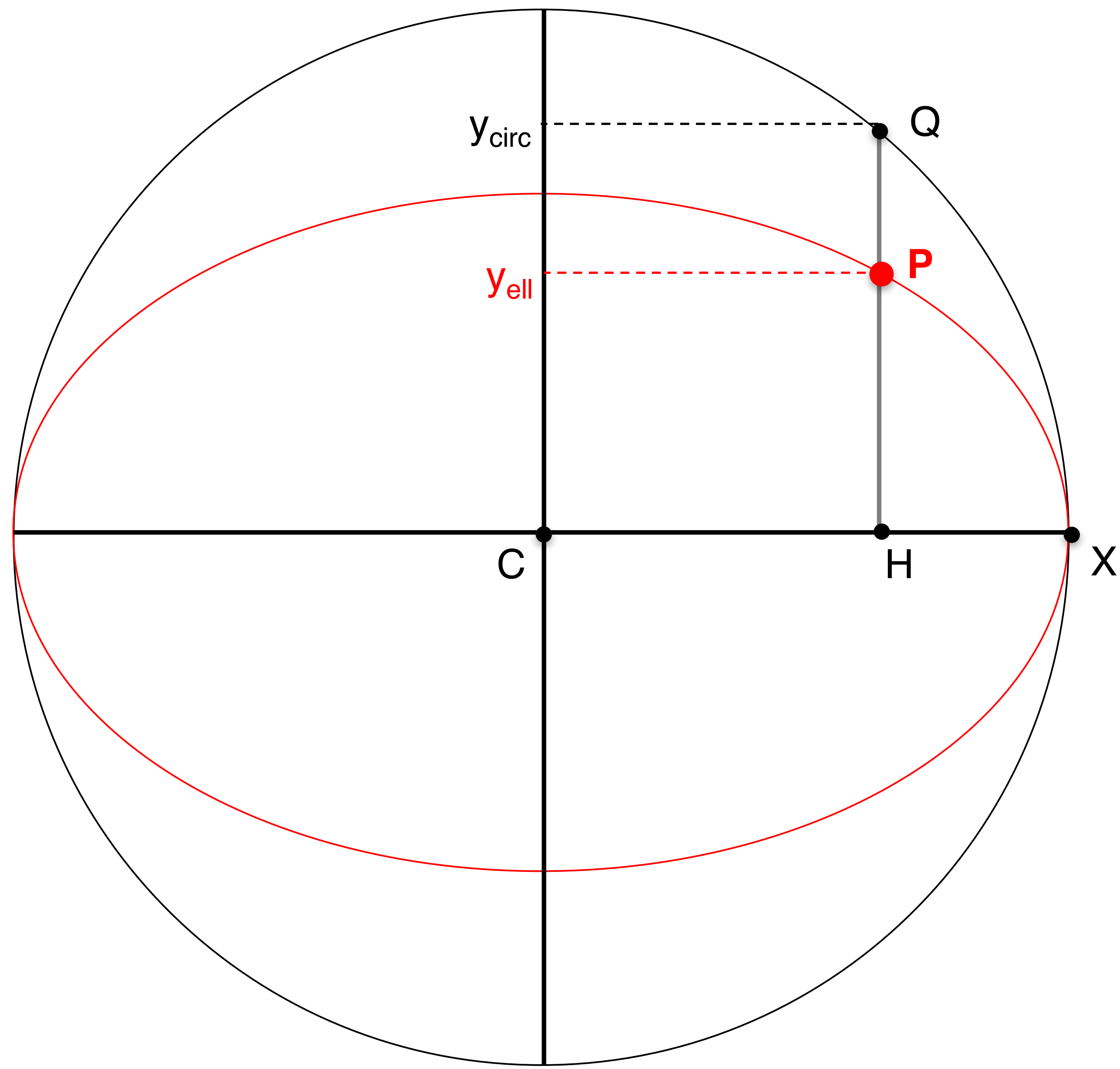


How big is the difference?

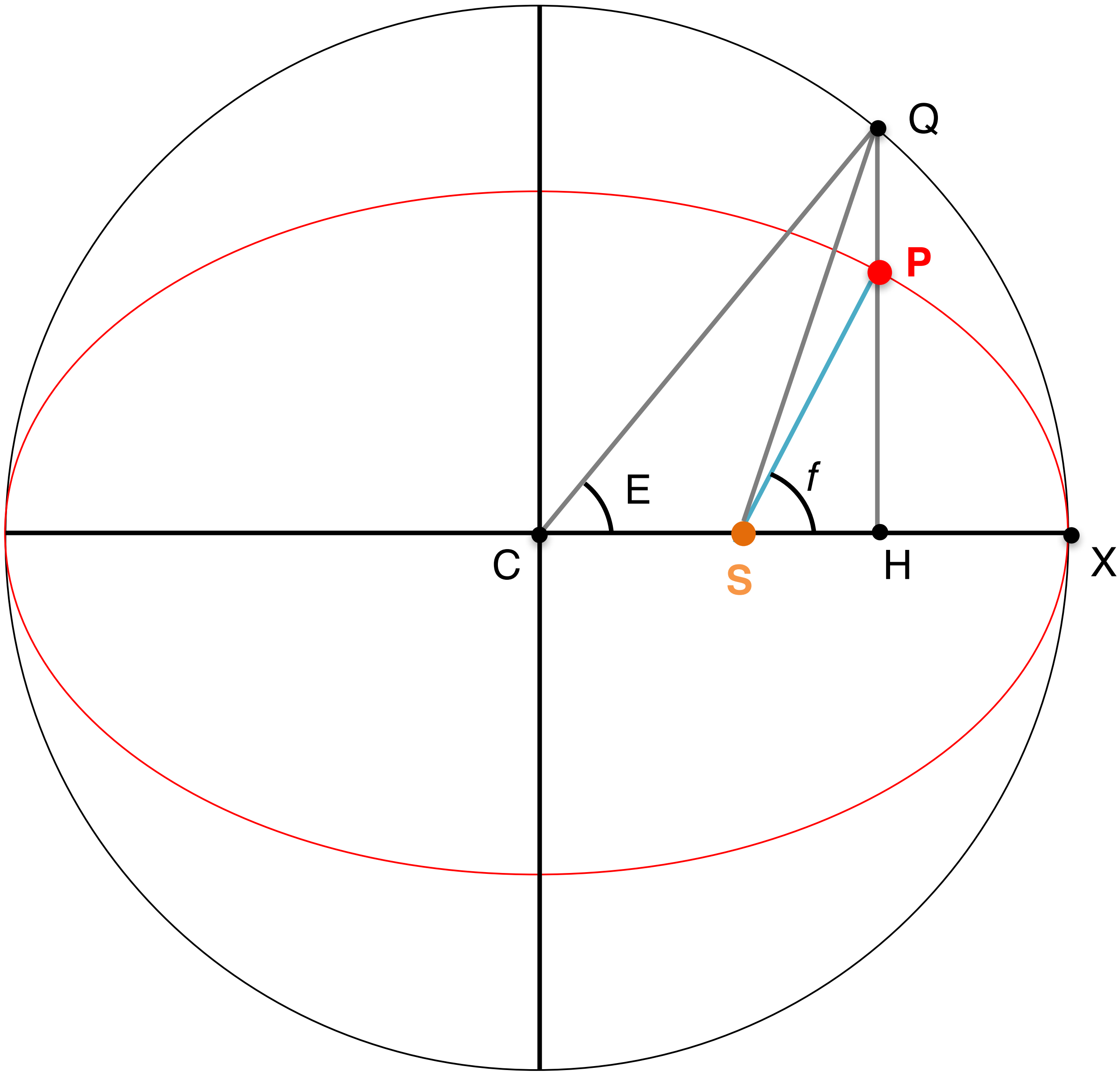


Eccentric anomaly and True anomaly



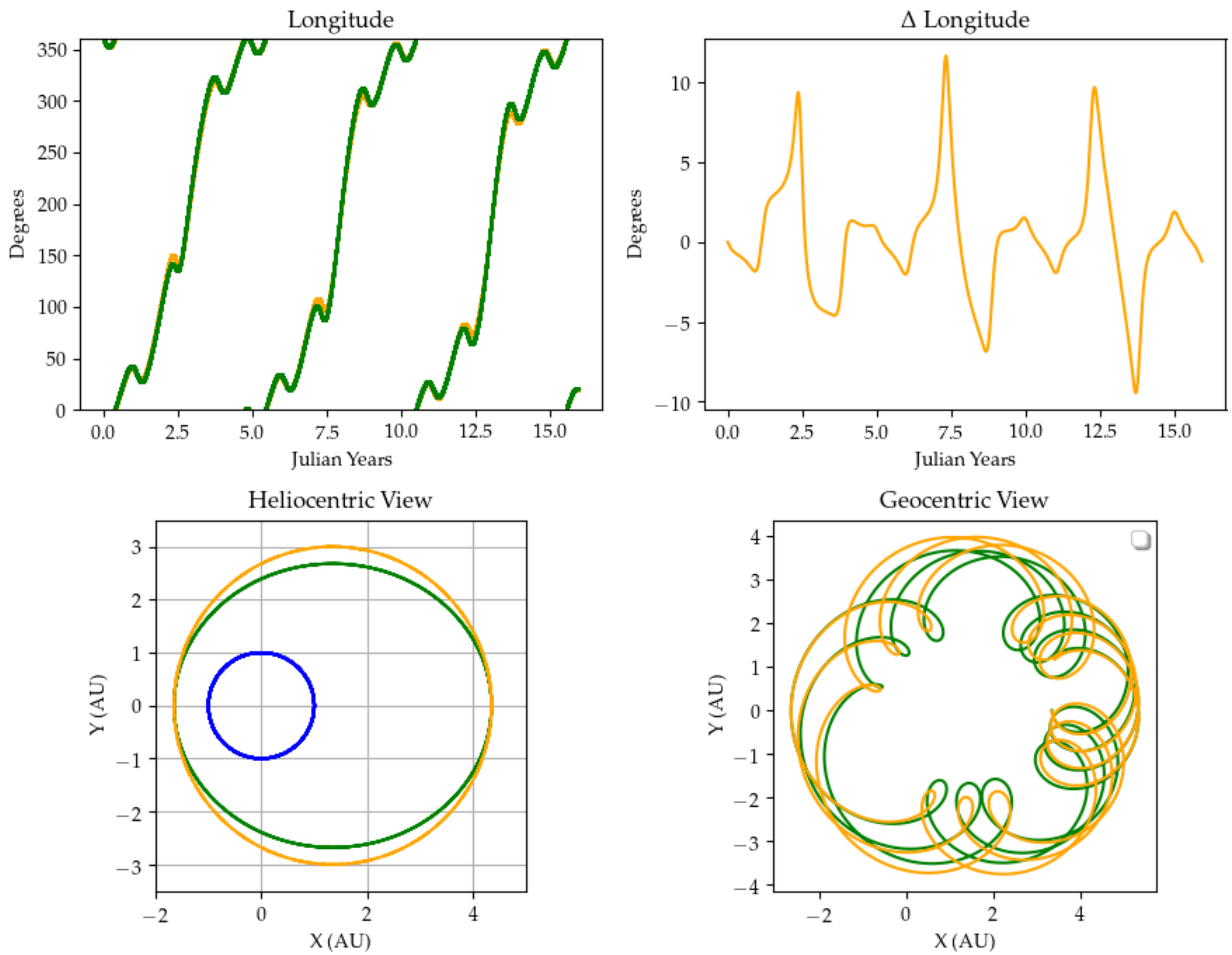


ycirc
Q
yell
P
C
H
X



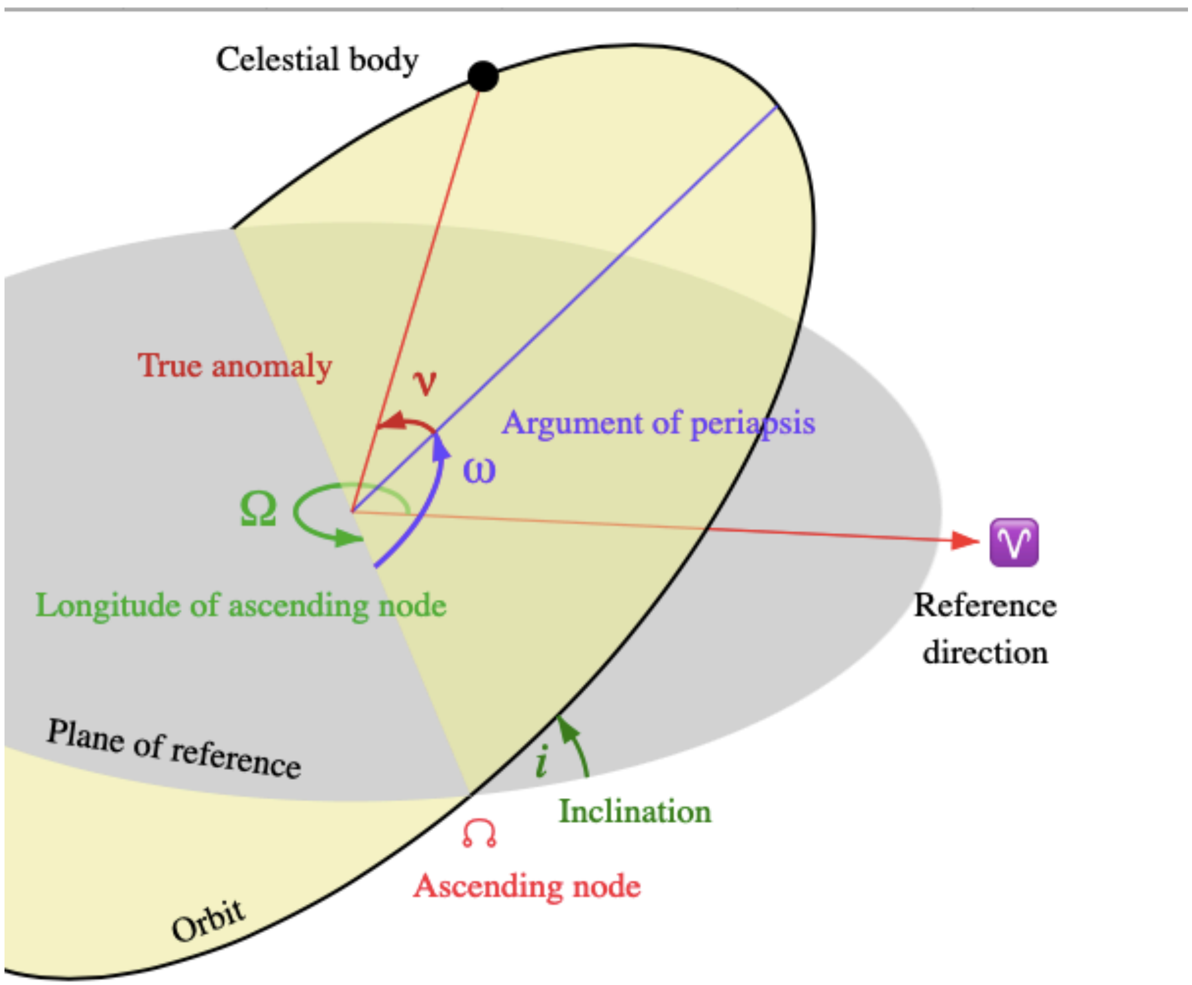
Q
P
E
f
C
S
H
X

Equant fails at larger eccentricities

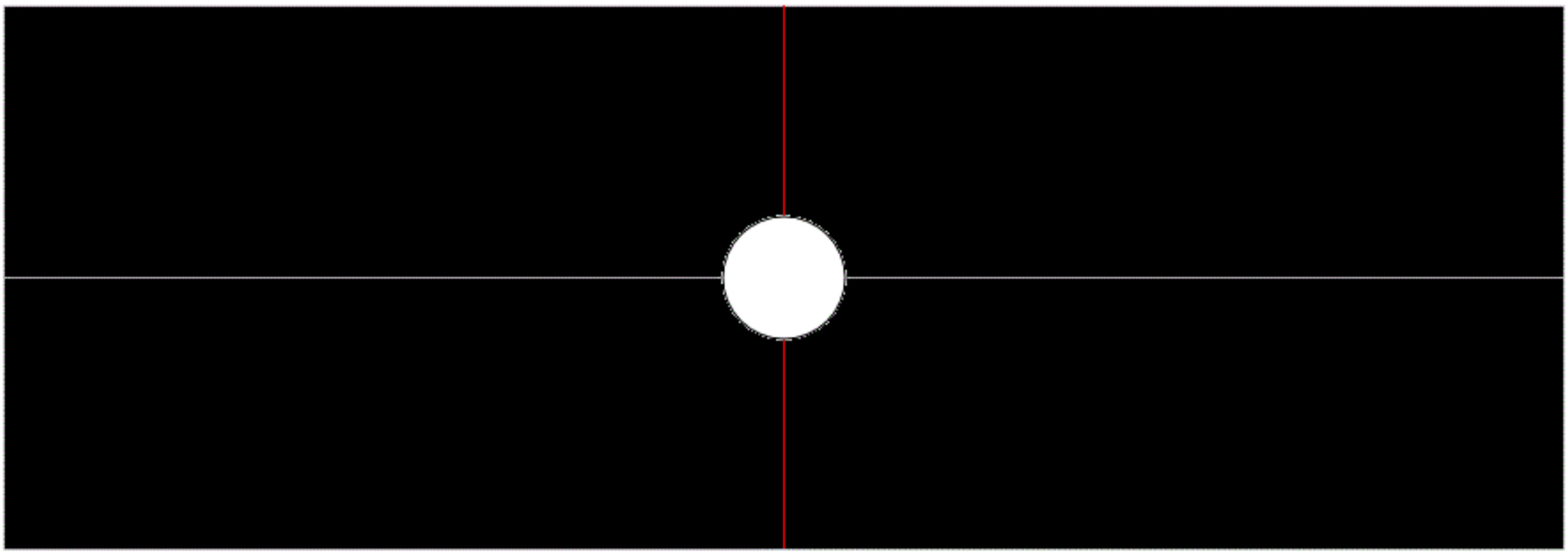


Hypothetical planet, *e=0.45*

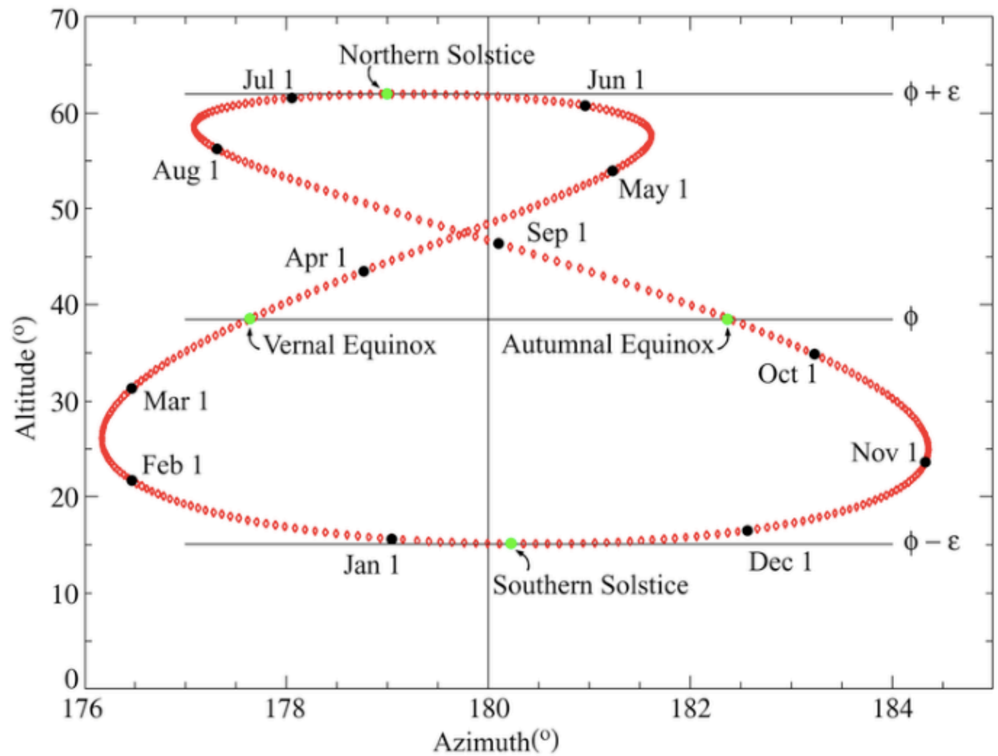
Orbital Elements

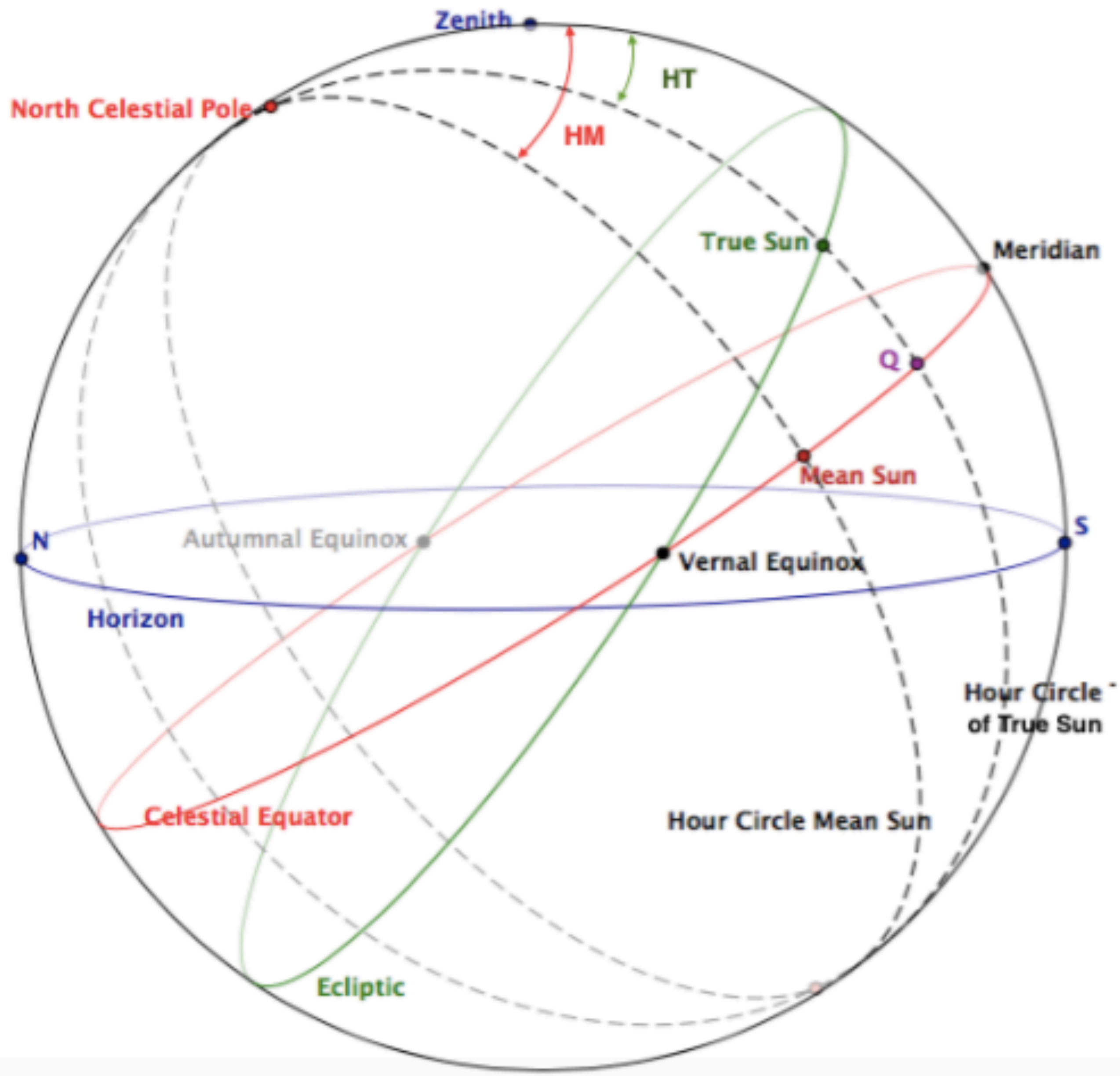


Deviation True and Mean Anomaly



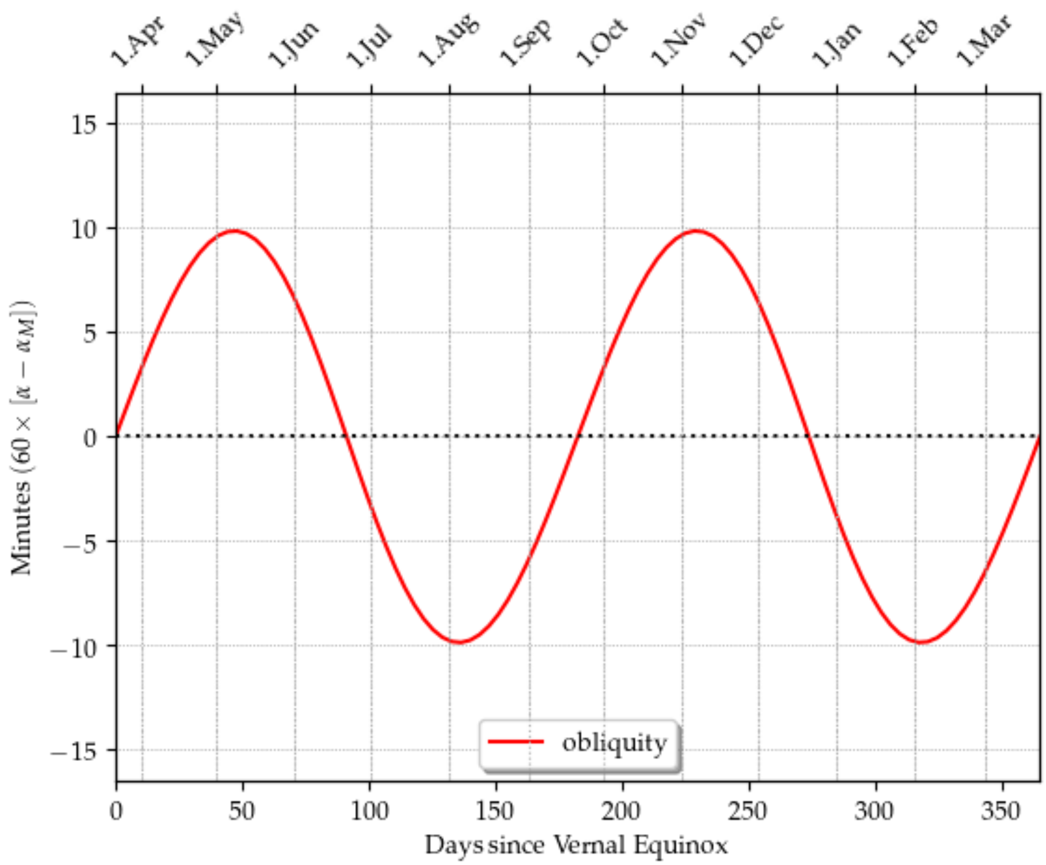
The analemma

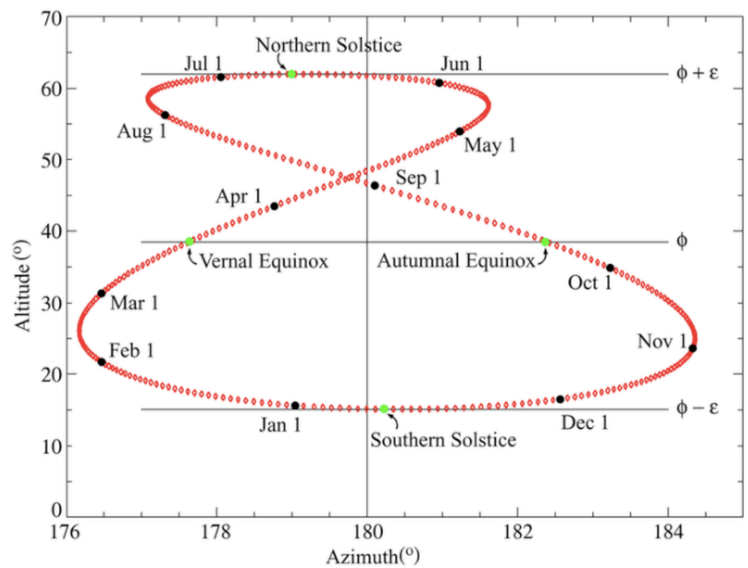




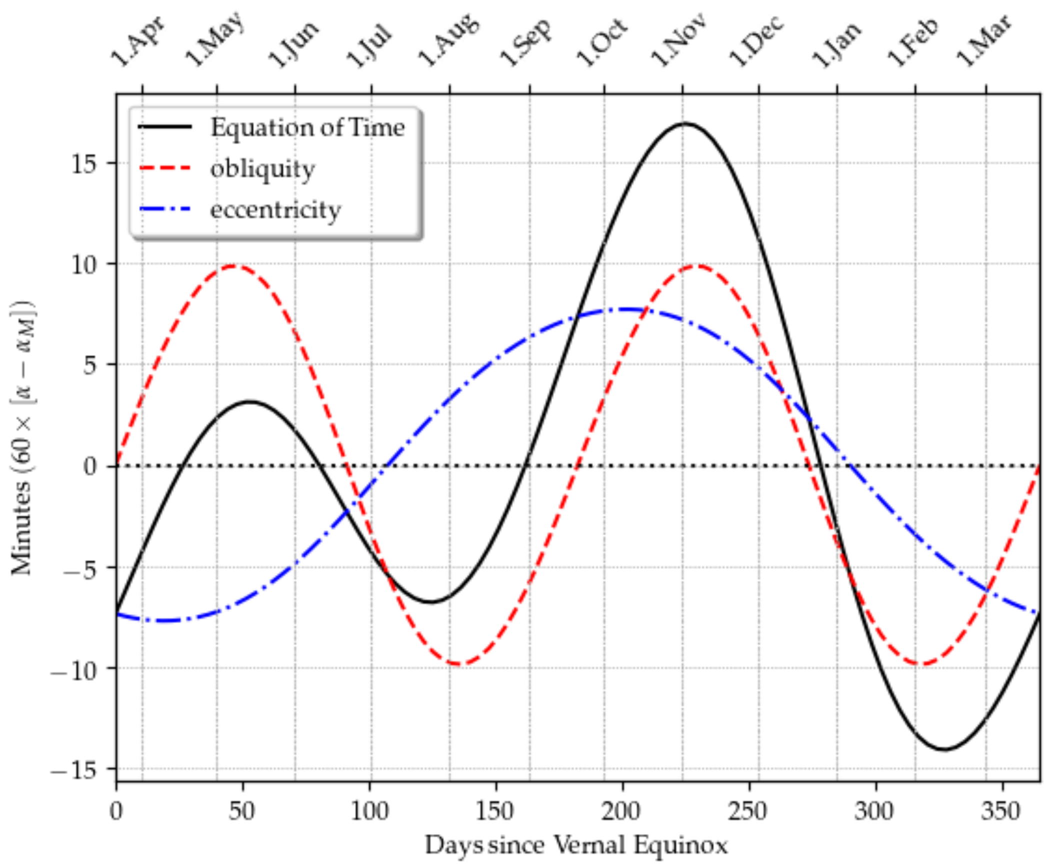
Zenith
HT
North Celestial Pole
HM
True Sun
Meridian
Q
Mean Sun
S
N
Autumnal Equinox
Vernal Equinox
Horizon
Hour Circle
of True Sun
Celestial Equator
Hour Circle Mean Sun
Ecliptic

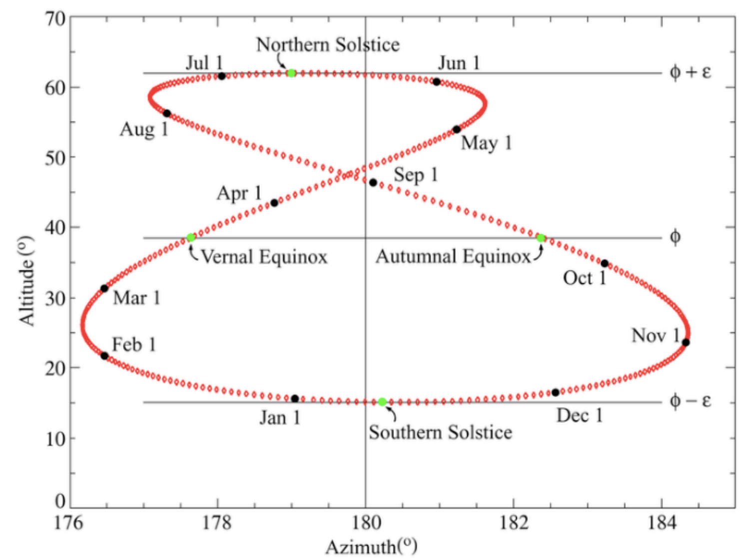
Equation of Time





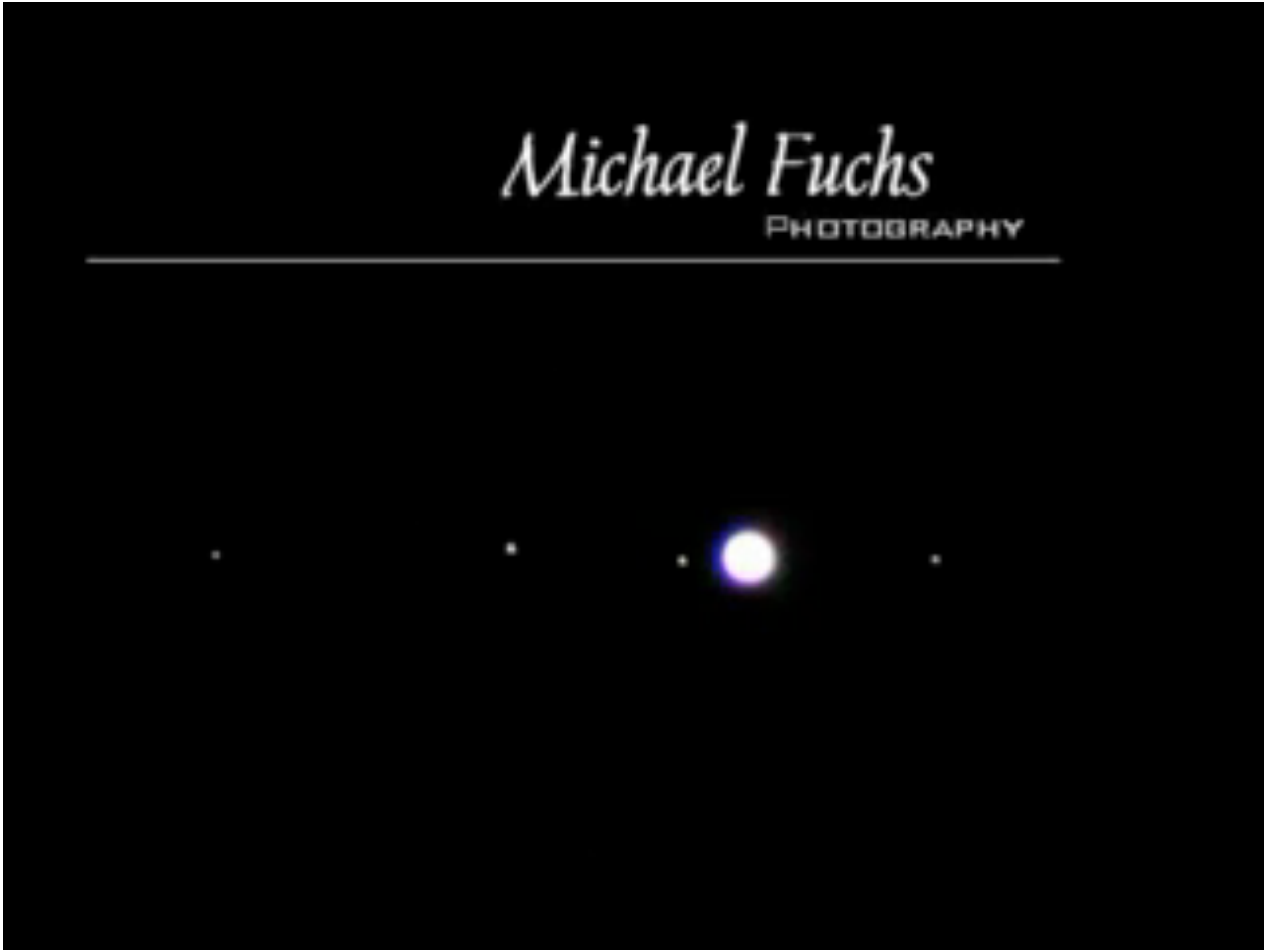
Equation of Time



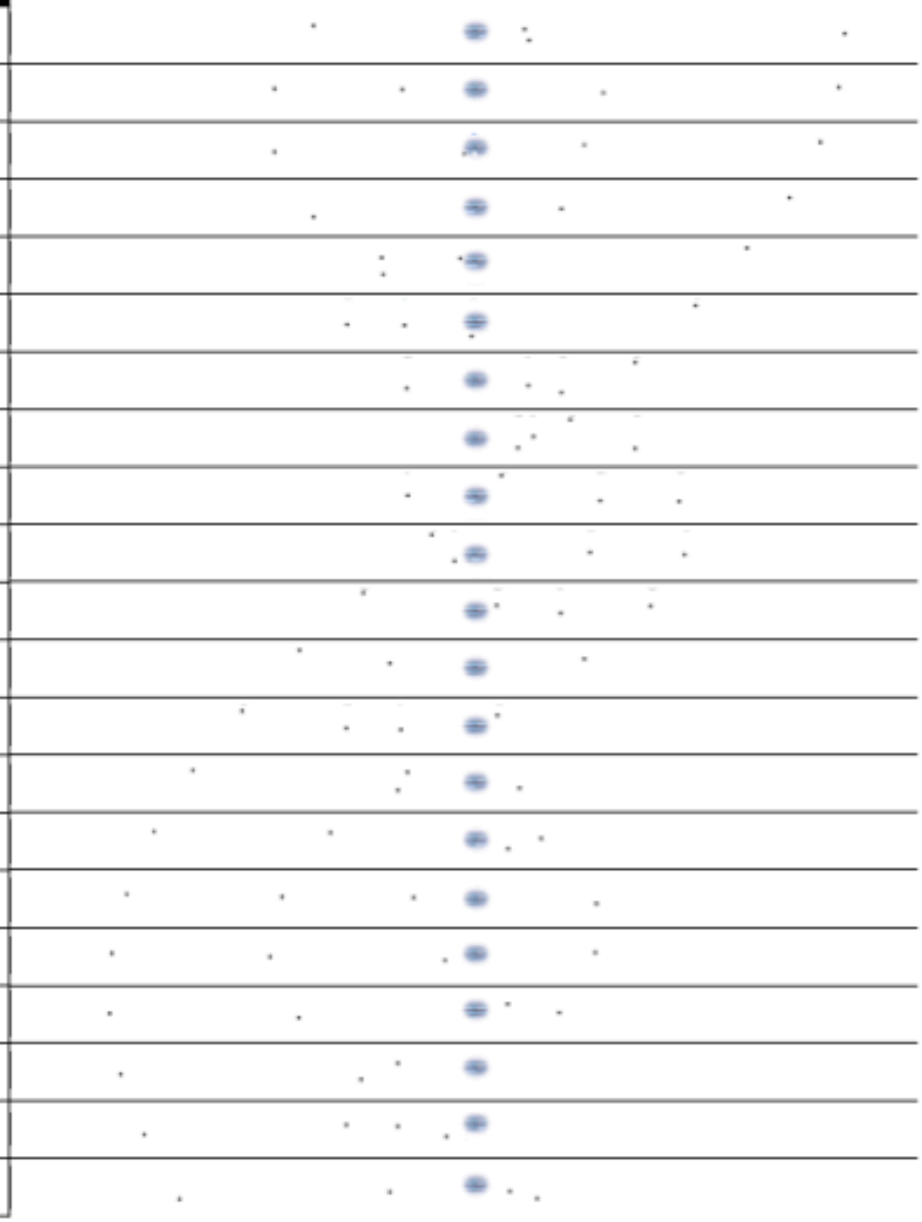


“If this wearisome method has filled you with loathing, it should more properly fill you with compassion for me as I have gone through it at least seventy times at the expense of a great deal of time.”

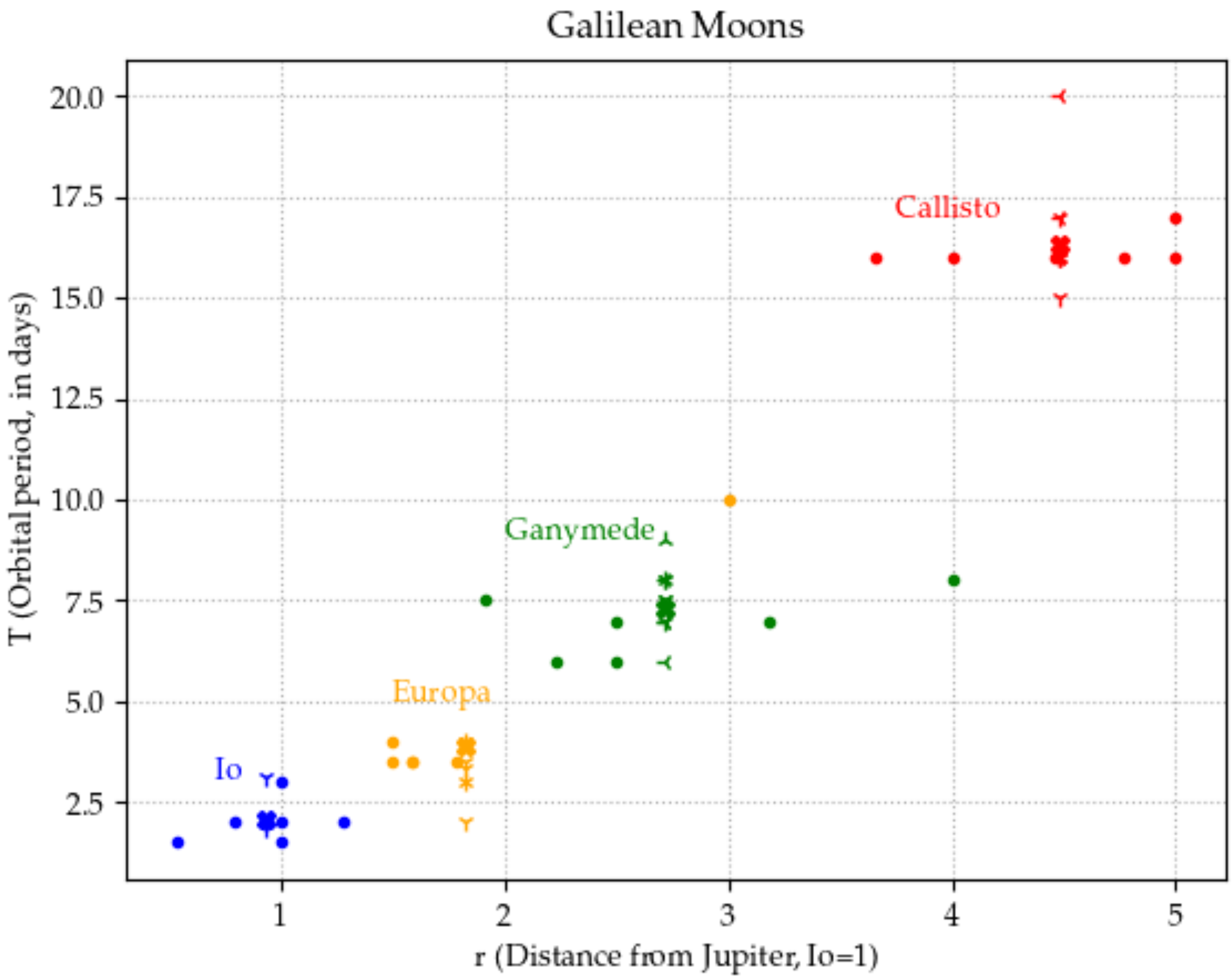
Kepler, Johannes, *Astronomia Nova*, 1609


Michael Fuchs
PHOTOGRAPHY

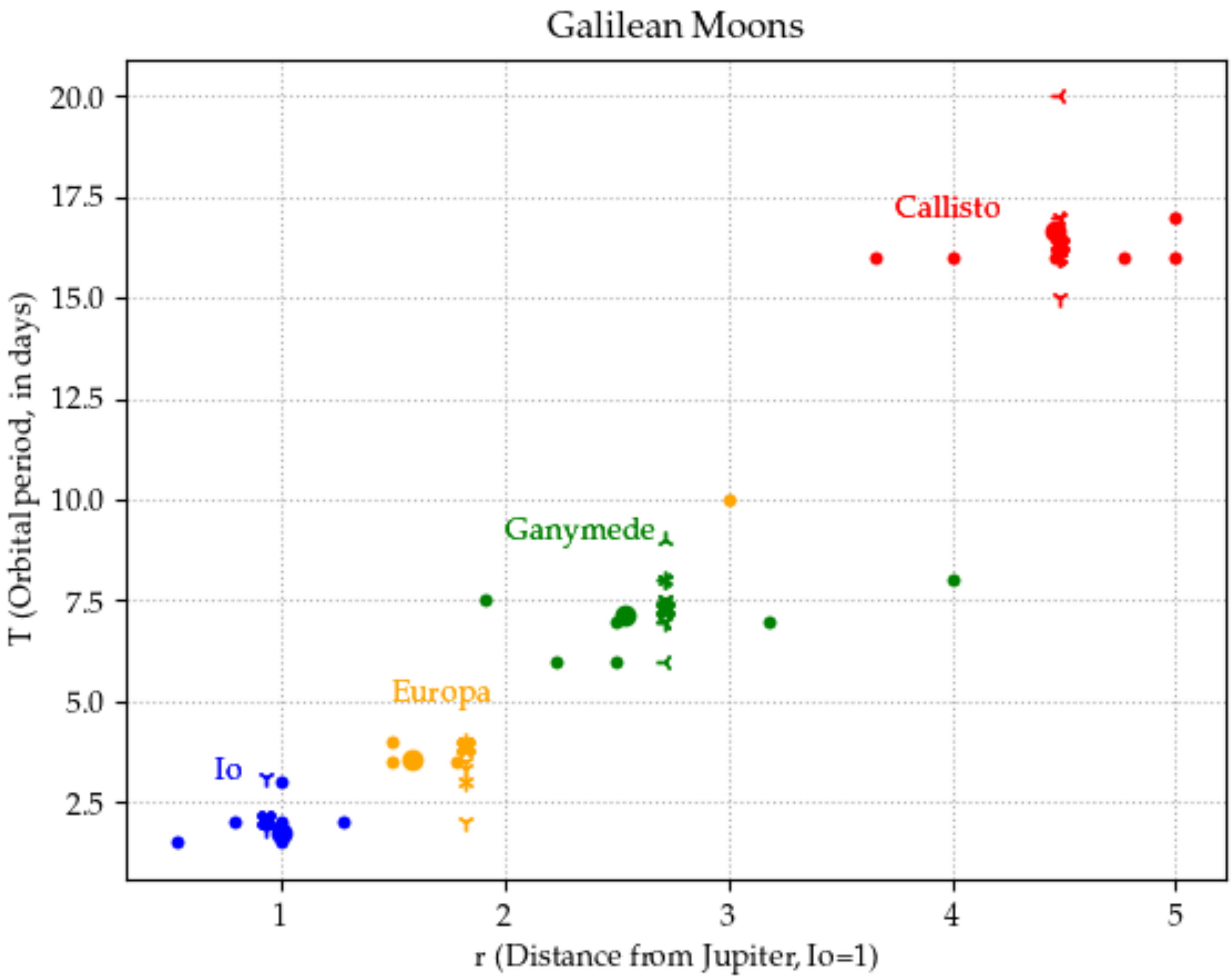
d	h
0	0
0	12
1	0
1	12
2	0
2	12
3	0
3	12
4	0
4	12
5	0
5	12
6	0
6	12
7	0
7	12
8	0
8	12
9	0
9	12
10	0

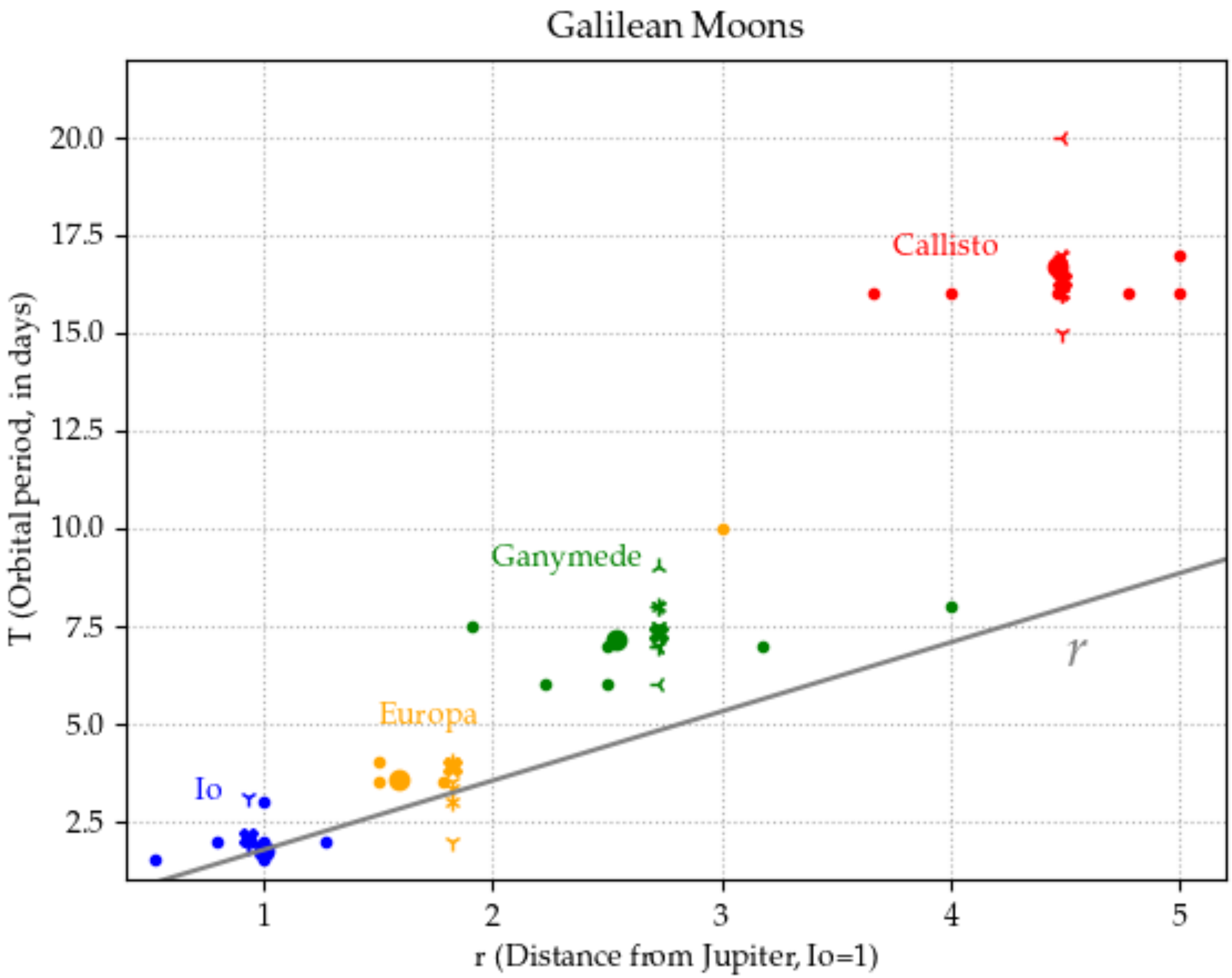


Images captured from http://www.shallowsky.com/jupiter/

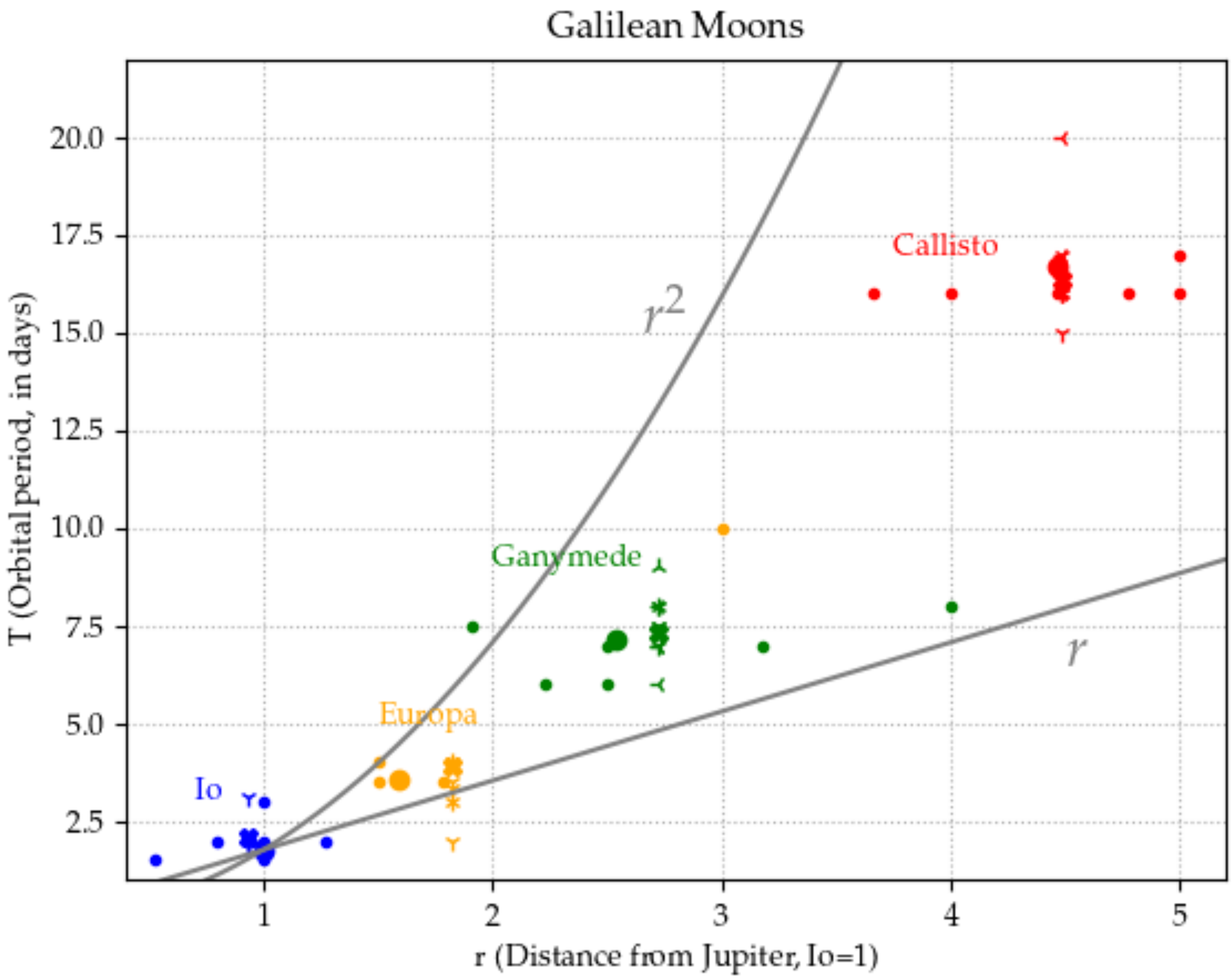


Galilean Moons
Callisto
Ganymede
Europa
Io
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
T (Orbital period, in days)
1
2
3
4
5
r (Distance from Jupiter, Io=1)

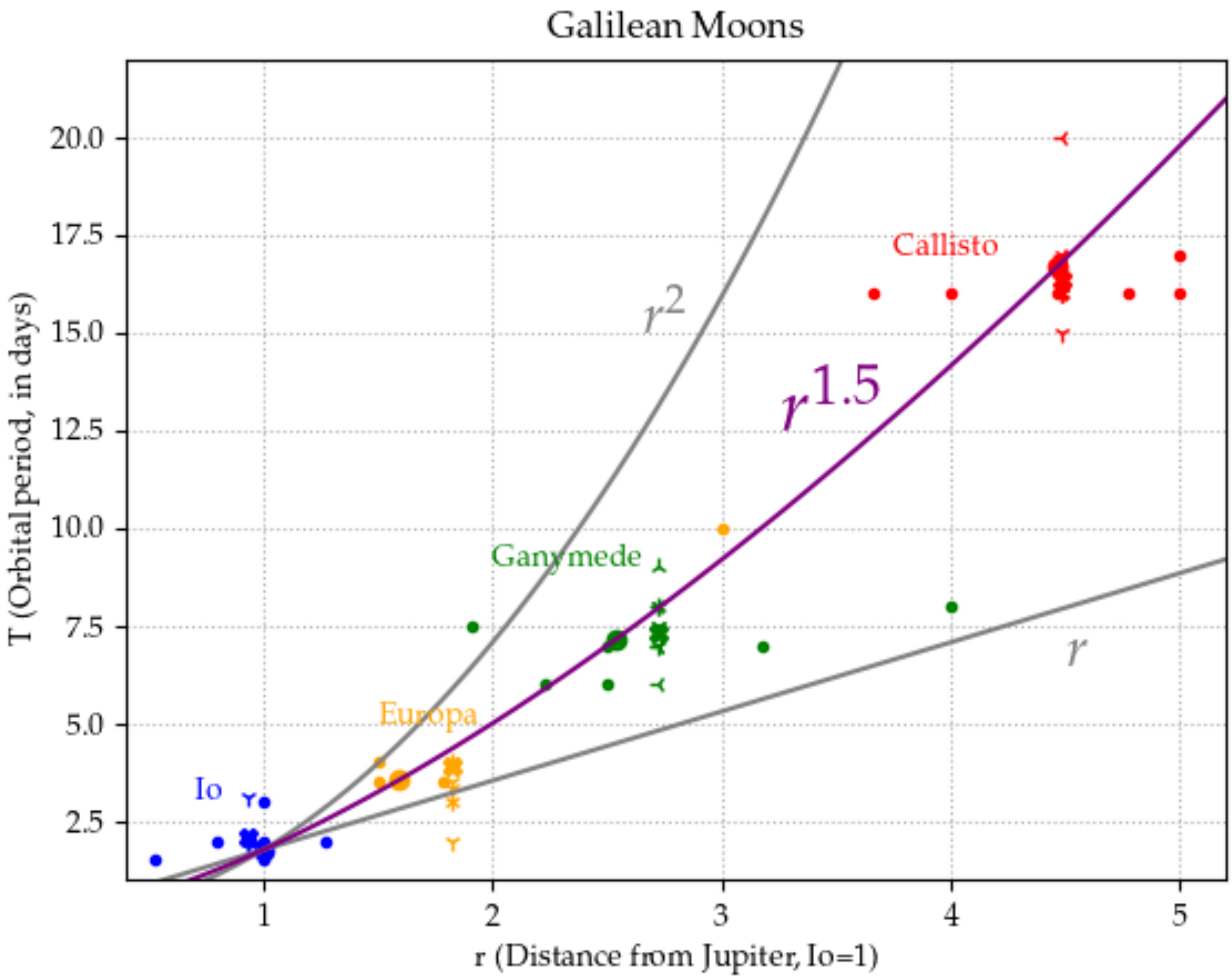

Galilean Moons
Callisto
Ganymede
Europa
Io
T (Orbital period, in days)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
1
2
3
4
5
r (Distance from Jupiter, Io=1)



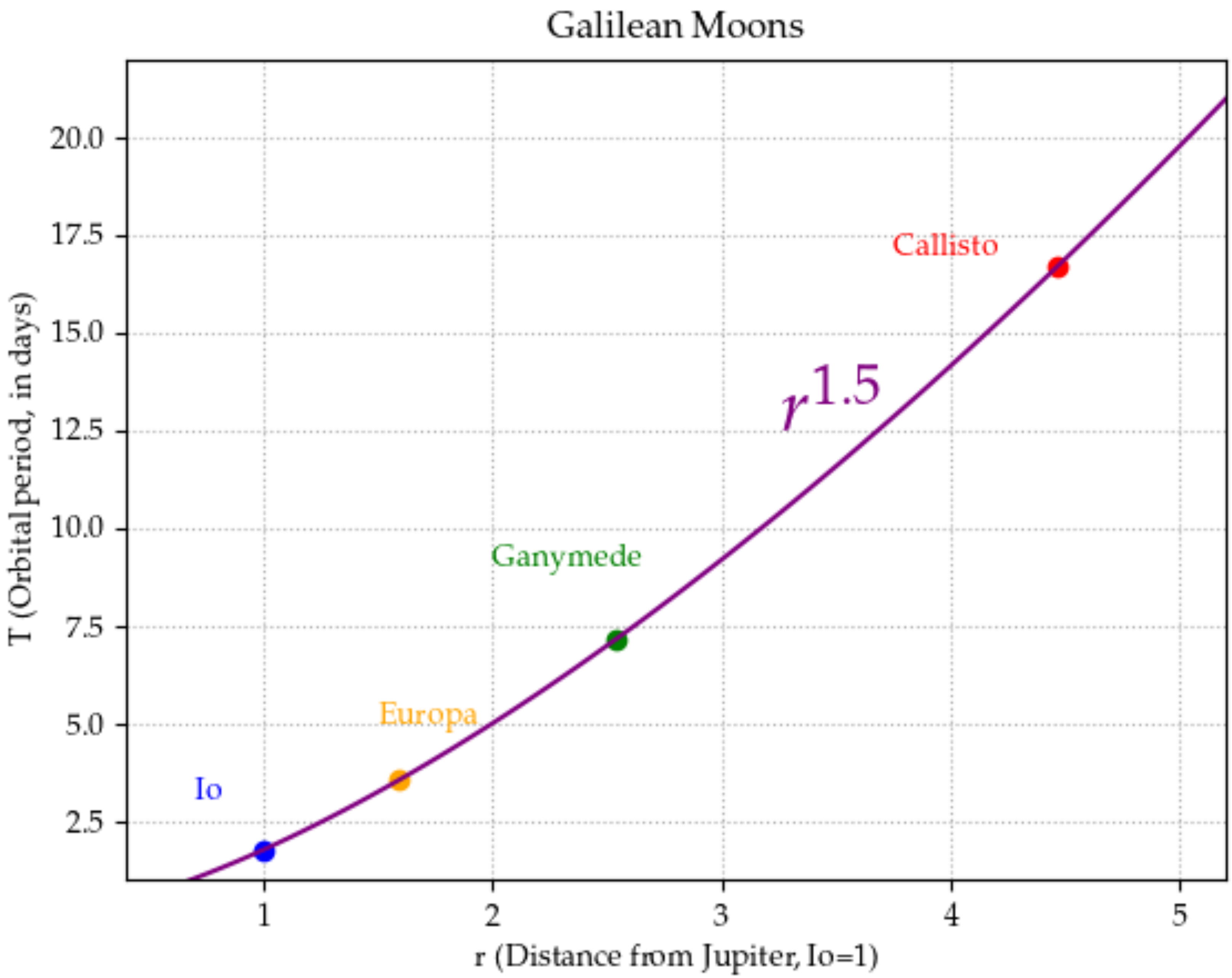
Galilean Moons
T (Orbital period, in days)
r (Distance from Jupiter, Io=1)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
1
2
3
4
5
Callisto
Ganymede
Europa
Io
r



Galilean Moons
T (Orbital period, in days)
r (Distance from Jupiter, Io=1)
Io
Europa
Ganymede
Callisto
r^2
r
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
1
2
3
4
5

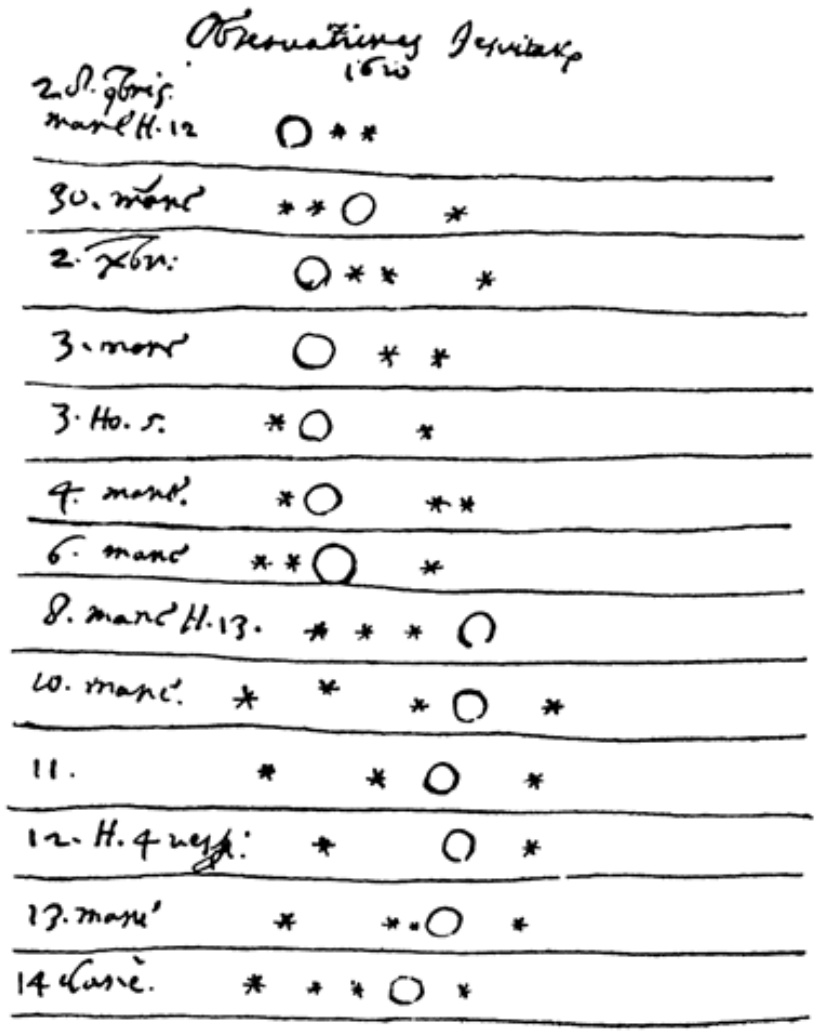


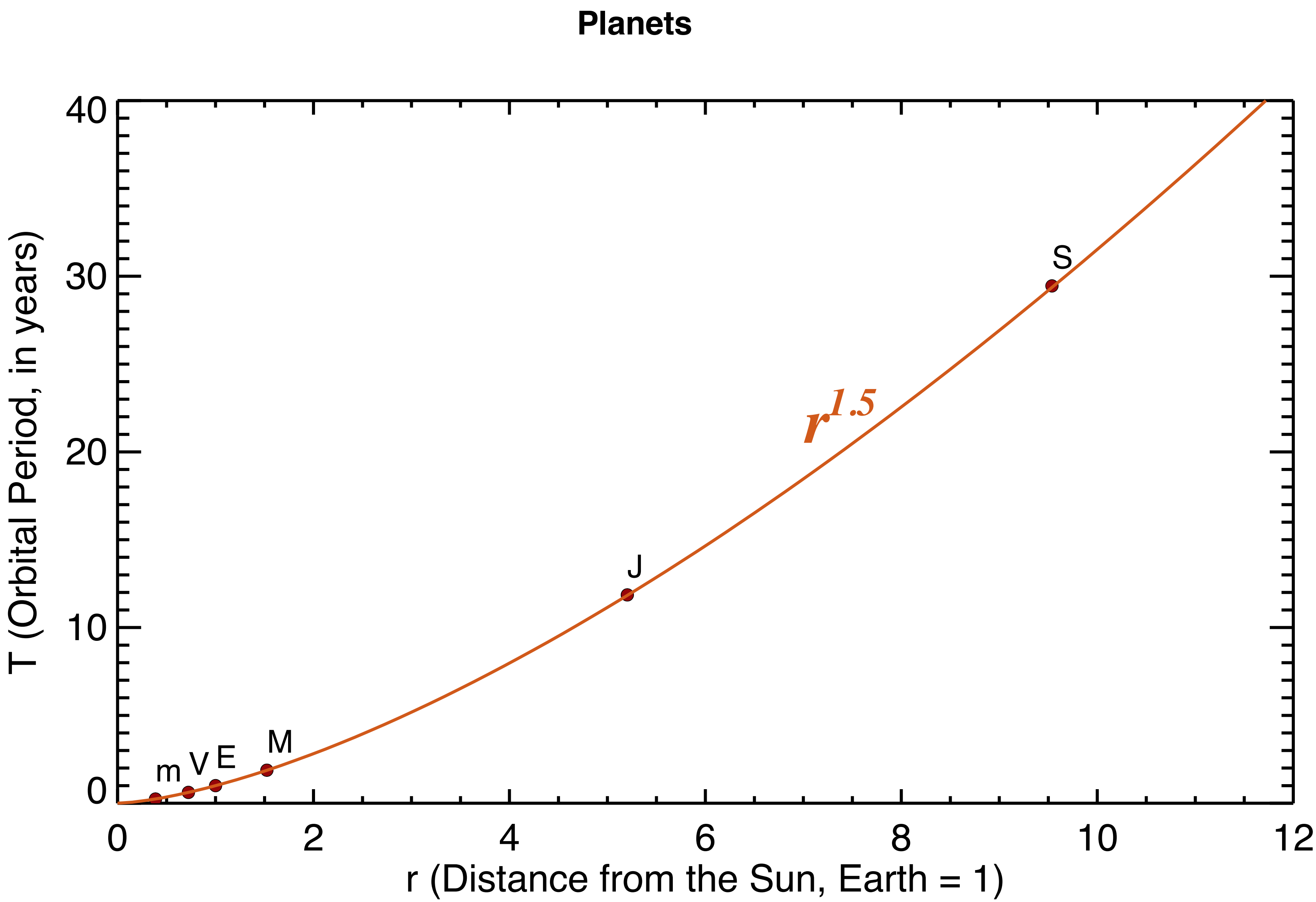
Galilean Moons
T (Orbital period, in days)
r (Distance from Jupiter, Io=1)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
1
2
3
4
5
Io
Europa
Ganymede
Callisto
r^2
$r^{1.5}$
r



Galilean Moons
T (Orbital period, in days)
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
1
2
3
4
5
r (Distance from Jupiter, Io=1)
Io
Europa
Ganymede
Callisto
$r^{1.5}$

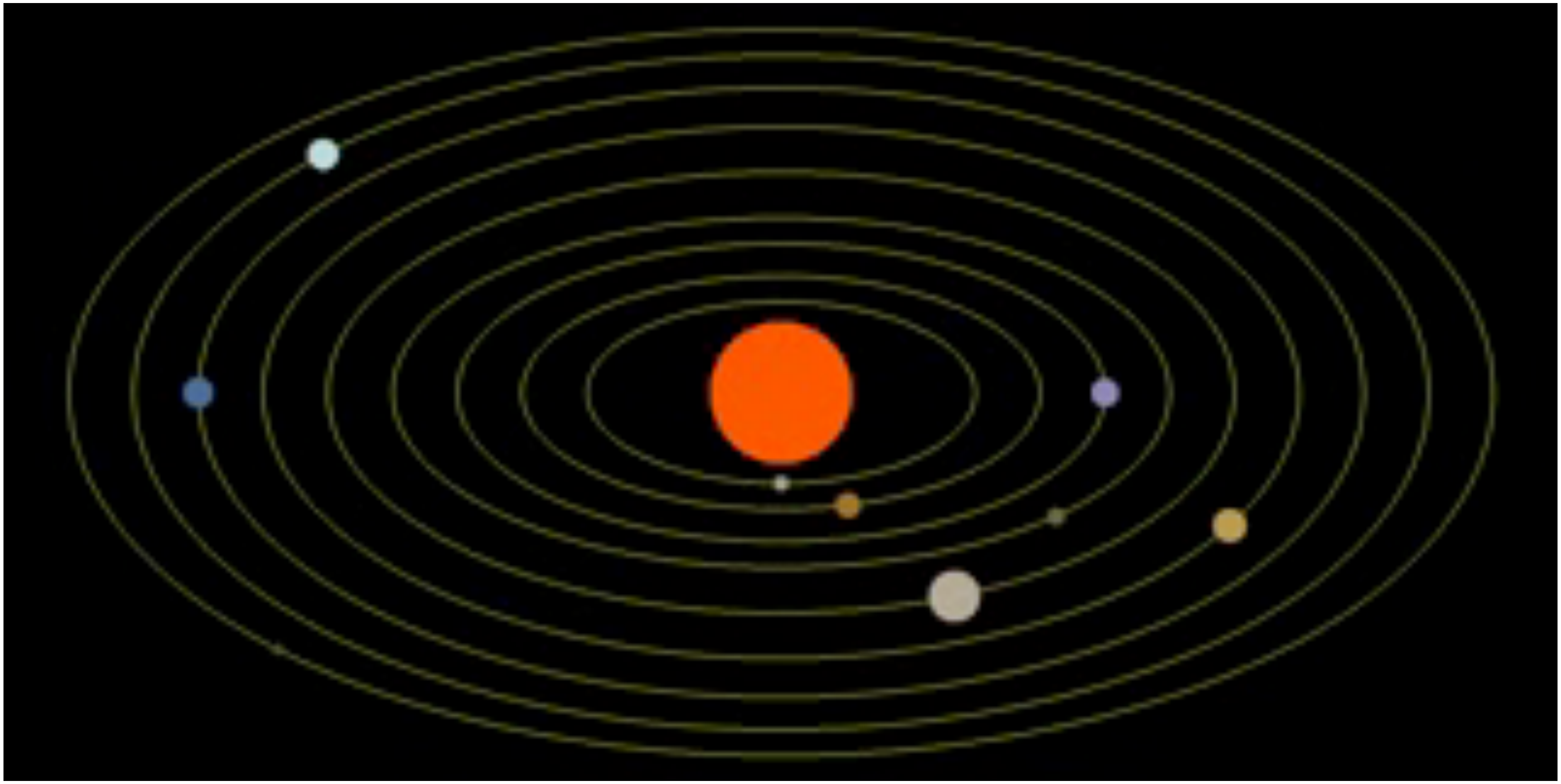
A page from Galileo's *Sidereus Nuncius*




Planets
T (Orbital Period, in years)
r (Distance from the Sun, Earth = 1)
$r^{1.5}$
m
V
E
M
J
S
0
10
20
30
40
0
2
4
6
8
10
12

Kepler's 3rd law

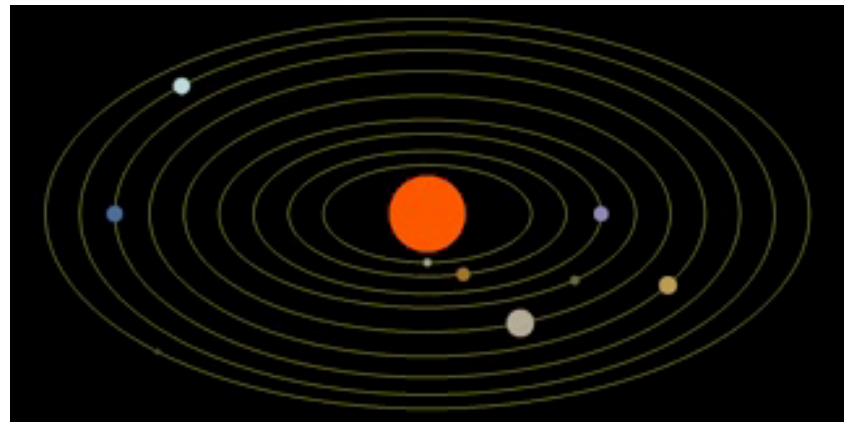
The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit.



Stuff **close in** moves **fast**
stuff **far out** moves **slow**

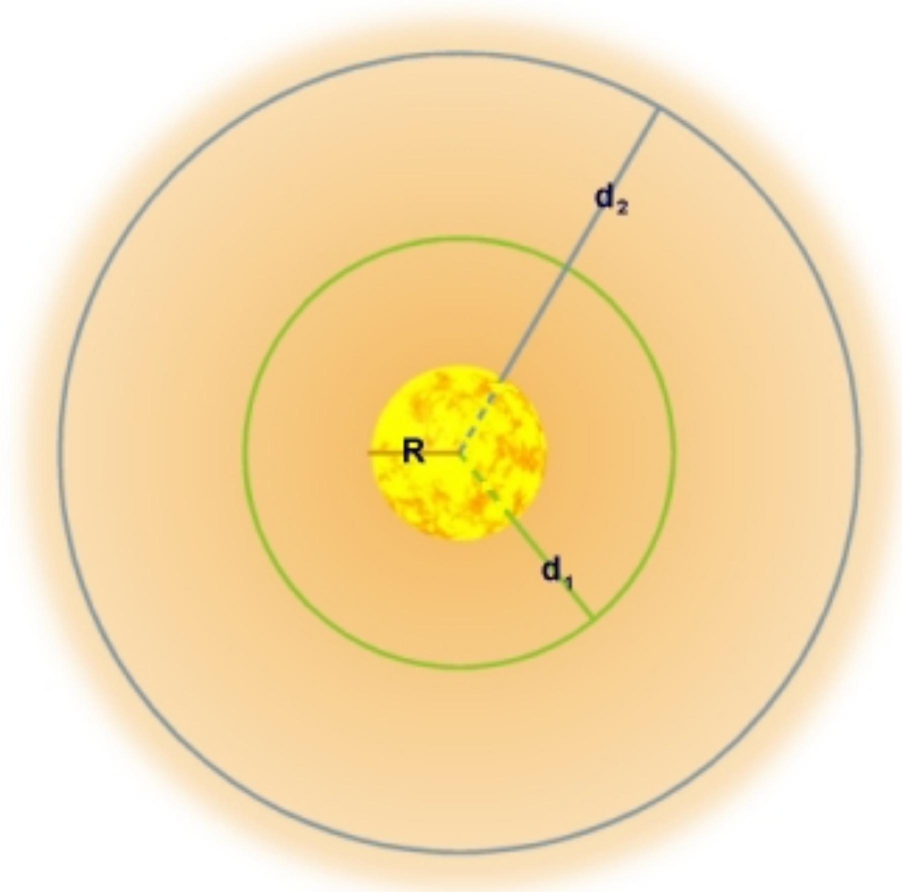
Hypothesis

What keeps the planets in motion
is *something* that
emanates from the Sun
and **dilutes with distance**.



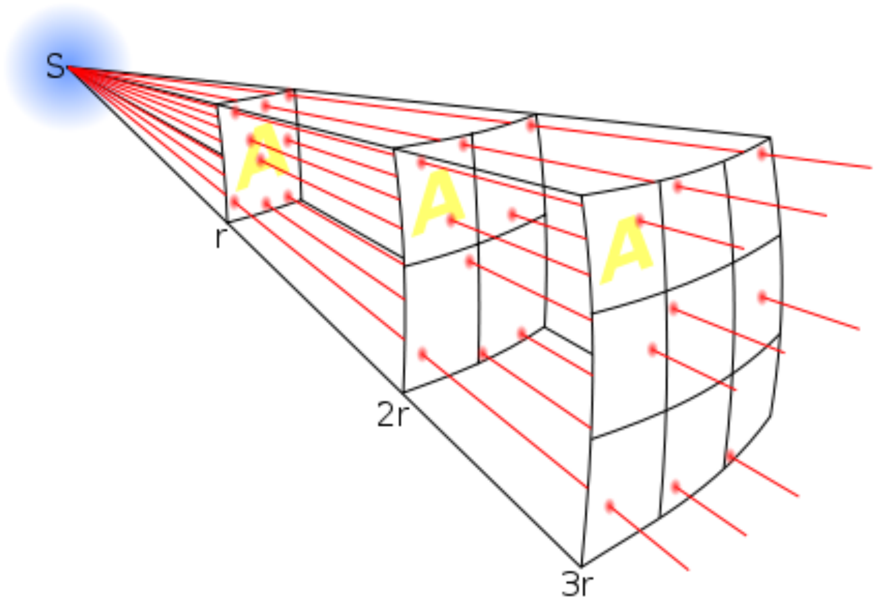
Stuff **close in** moves **fast**
stuff **far out** moves **slow**

Geometric dilution



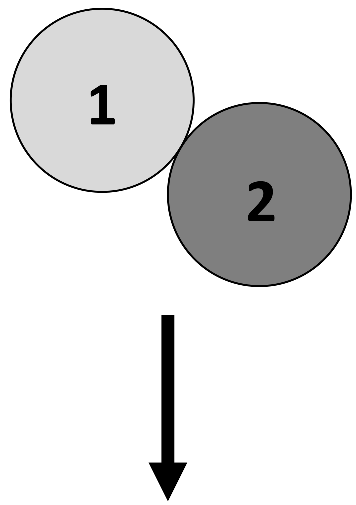
The same amount of light,
expanding spherically outwards,
crosses progressively
larger areas.

Inverse square

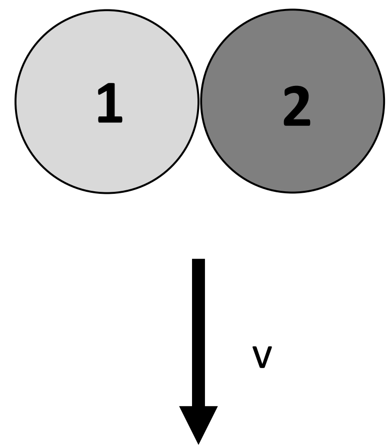


$$g \propto \frac{1}{r^2}$$

As distance increases, the same energy spreads through a larger area



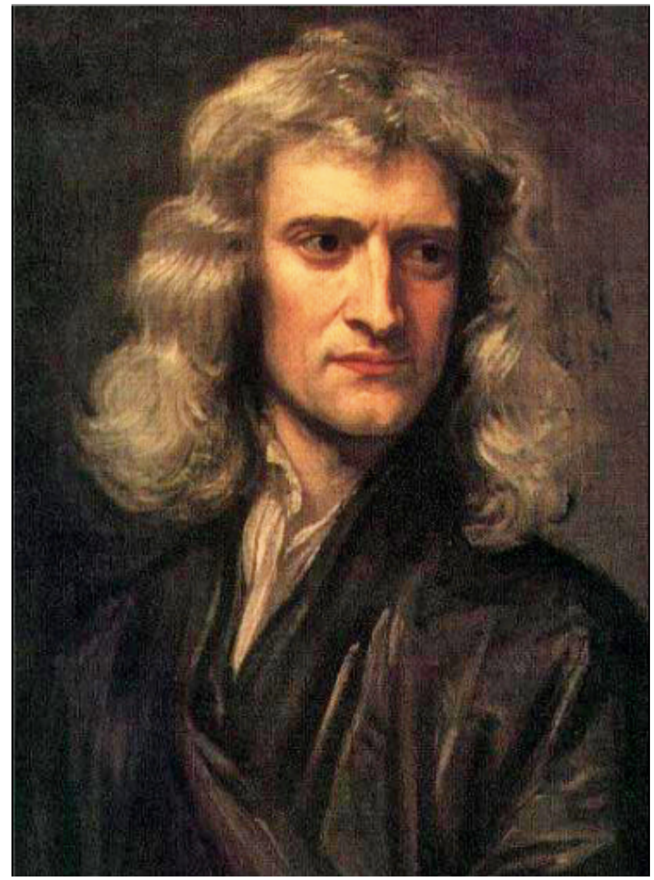
$v_1 < v < v_2$



$v_1 < v_2 < v$

” And the same year [1665] I began to think of gravity […] from Kepler’s rule of the periodical times of the planets being in a sesquialterate proportion of their distances from the centers of their orbs, I deduced that the forces which keep the planets in their orbs must be reciprocally as the squares 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 they answer pretty nearly.”

— *Isaac Newton, 1665-1666*



Isaac Newton, 1642-1727

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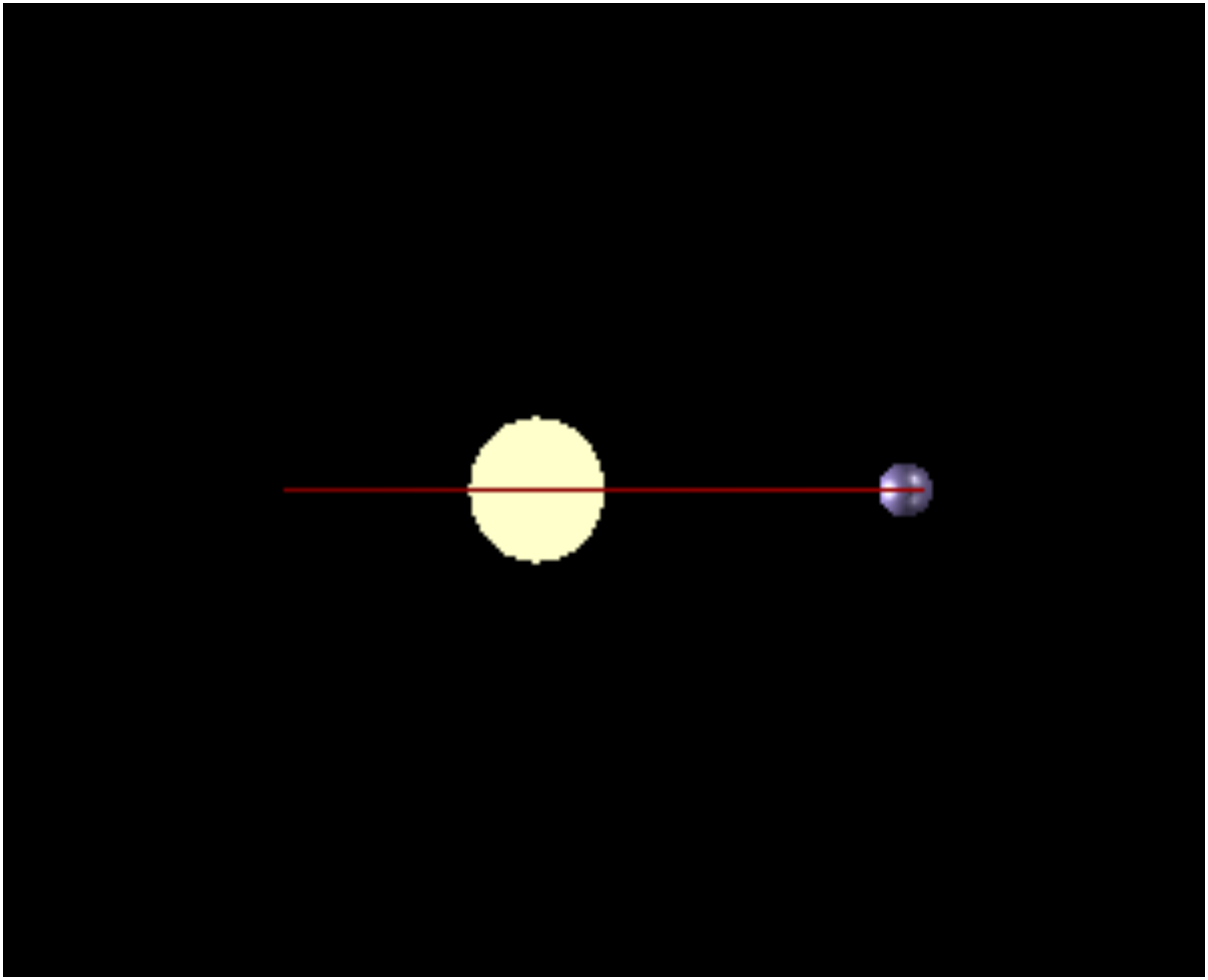
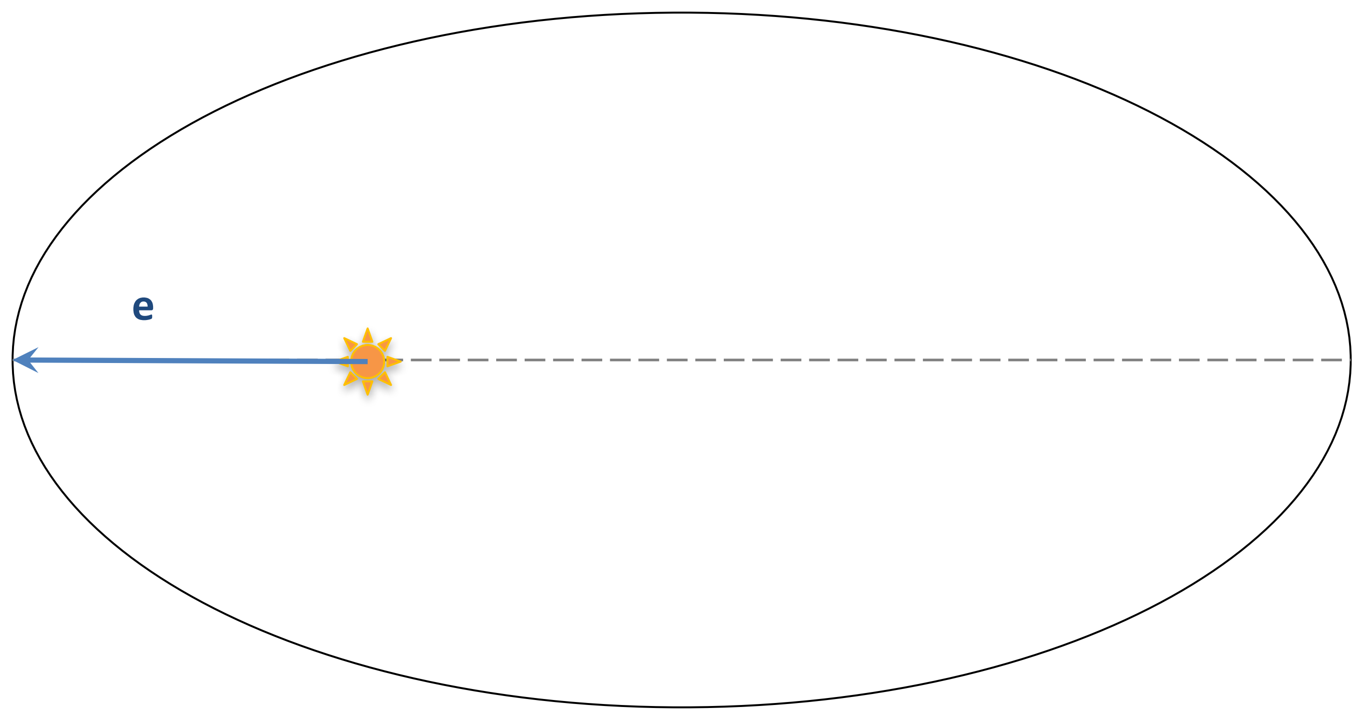
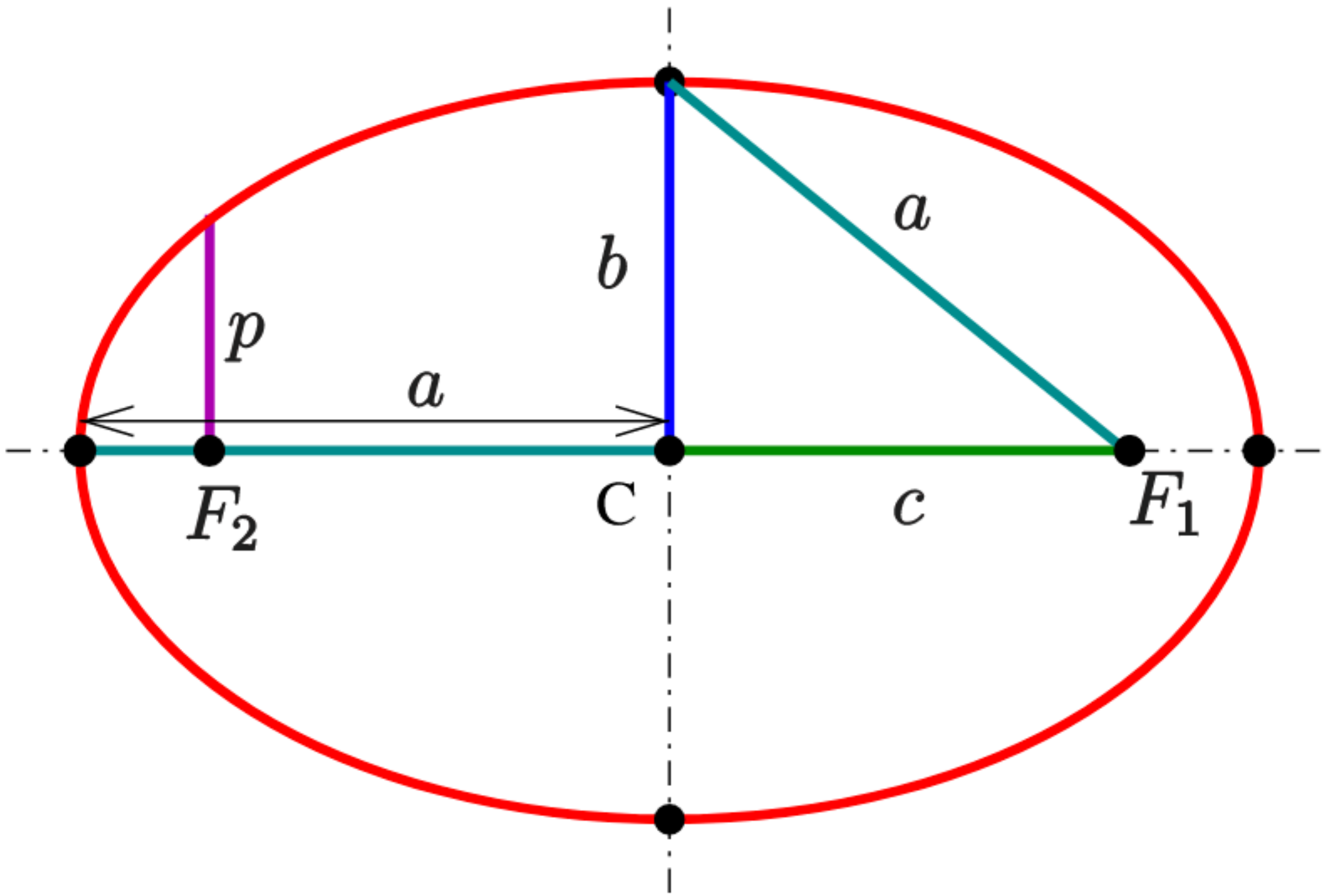
— Isaac Newton, 1665-1666

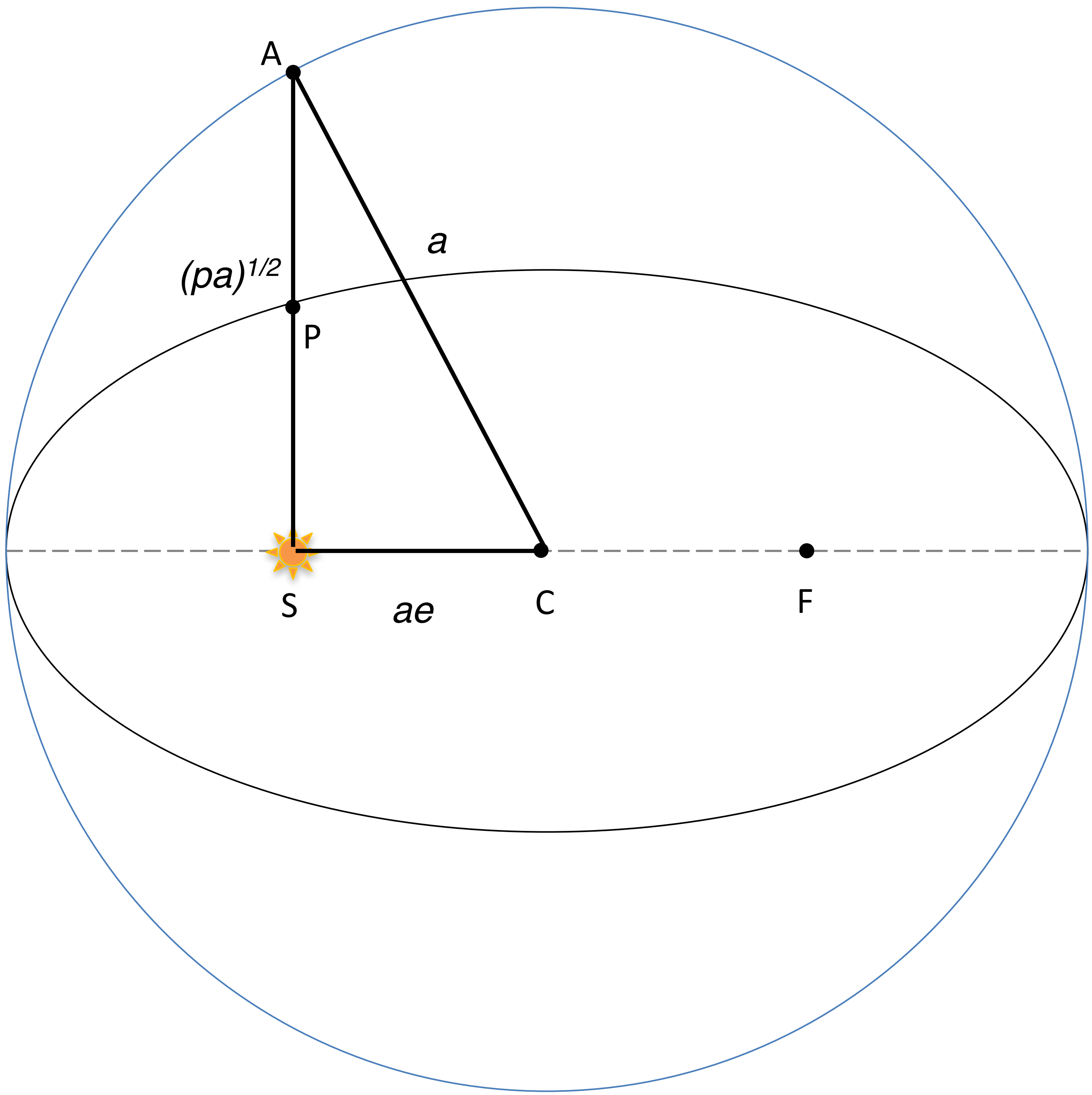
22-23 y-old Isaac Newton, 1642-1727

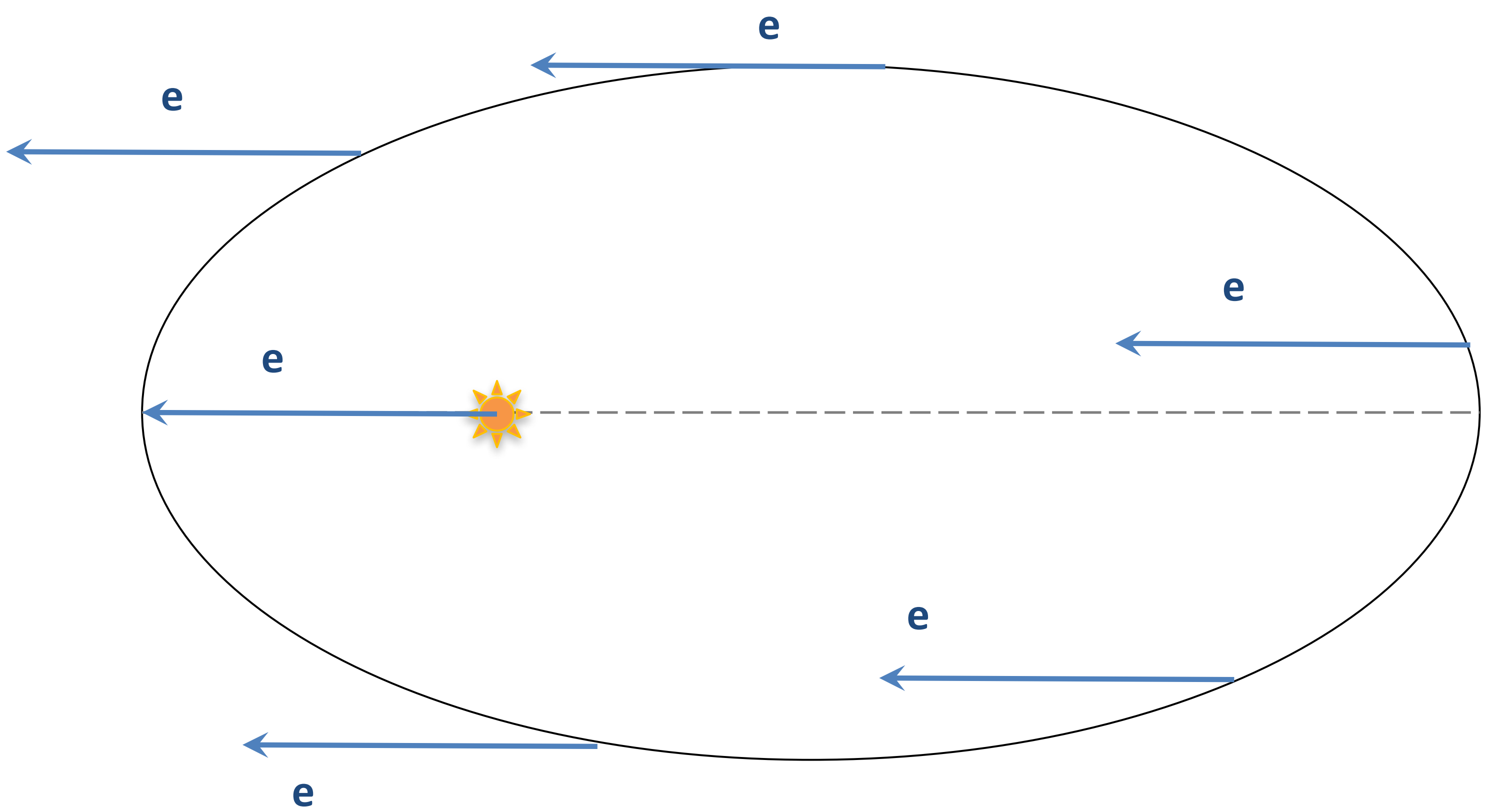


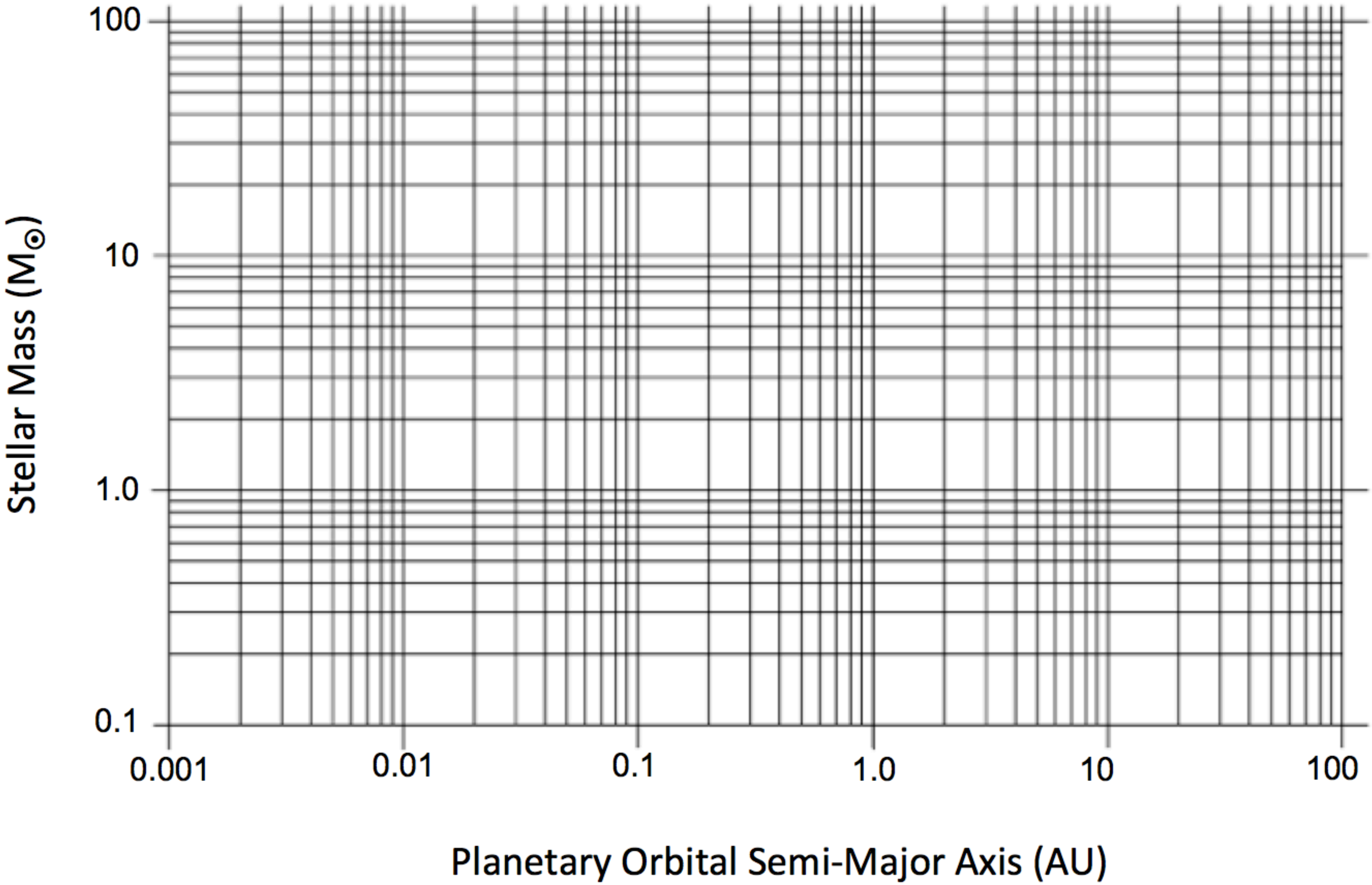

e



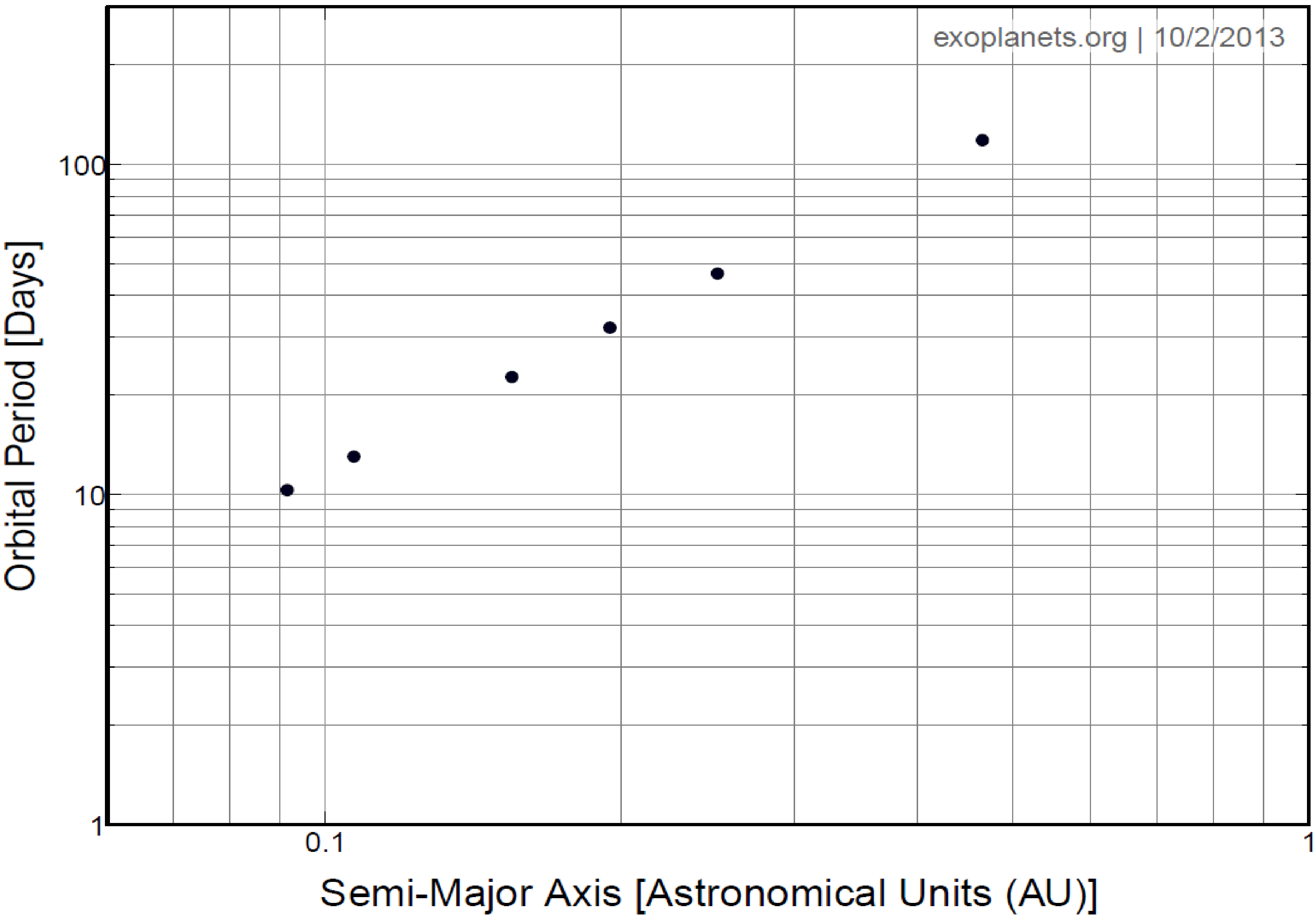
a
b
p
a
C
c
F2
F1

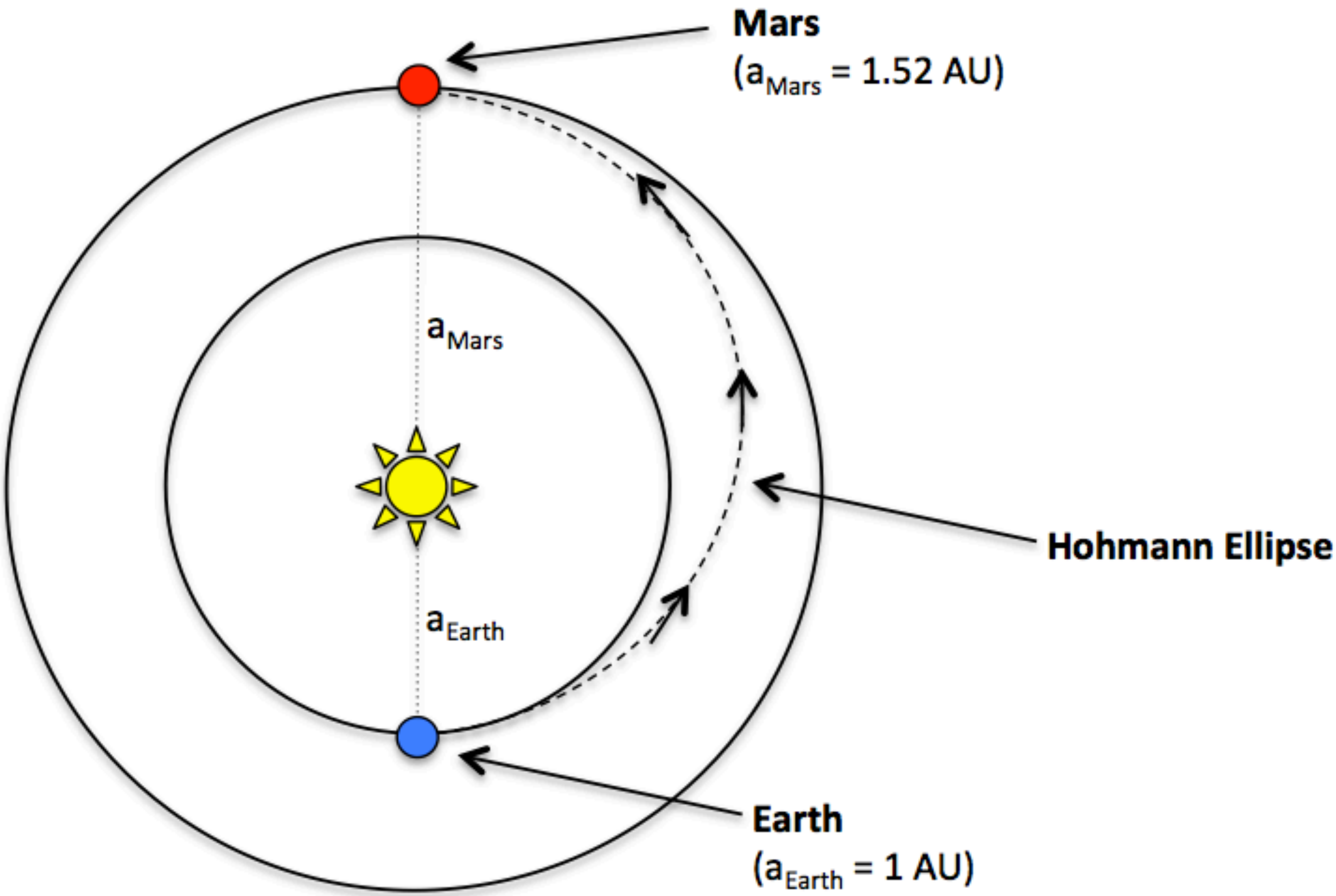

A
a
(pa)^1/2
P
S
ae
C
F


e
e
e
e
e
e

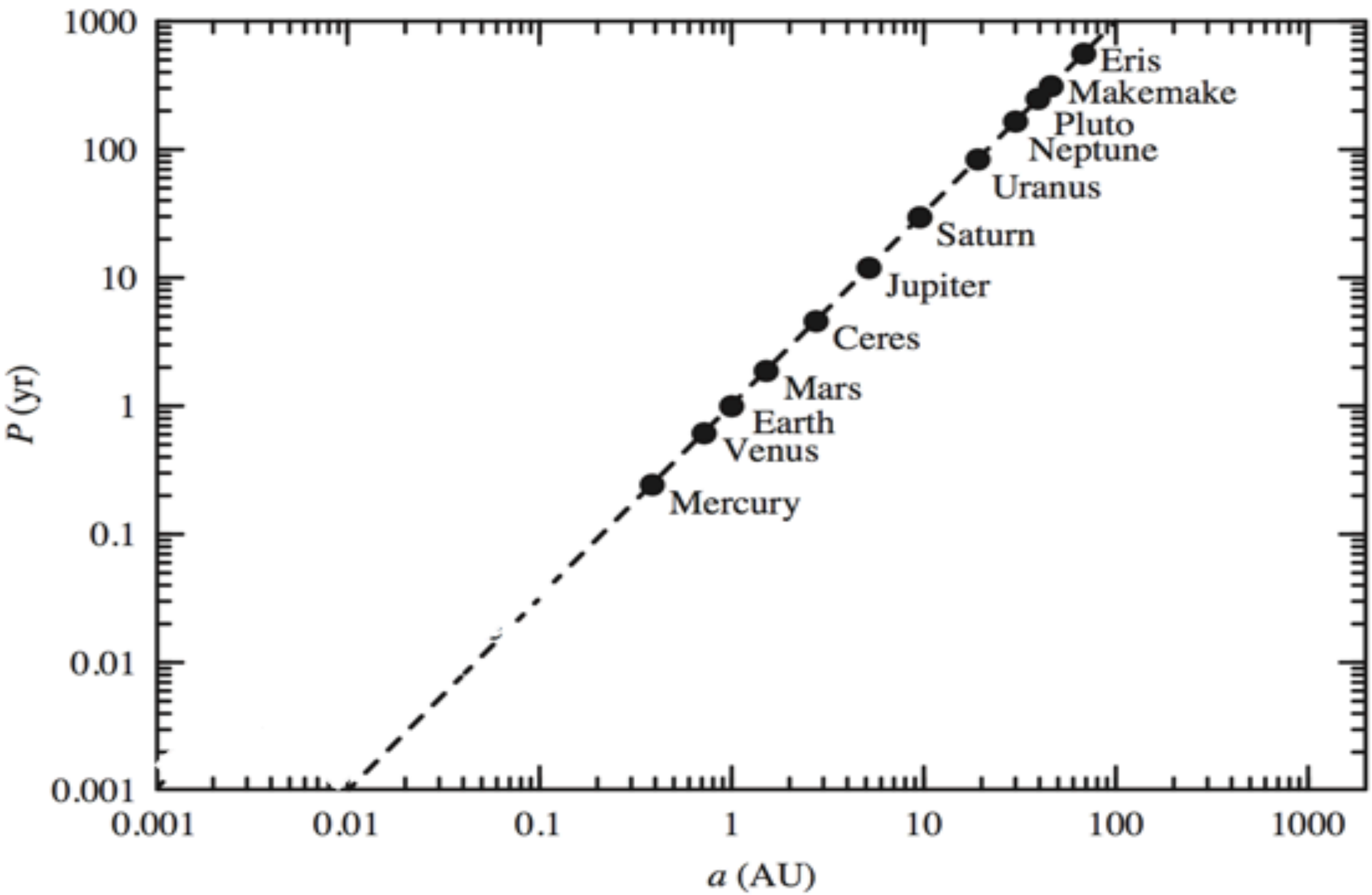


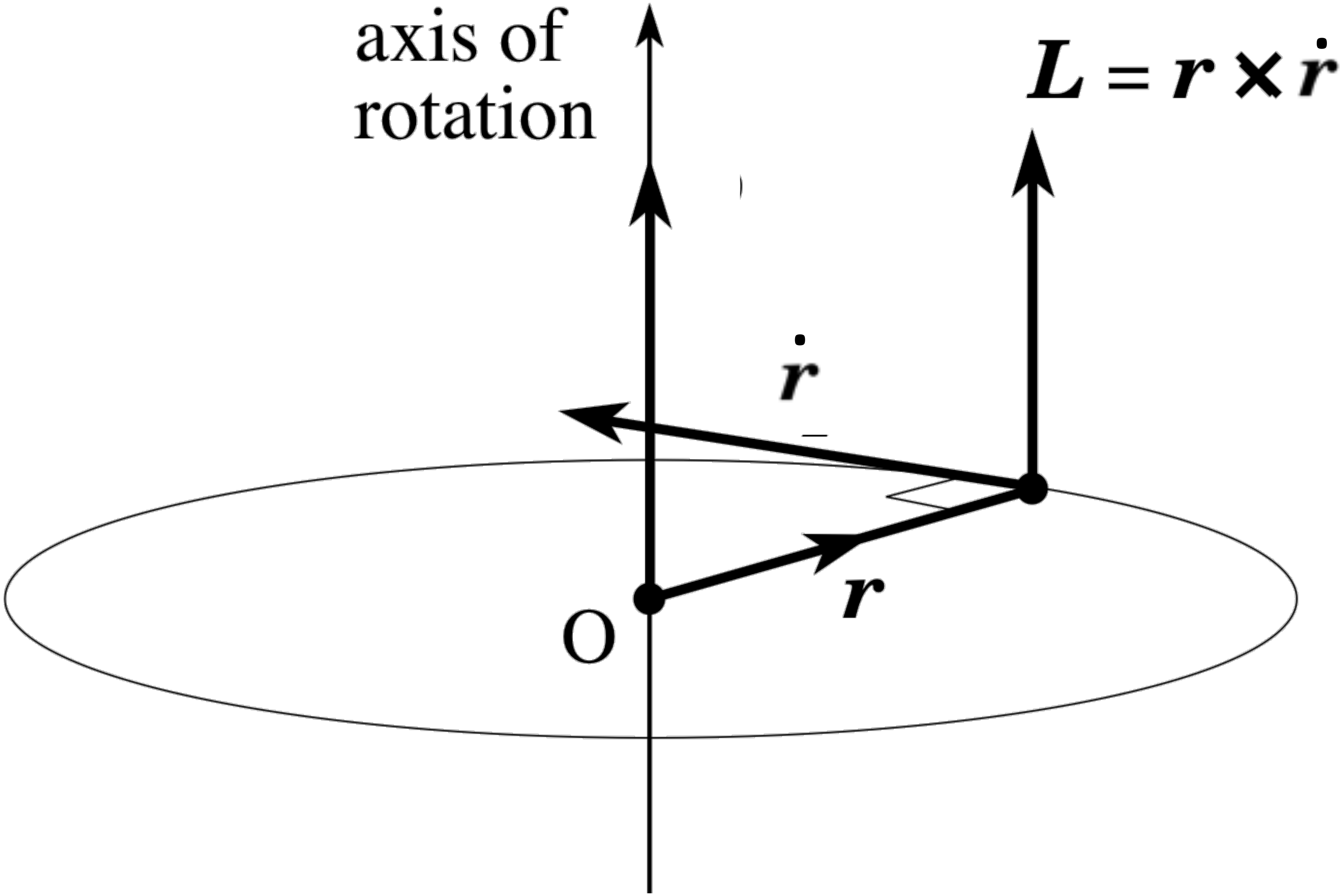
100
10
1.0
0.1
Stellar Mass ($M_\odot$)
0.001
0.01
0.1
1.0
10
100
Planetary Orbital Semi-Major Axis (AU)


exoplanets.org | 10/2/2013
Orbital Period [Days]
100
10
1
0.1
1
Semi-Major Axis [Astronomical Units (AU)]



Mars
(a_{Mars} = 1.52 AU)
a_{Mars}
a_{Earth}
Hohmann Ellipse
Earth
(a_{Earth} = 1 AU)


1000
100
10
1
0.1
0.01
0.001
P (yr)
0.001
0.01
0.1
1
10
100
1000
a (AU)
Eris
Makemake
Pluto
Neptune
Uranus
Saturn
Jupiter
Ceres
Mars
Earth
Venus
Mercury

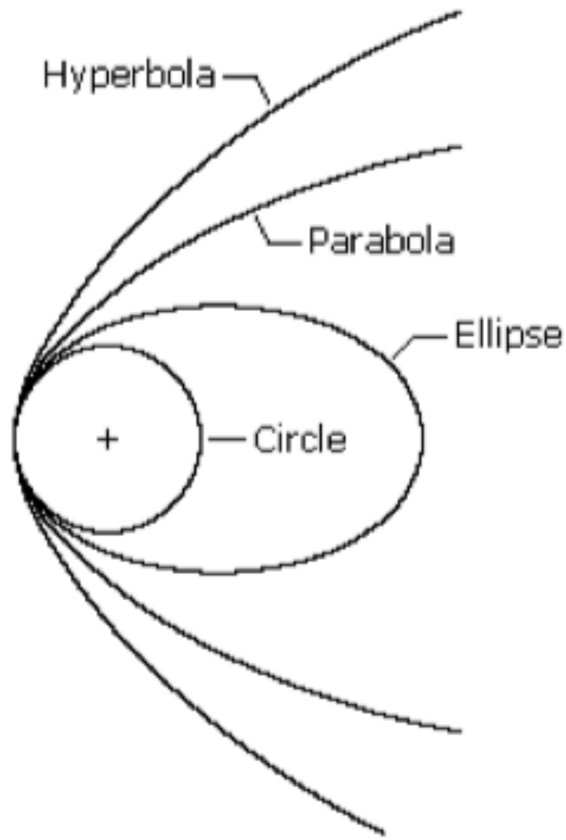

axis of rotation
$\boldsymbol{L} = \boldsymbol{r} \times \dot{\boldsymbol{r}}$
$\dot{\boldsymbol{r}}$
$\boldsymbol{r}$
O

Types of orbit

Orbit Type	Eccentricity	Energy
Circle	$e = 0$	$E = E_{min}$
Ellipse	$0 < e < 1$	$E_{min} < E < 0$
Parabola	$e=1$	$E = 0$
Hyperbola	$e > 1$	$E > 0$

Bound

Unbound



Conic Sections

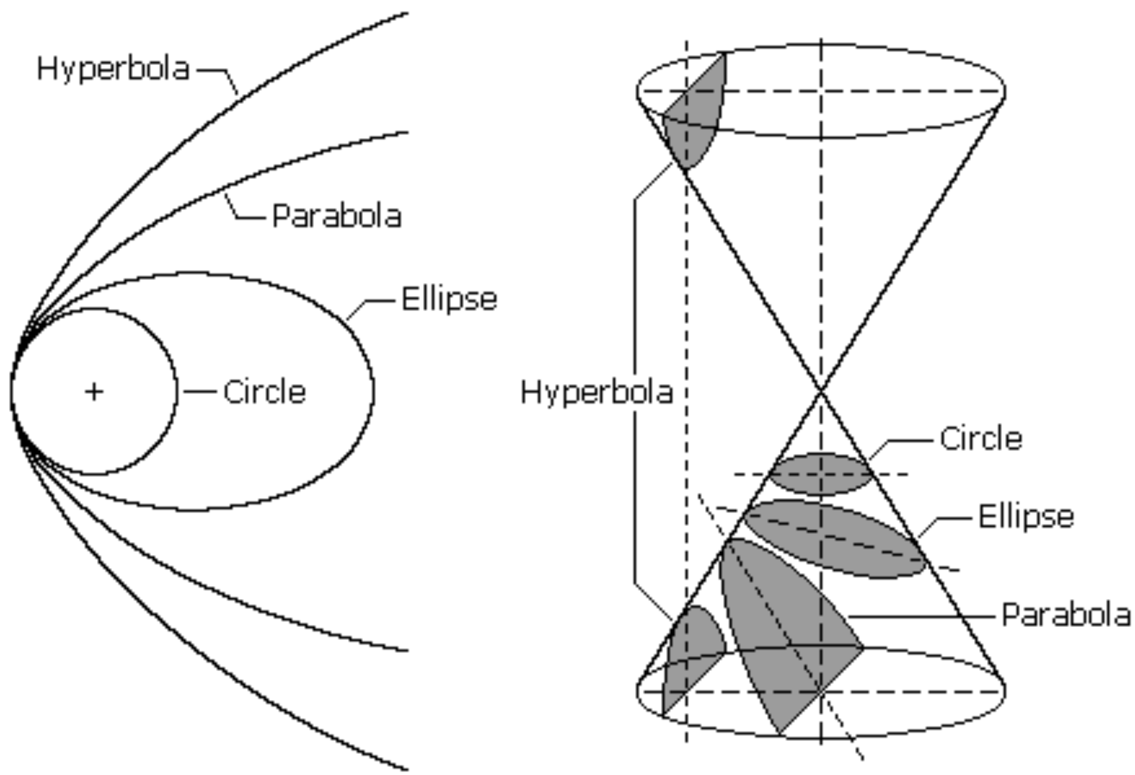
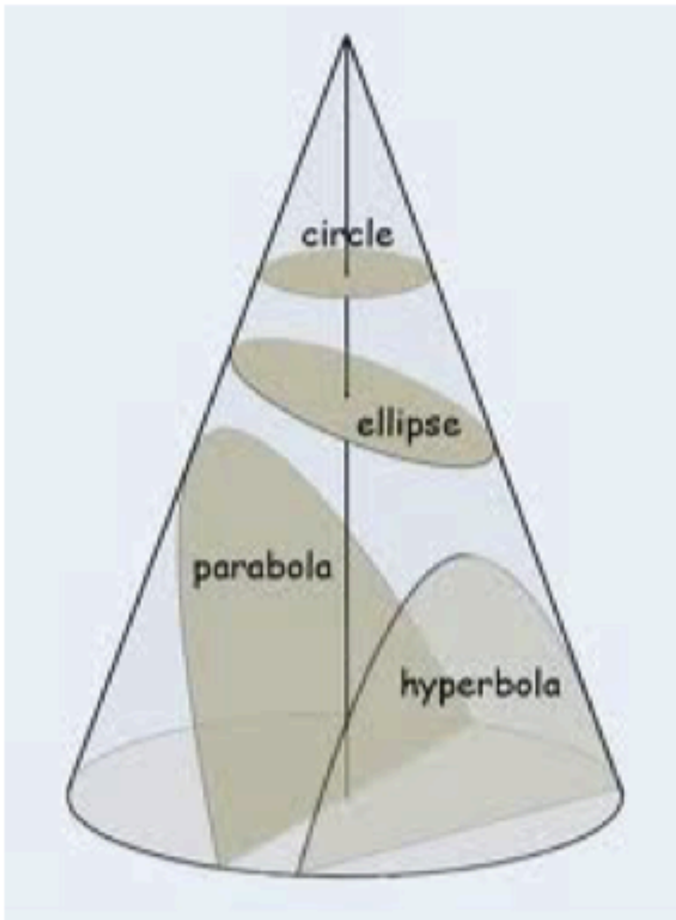
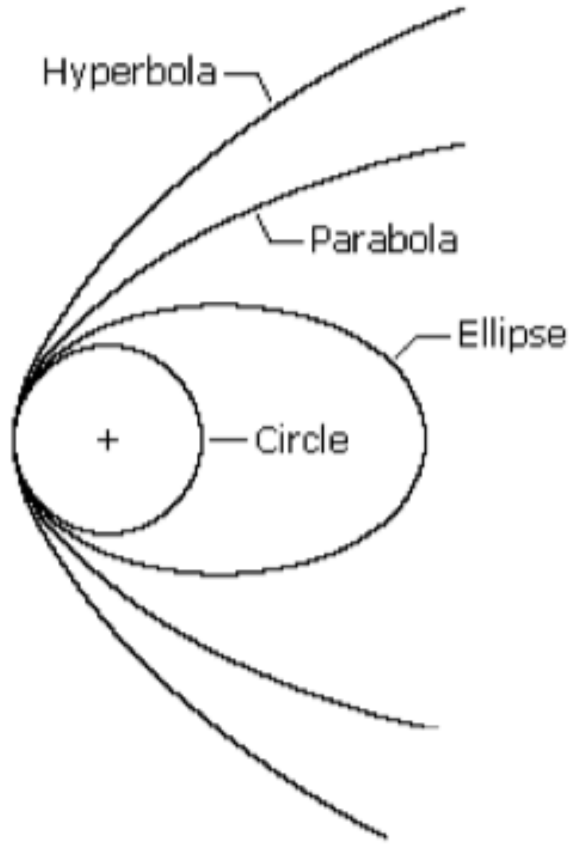
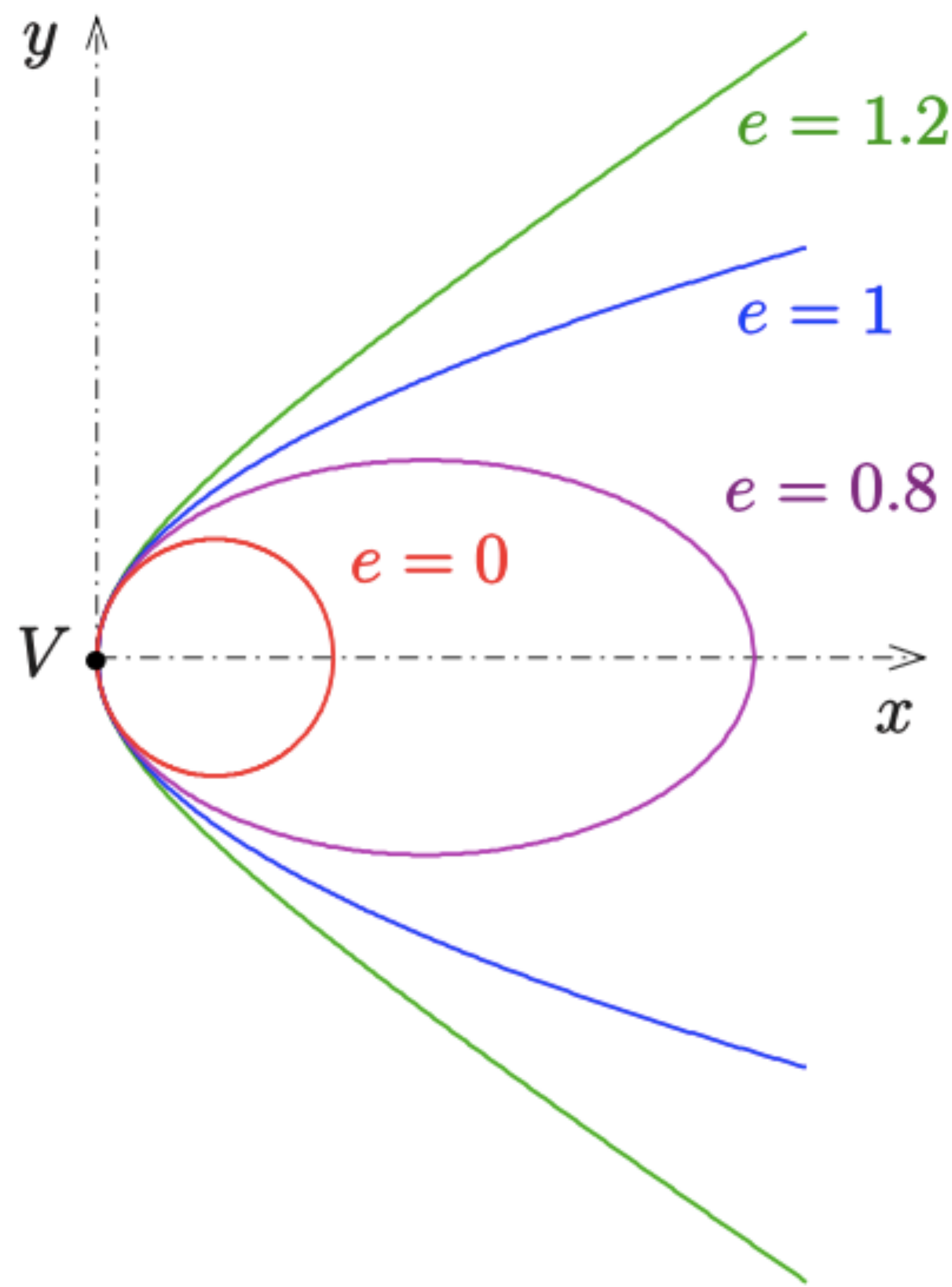


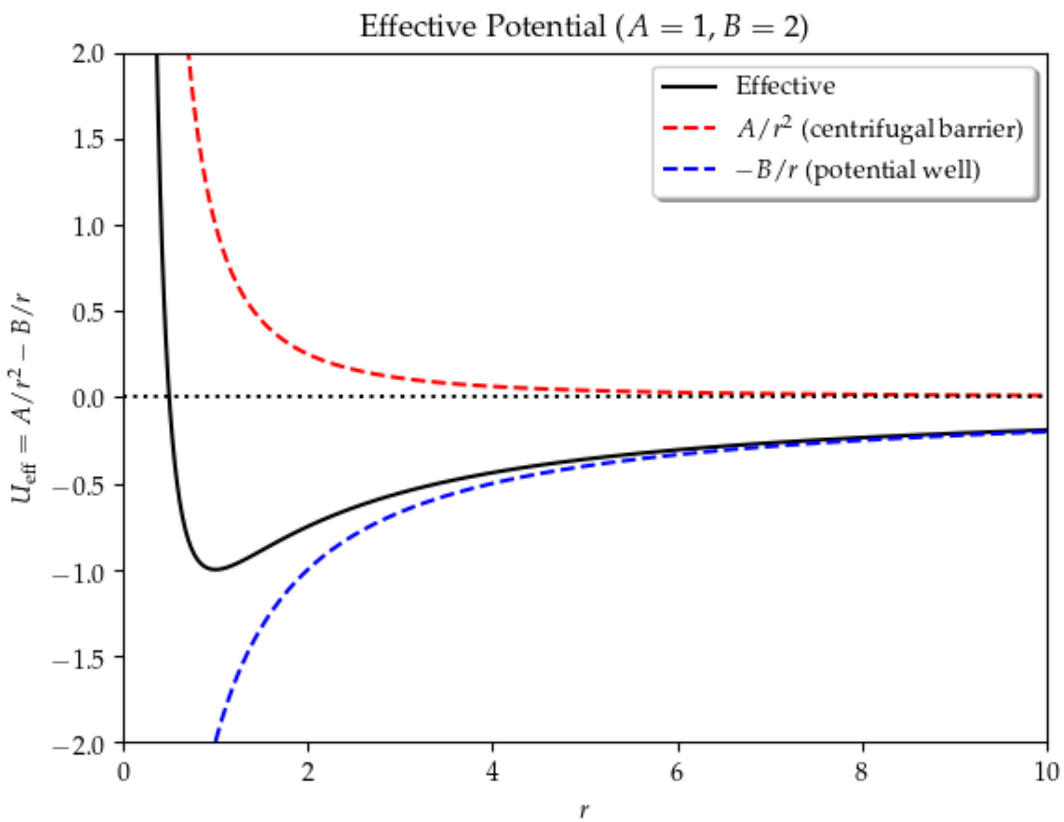
Figure 4.1

Types of orbit: Conic Sections

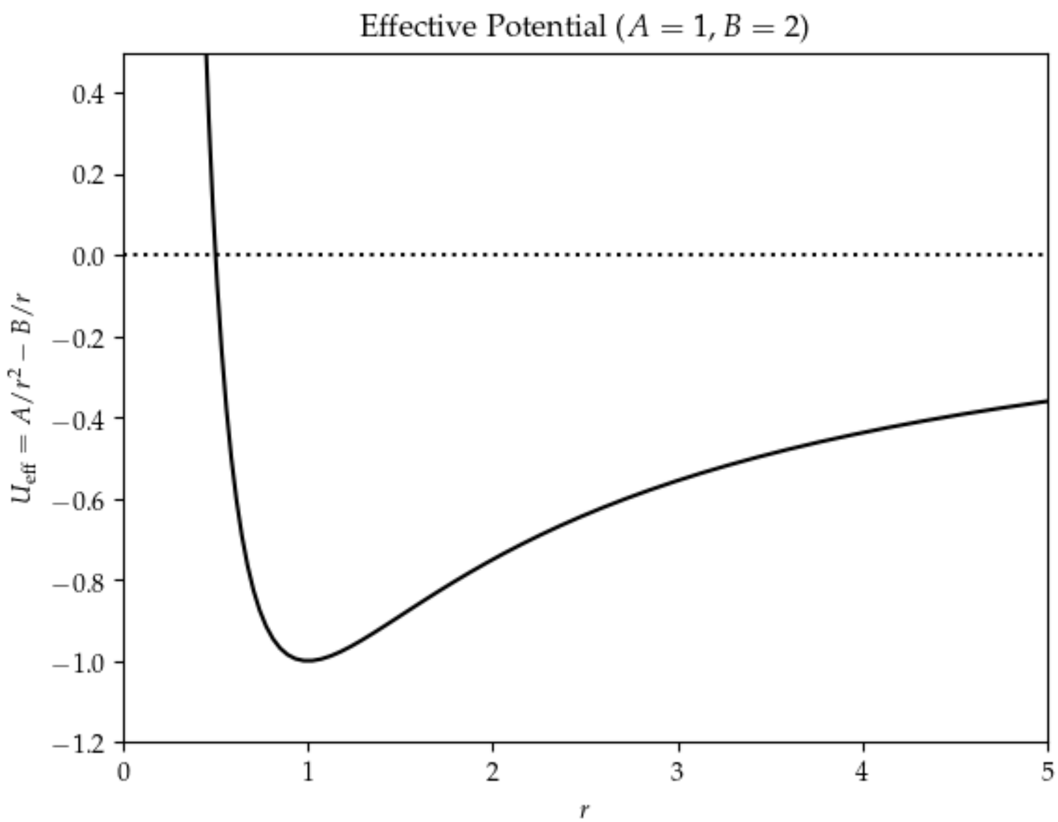


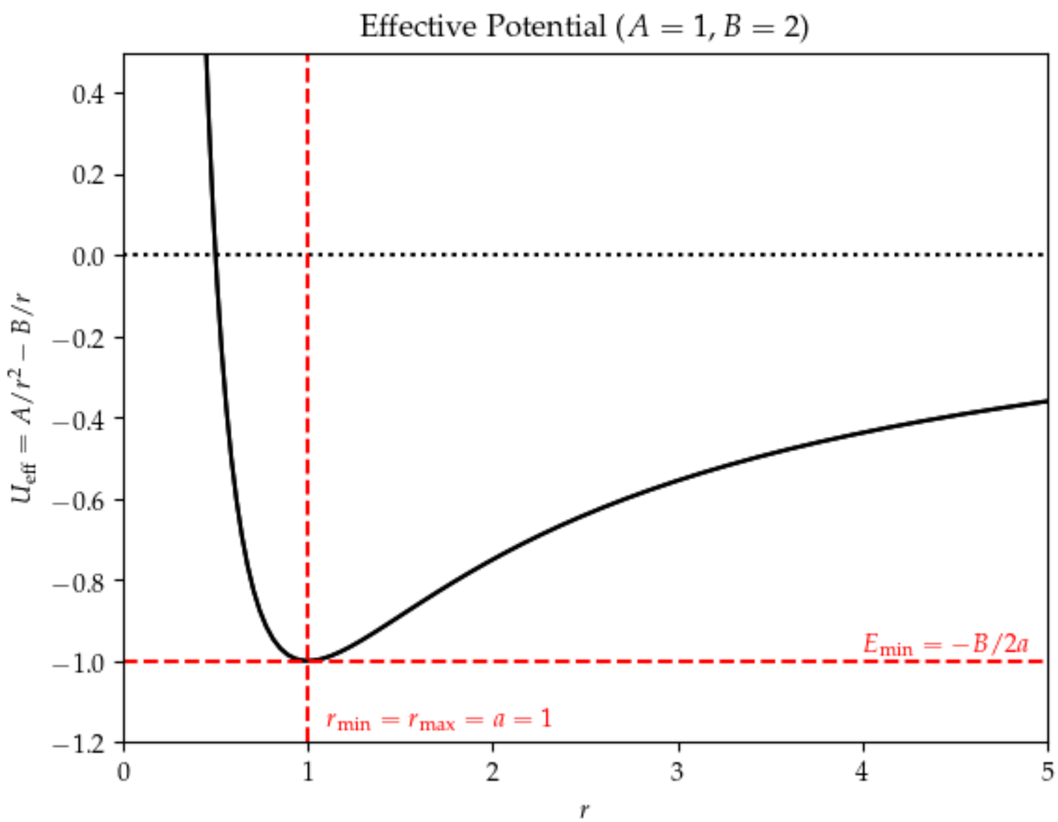



y
e = 1.2
e = 1
e = 0.8
e = 0
V
x

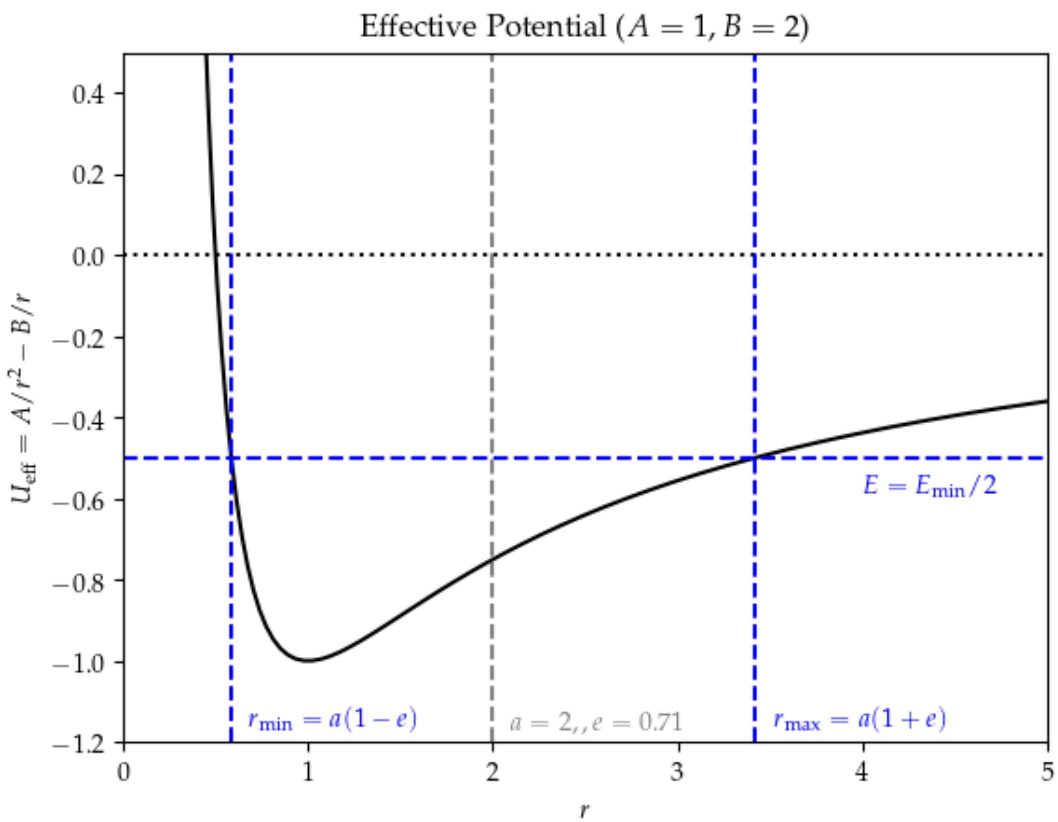


Effective Potential ($A = 1, B = 2$)
Effective
A/r^2 (centrifugal barrier)
$-B/r$ (potential well)
$U_{\text{eff}} = A/r^2 - B/r$
r
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−2.0
0
2
4
6
8
10

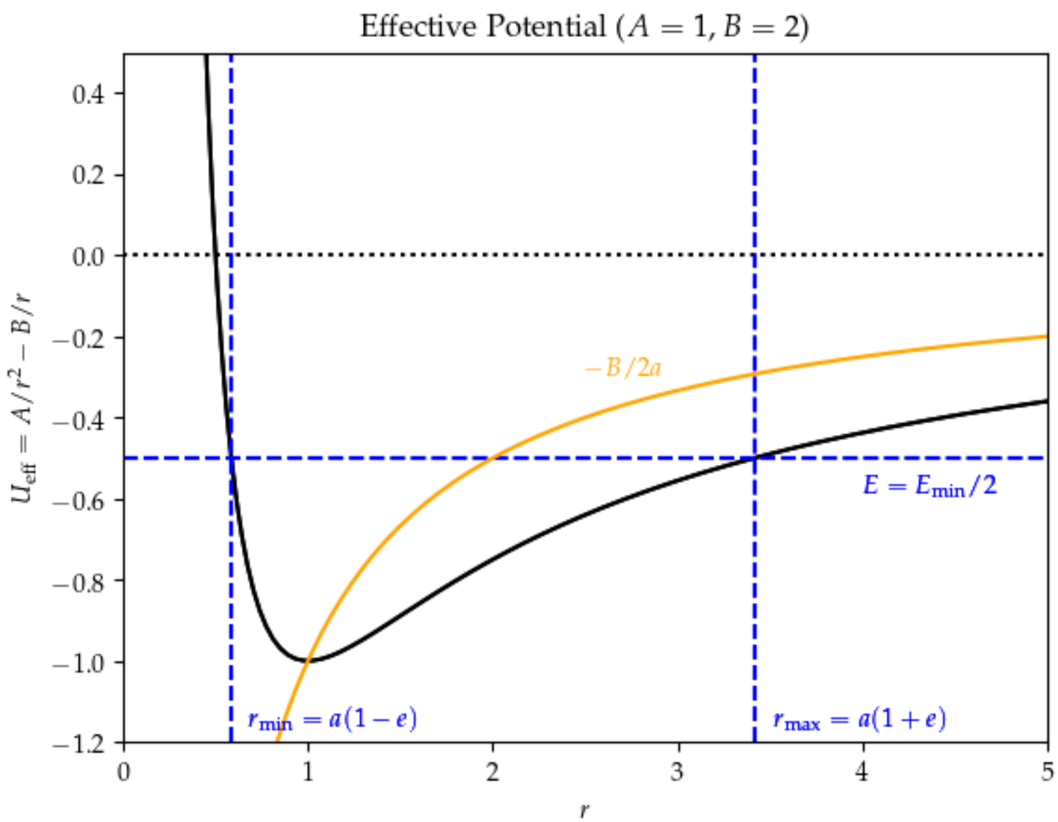

Effective Potential ($A = 1, B = 2$)
$U_{\text{eff}} = A/r^2 - B/r$
r
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0
1
2
3
4
5



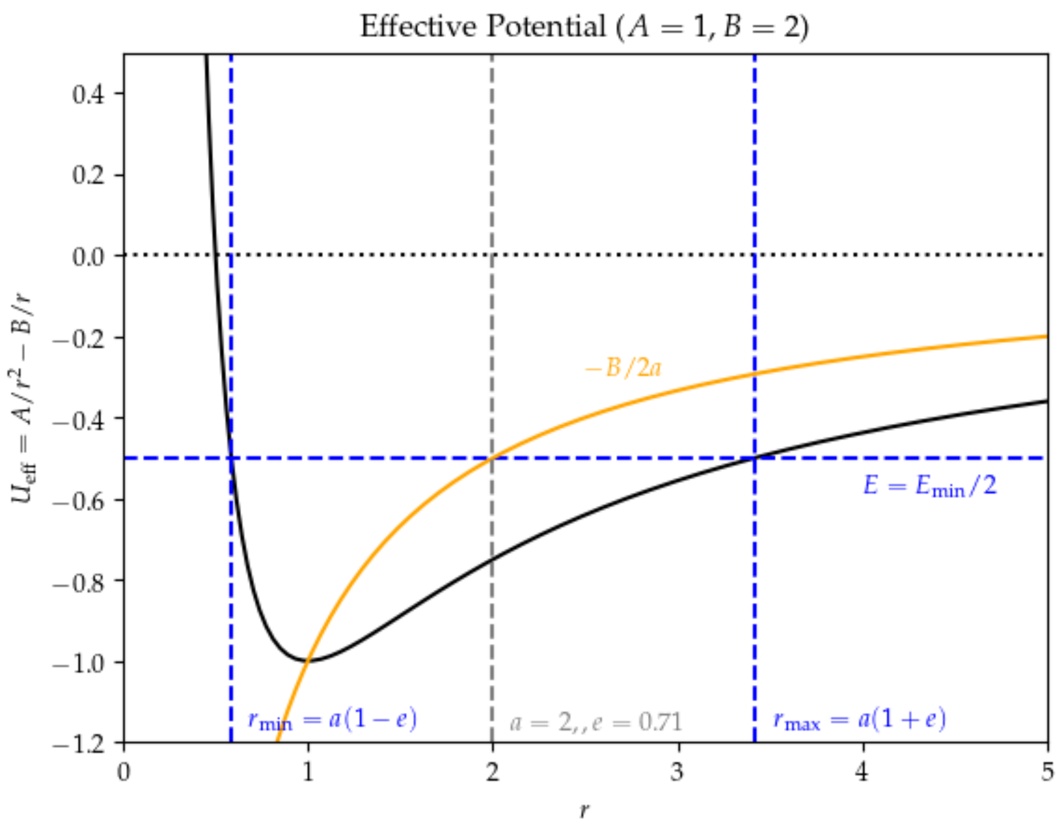
Effective Potential ($A = 1, B = 2$)
$U_{\text{eff}} = A/r^2 - B/r$
r
$E_{\text{min}} = -B/2a$
$r_{\text{min}} = r_{\text{max}} = a = 1$
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0
1
2
3
4
5



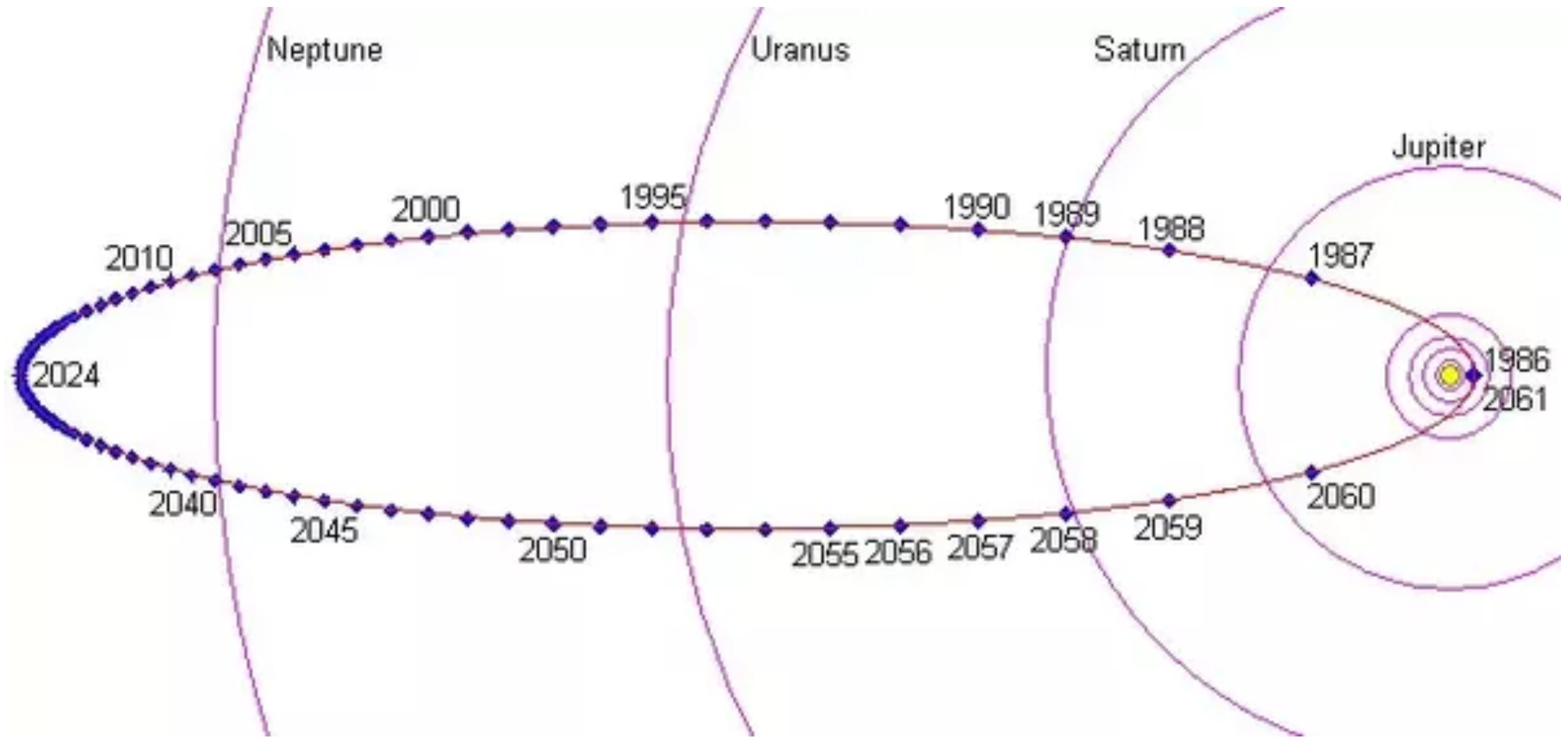
Effective Potential ($A = 1, B = 2$)
$U_{\mathrm{eff}} = A/r^2 - B/r$
r
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0
1
2
3
4
5
$E = E_{\min}/2$
$r_{\min} = a(1-e)$
$a = 2,, e = 0.71$
$r_{\max} = a(1+e)$



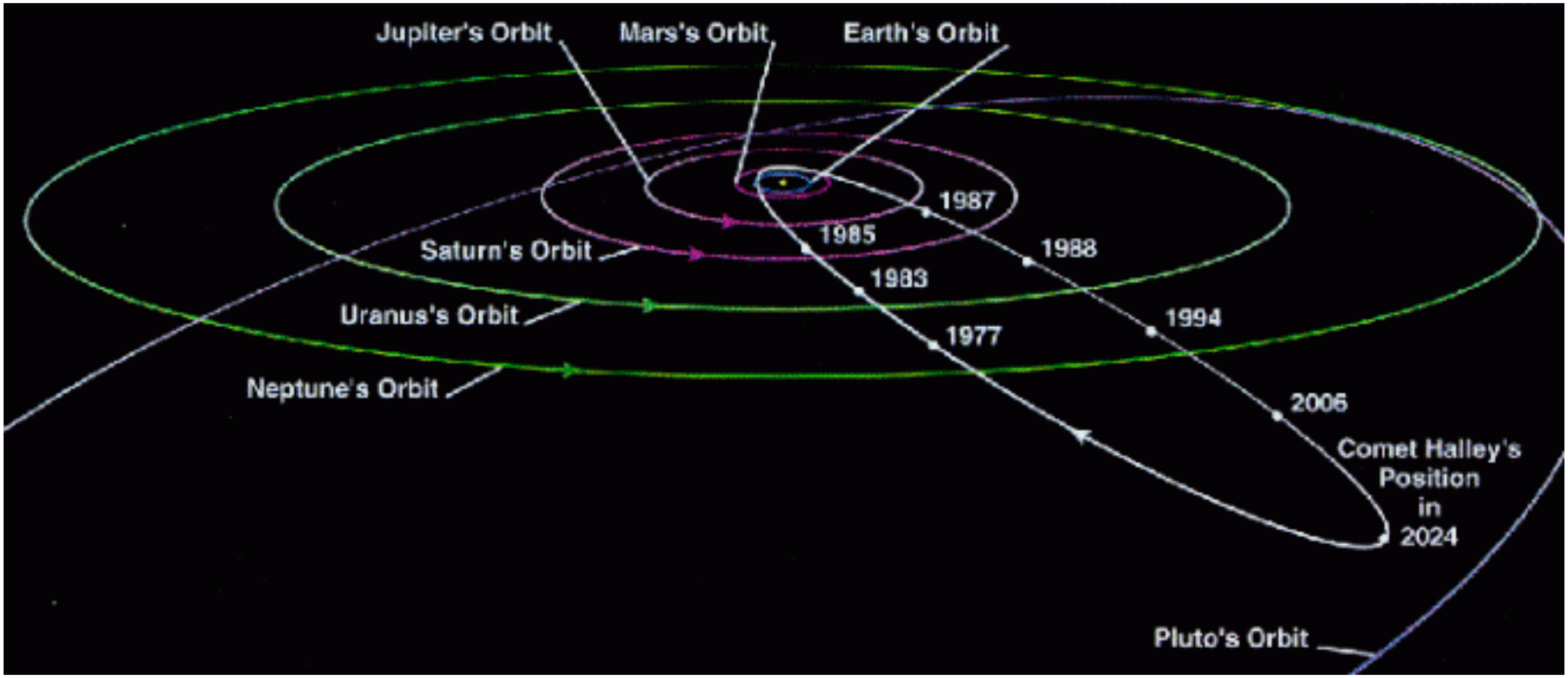
Effective Potential ($A = 1, B = 2$)
$U_{\text{eff}} = A/r^2 - B/r$
r
$-B/2a$
$E = E_{\text{min}}/2$
$r_{\text{min}} = a(1-e)$
$r_{\text{max}} = a(1+e)$
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0
1
2
3
4
5

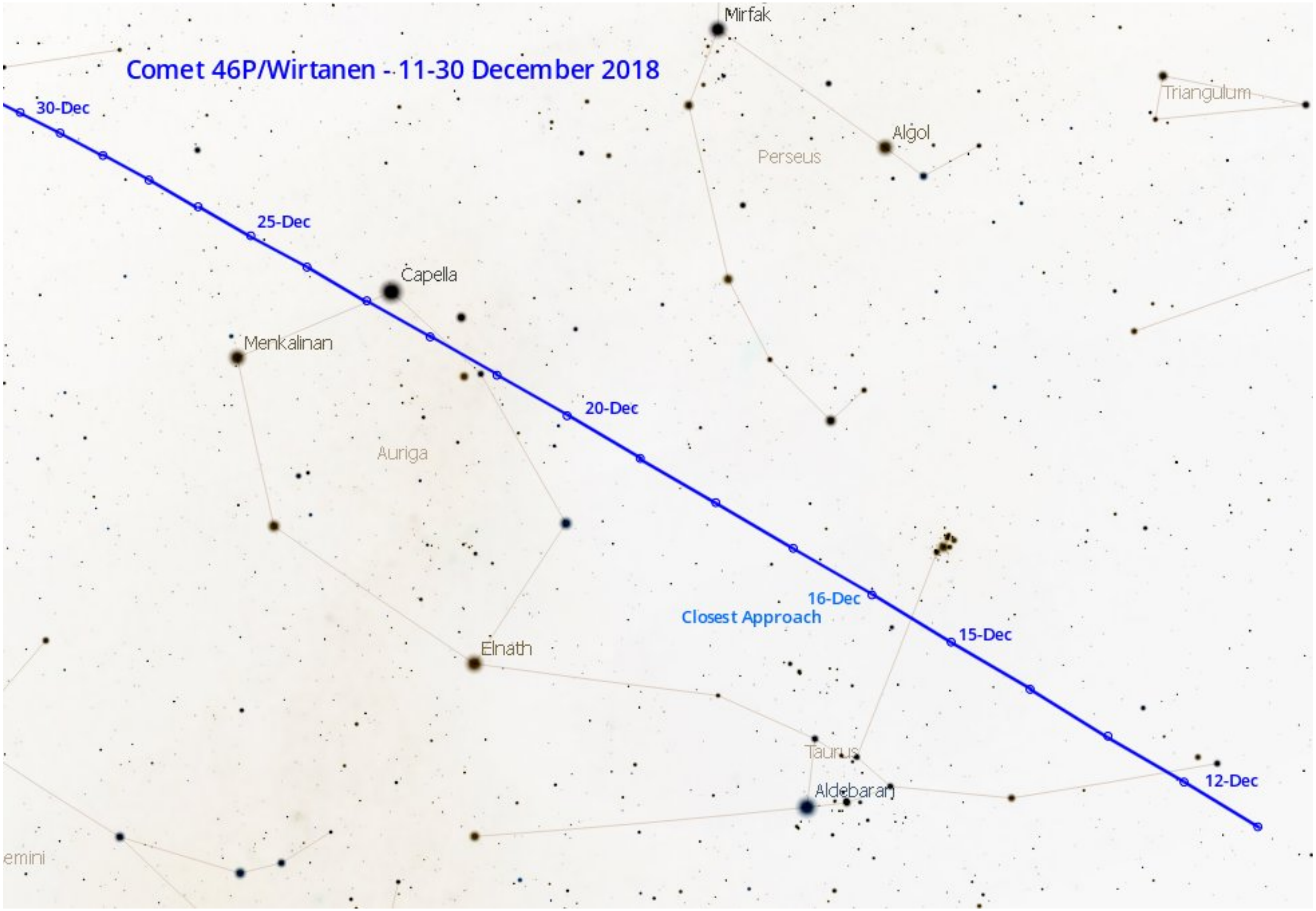

Effective Potential ($A = 1, B = 2$)
$U_{\text{eff}} = A/r^2 - B/r$
r
$-B/2a$
$E = E_{\min}/2$
$r_{\min} = a(1-e)$
$a = 2,, e = 0.71$
$r_{\max} = a(1+e)$
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
0
1
2
3
4
5

Halley's comet

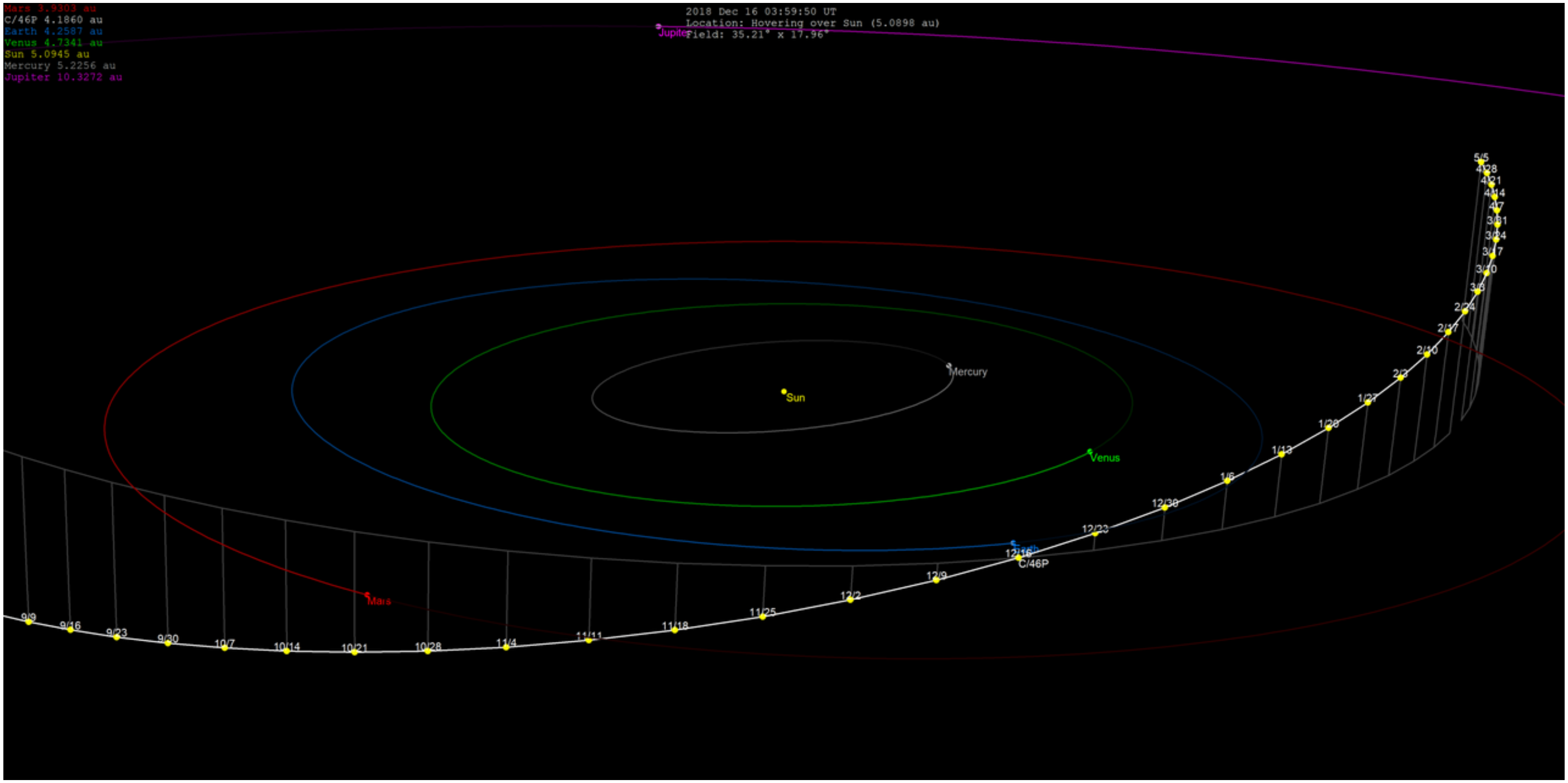


Halley's comet





Comet 46P/Wirtanen - 11-30 December 2018
30-Dec
25-Dec
20-Dec
16-Dec
Closest Approach
15-Dec
12-Dec
Mirfak
Triangulum
Algol
Perseus
Capella
Menkalinan
Auriga
Elnath
Taurus
Aldebaran
emini



Mars 3.9303 au
C/46P 4.1860 au
Earth 4.2587 au
Venus 4.7341 au
Sun 5.0945 au
Mercury 5.2256 au
Jupiter 10.3272 au
2018 Dec 16 03:59:50 UT
Location: Hovering over Sun (5.0898 au)
Field: 35.21° x 17.96°
Jupiter
Mercury
Sun
Venus
Mars
C/46P
12/16
9/9
9/16
9/23
9/30
10/7
10/14
10/21
10/28
11/4
11/11
11/18
11/25
12/2
12/9
12/23
12/30
1/6
1/13
1/20
1/27
2/3
2/10
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3/24
3/31
4/7
4/14
4/21
4/28
5/5

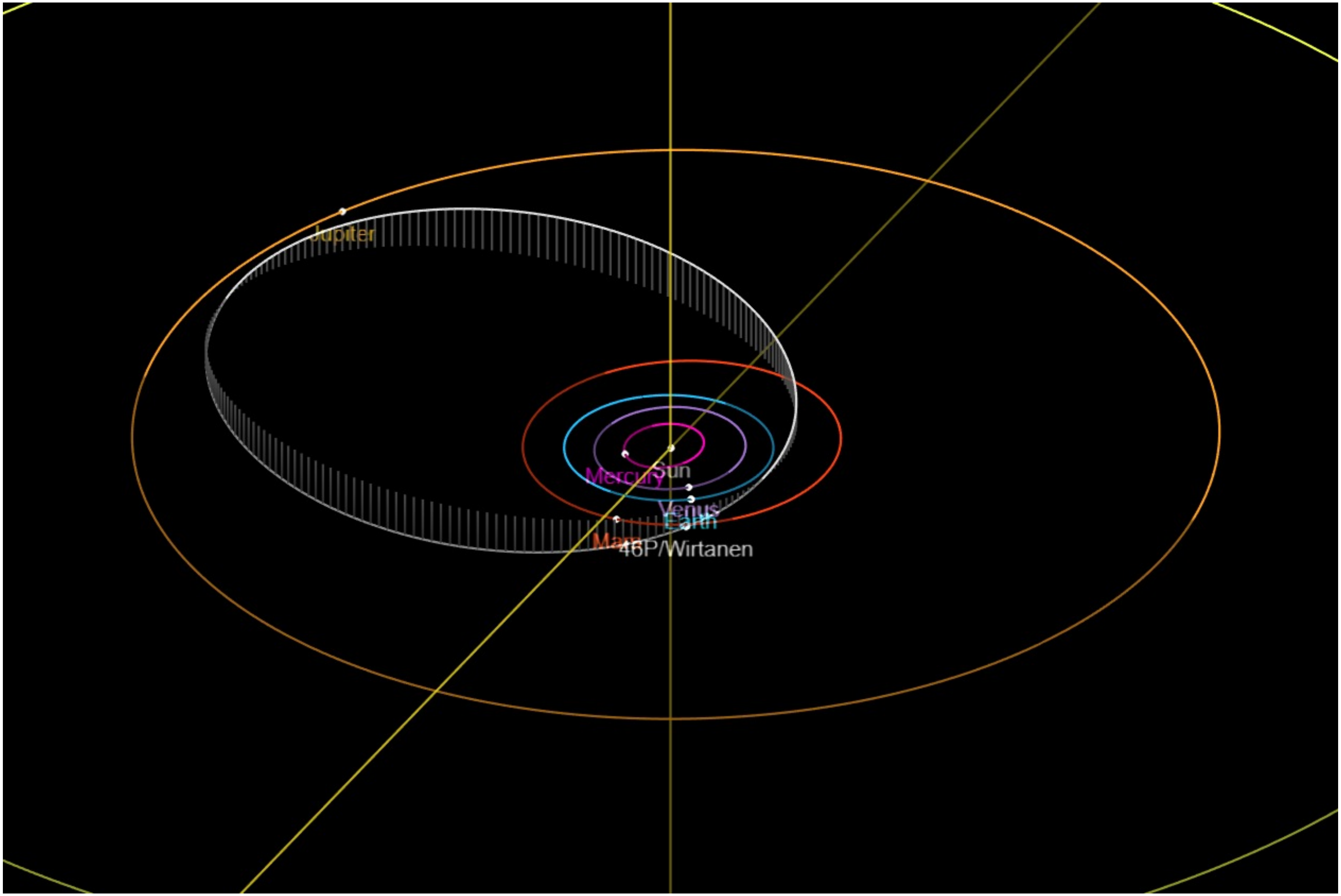

Jupiter
Mercury
Sun
Venus
Earth
Mars
46P/Wirtanen

Figure 1a: Comet Semimajor Axis Distribution

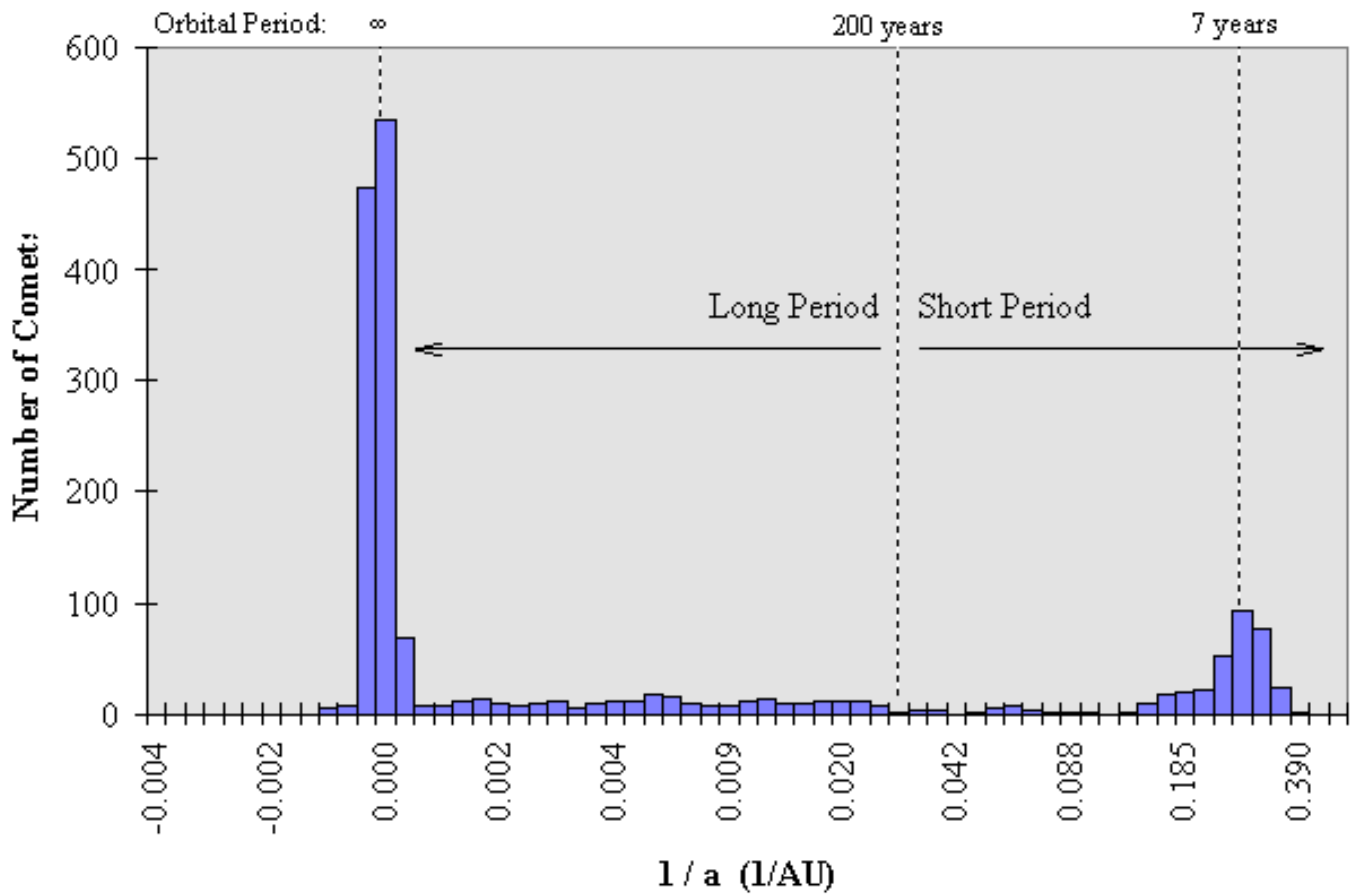
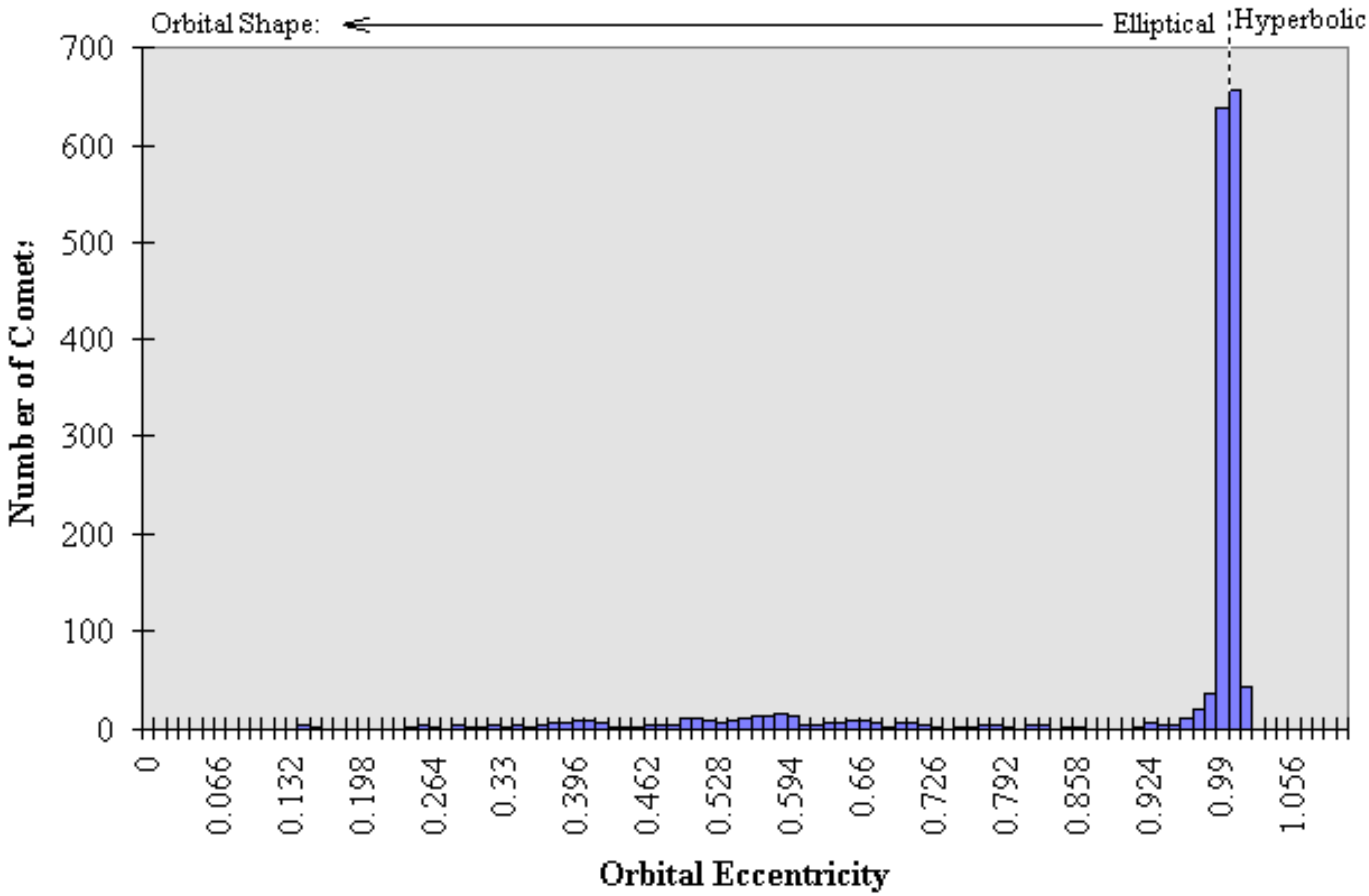


Figure 1b: Comet Eccentricity Distribution



A majority of comets have parabolic orbits

Figure 1a: Comet Semimajor Axis Distribution

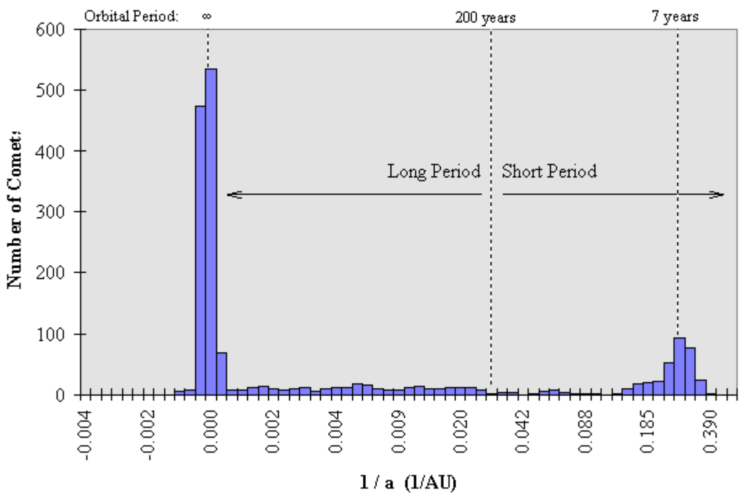
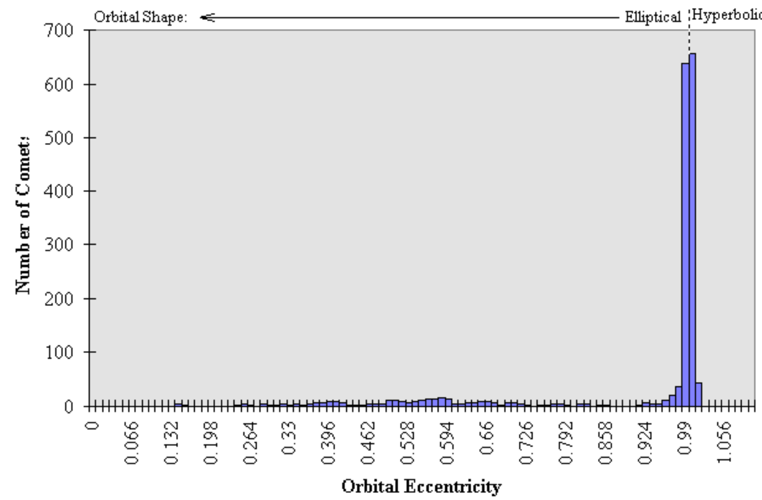
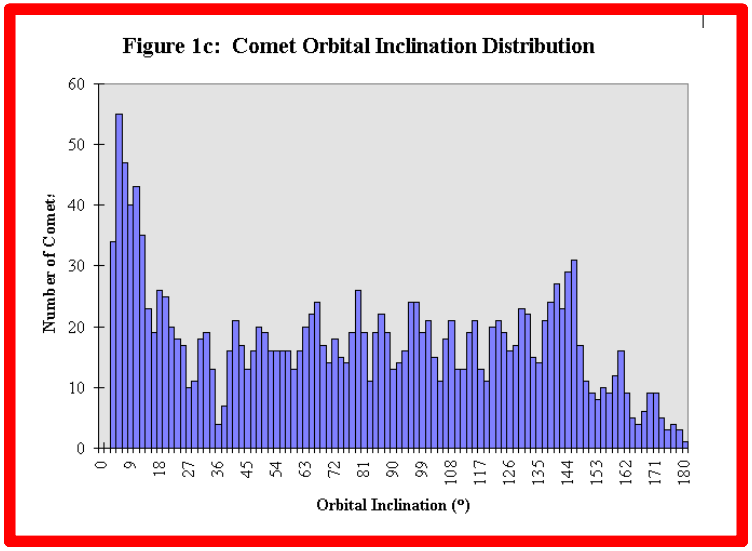
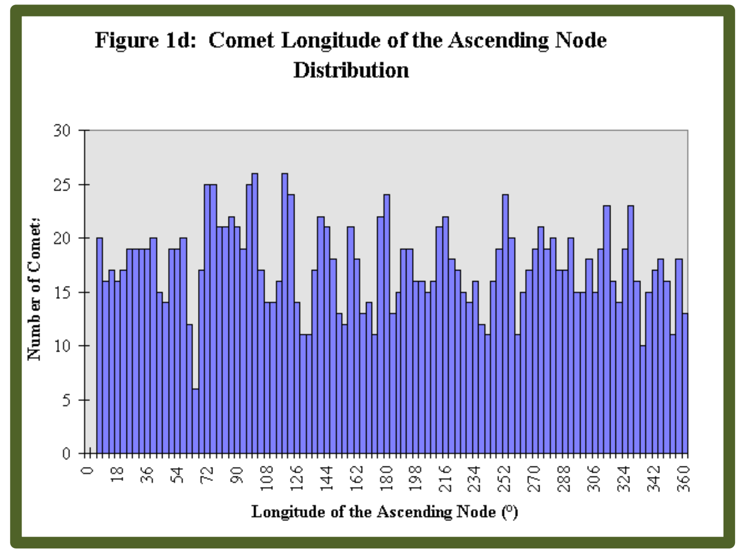


Figure 1b: Comet Eccentricity Distribution

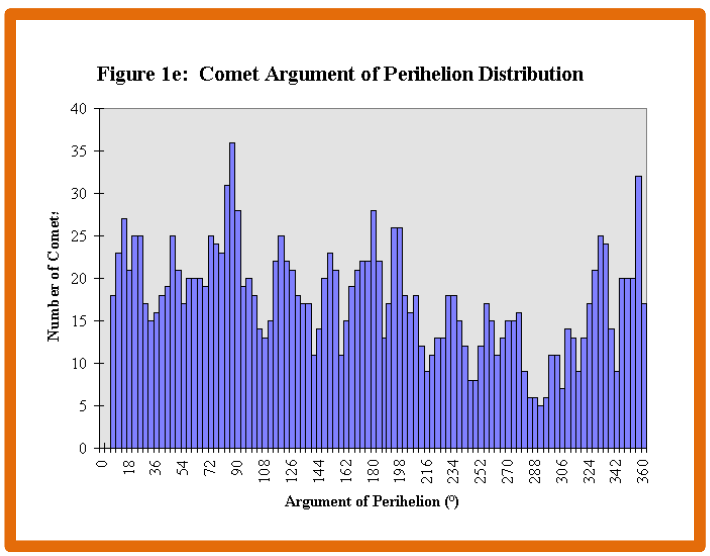




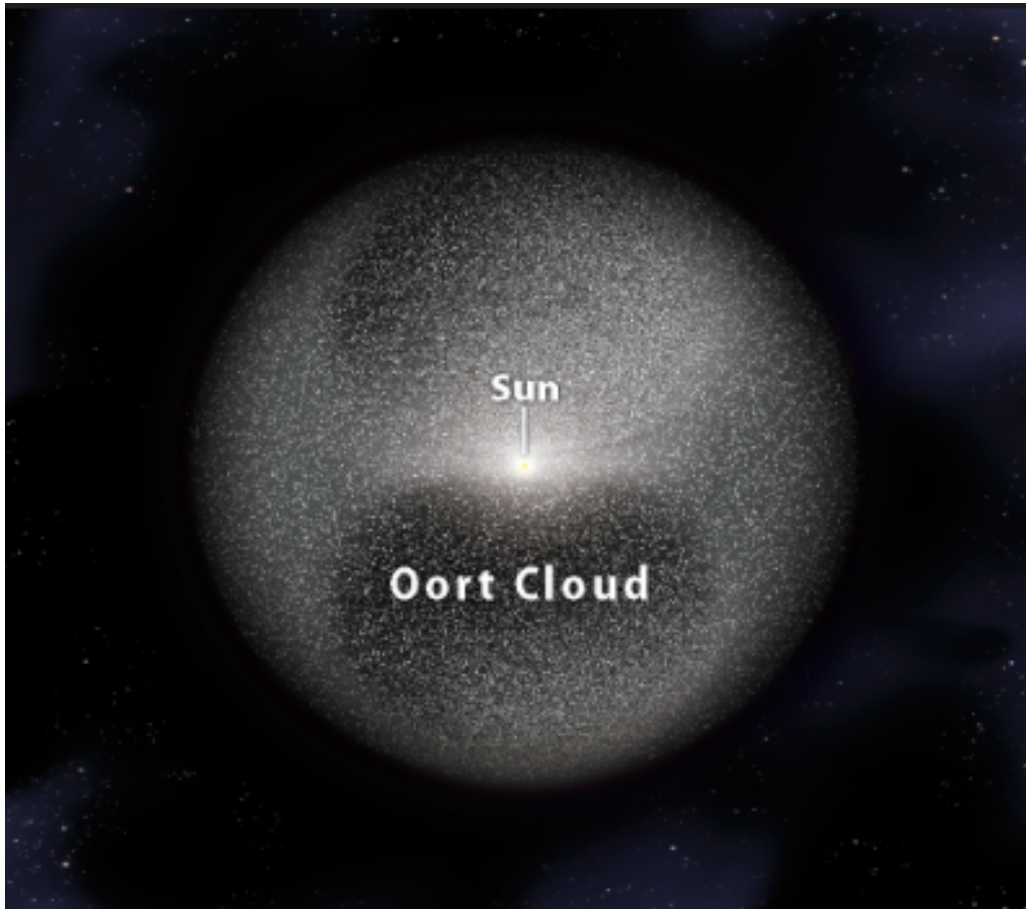
Inclination

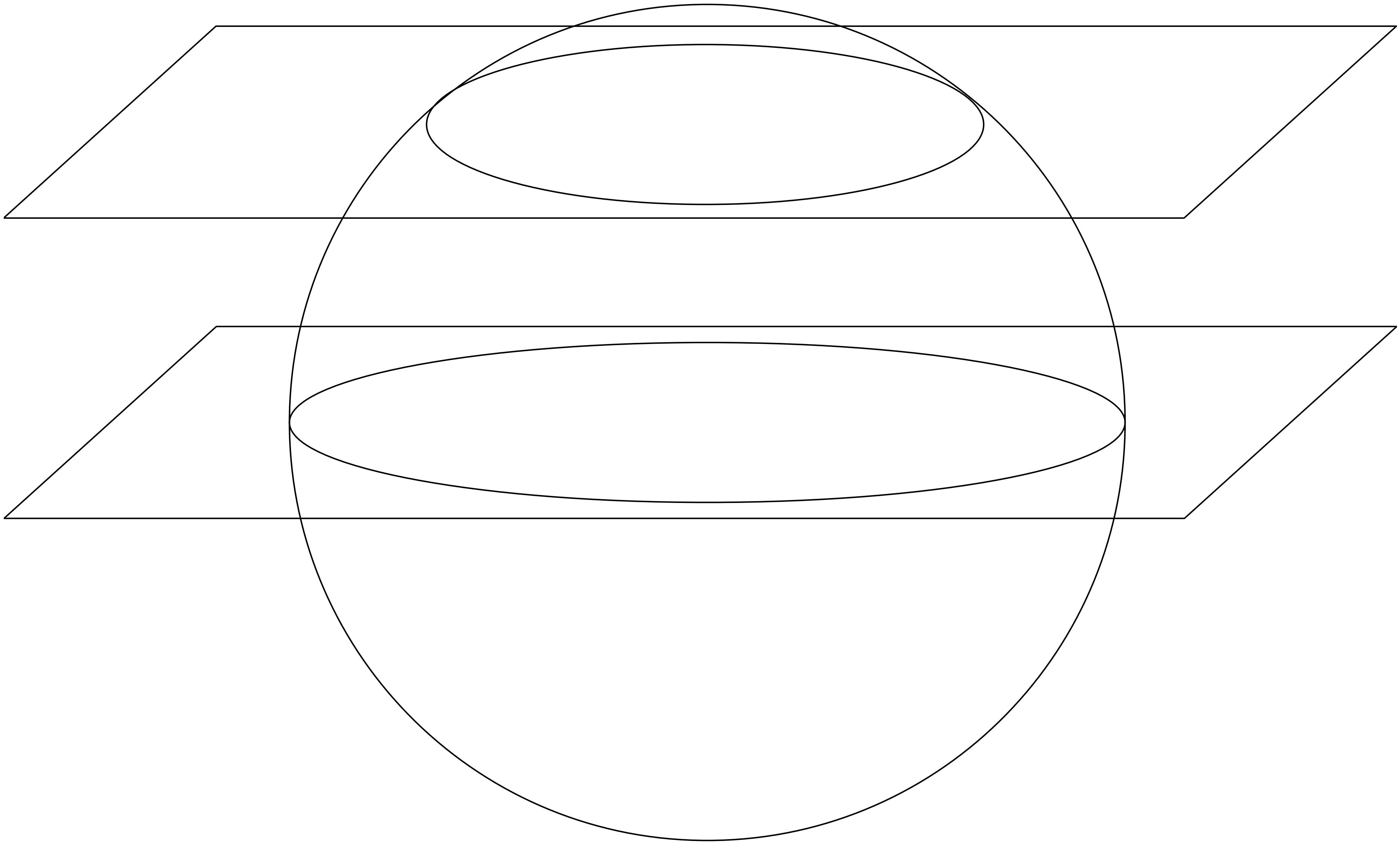


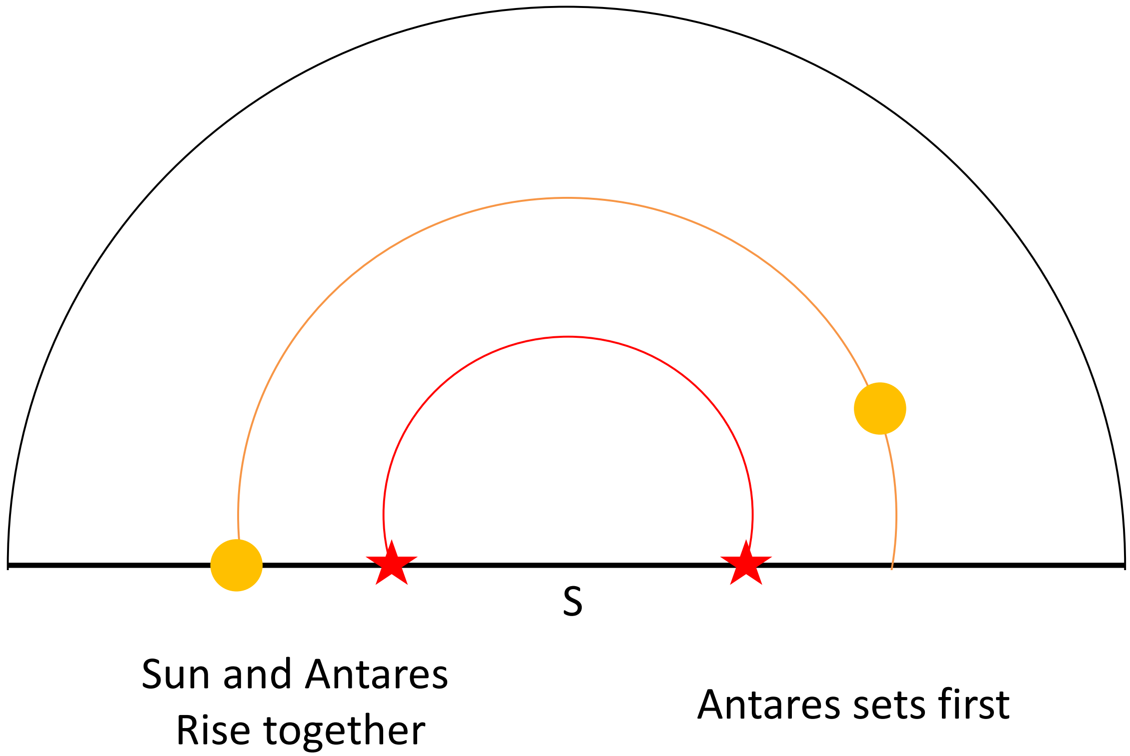
Longitude of Ascending Node

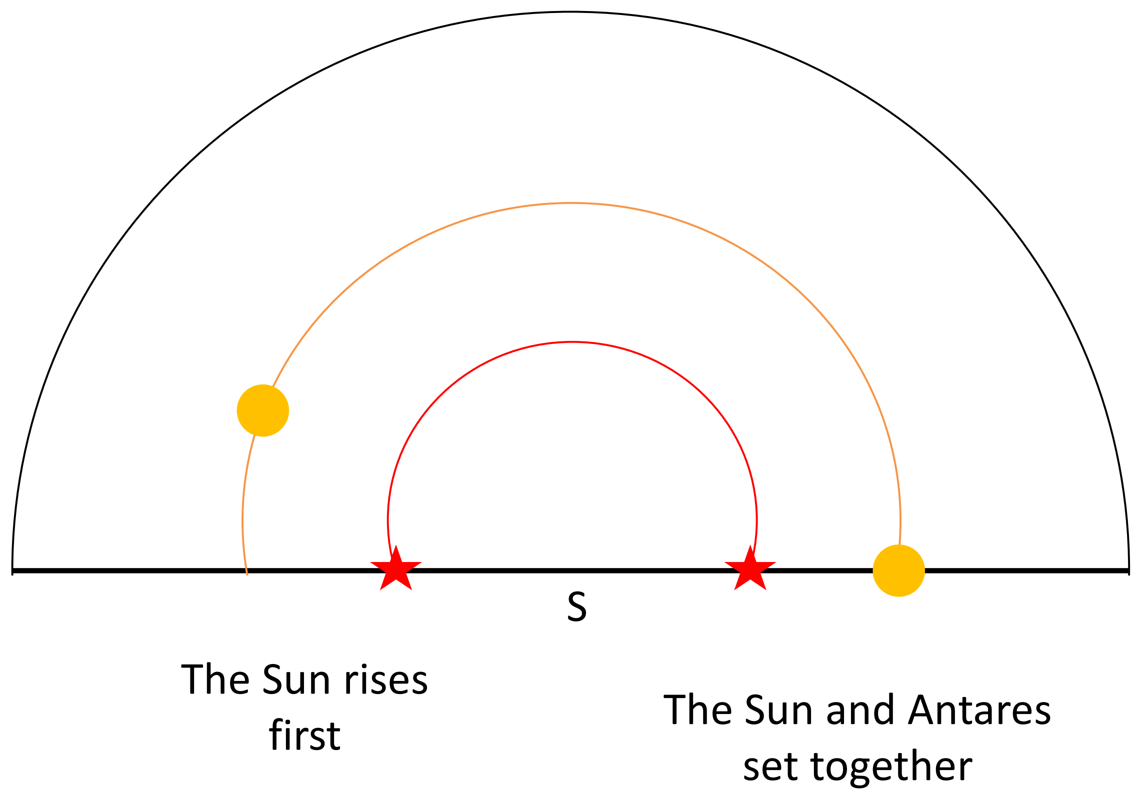


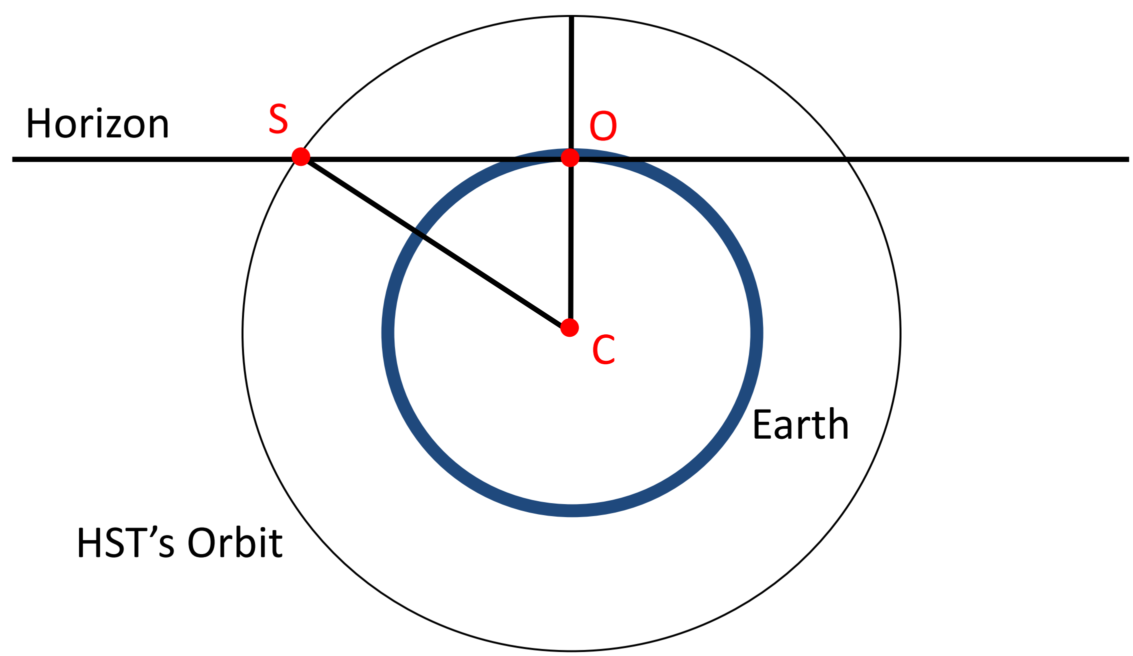
Argument of Perihelion


Sun
Oort Cloud




S
Sun and Antares
Rise together
Antares sets first


S
The Sun rises first
The Sun and Antares set together


Horizon
S
O
C
Earth
HST's Orbit