

Introduction to Orbits

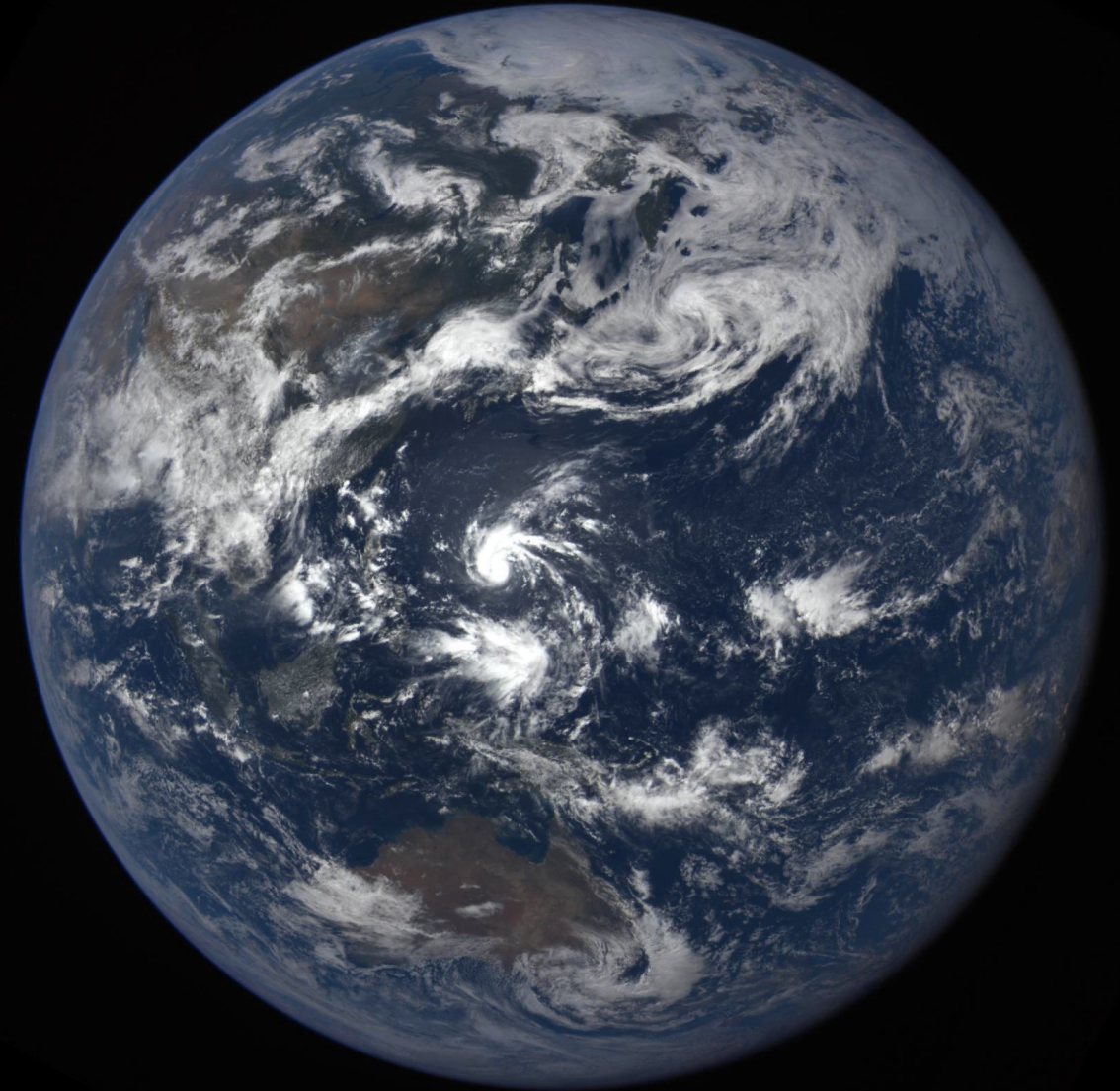
Aerospace
and Aviation Academy

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Acknowledgements

Information and image sources are cited on each slide.

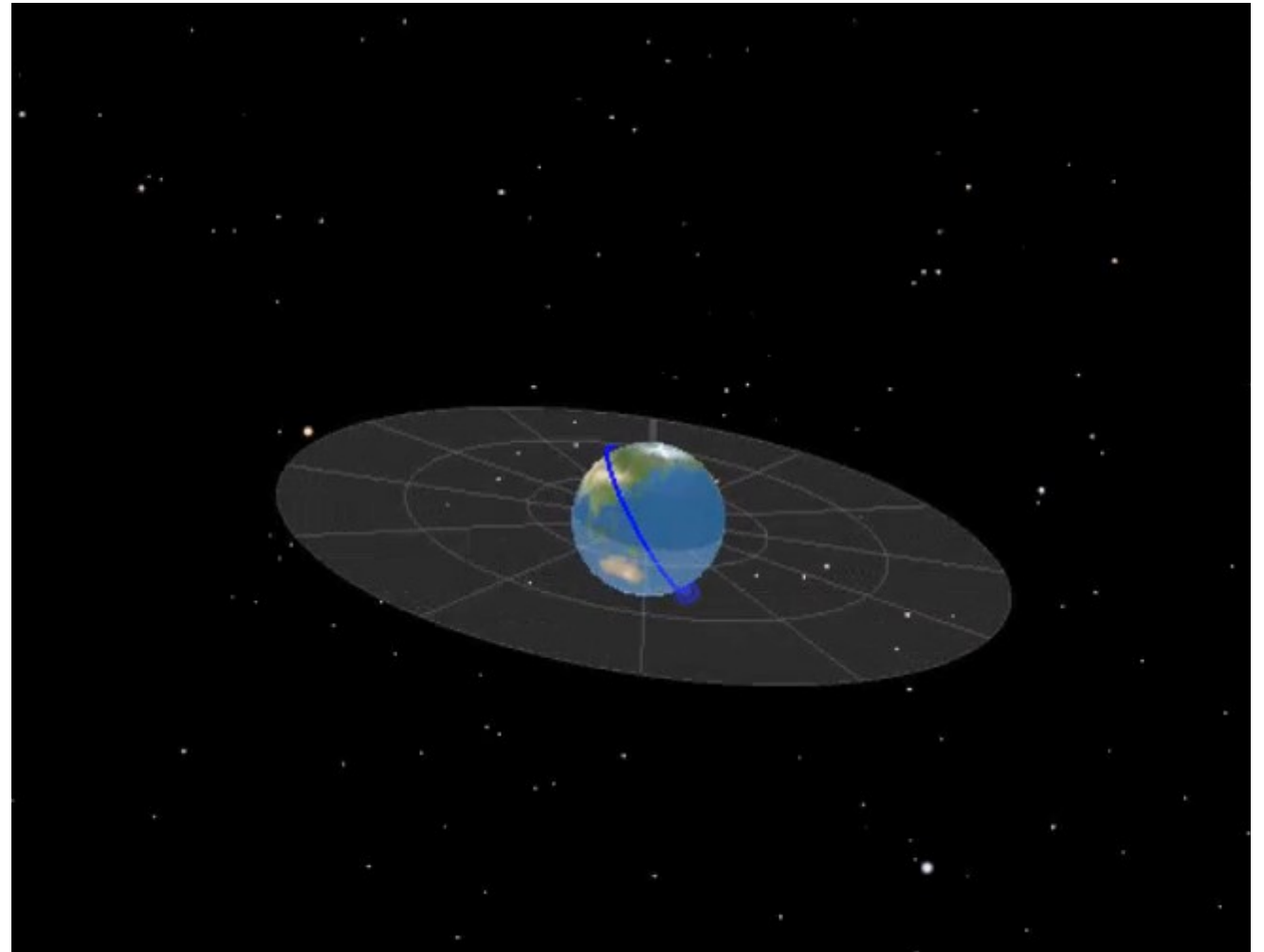
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Microsoft® Clip Art was used in the presentation.

Some content from Bate, R. R., Mueller, D. D., and White, J. E., *Fundamentals of Astrodynamics*, Dover Publications, New York, 1971.

What is an Orbit?

An orbit is “the curved path, usually elliptical, described by a planet, satellite, spaceship, etc.”

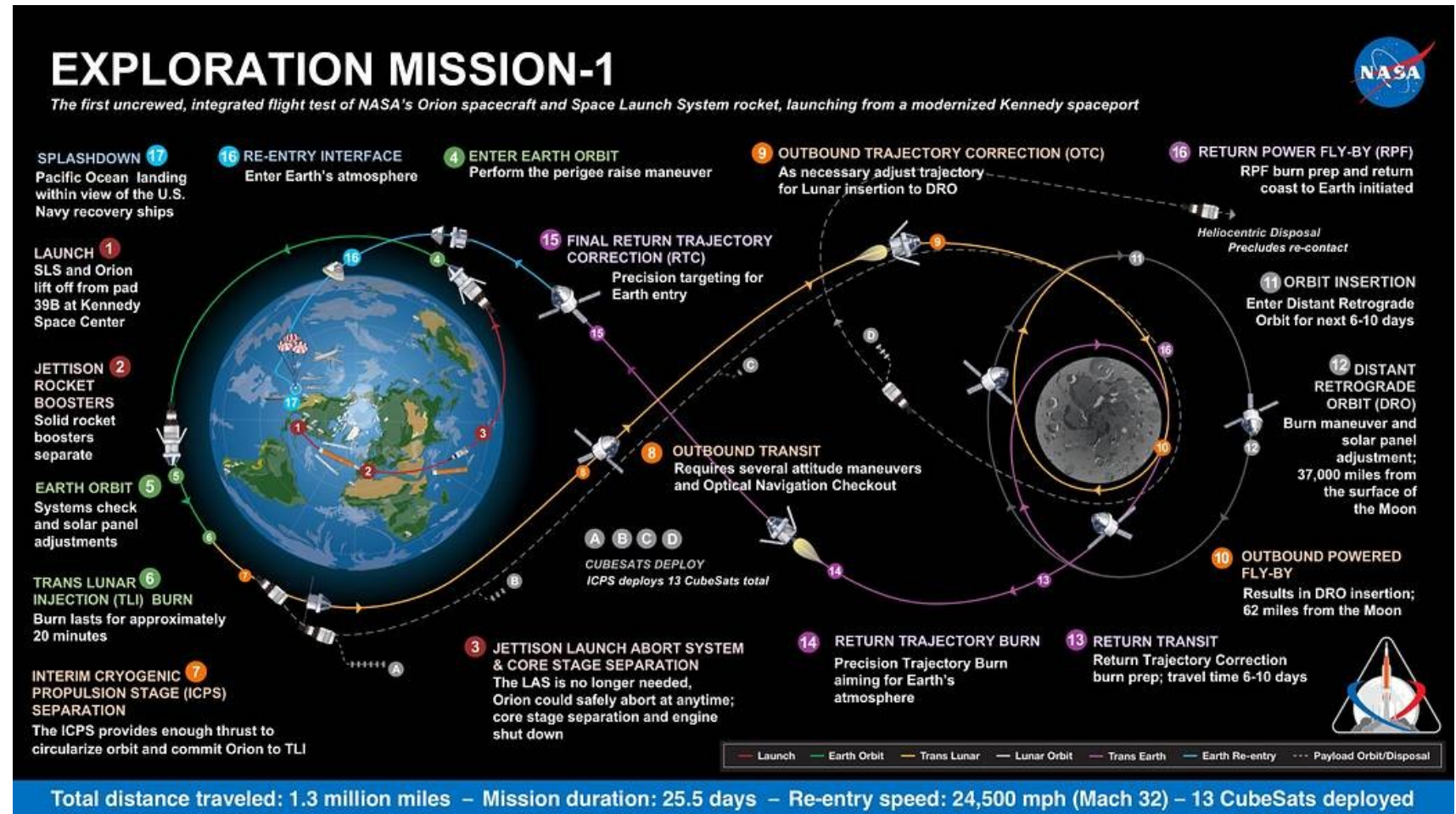


Circular Orbit About the Earth

Why Study Orbits?

Orbits are the paths a spacecraft takes in space;

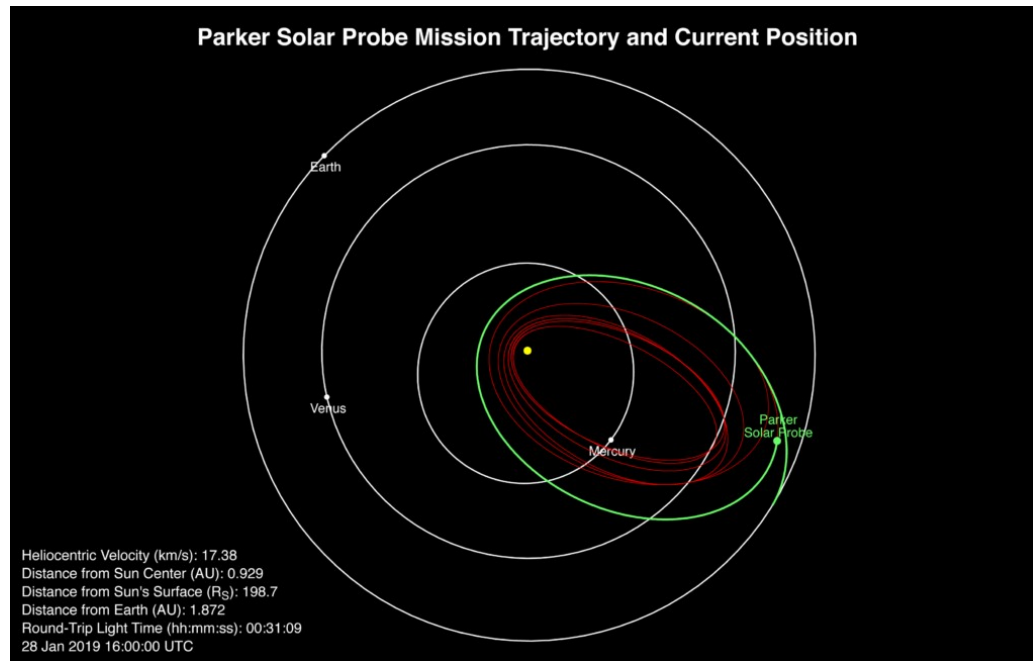
They are used to go from one location in space to another, for example, from the Earth to the Moon, and back.



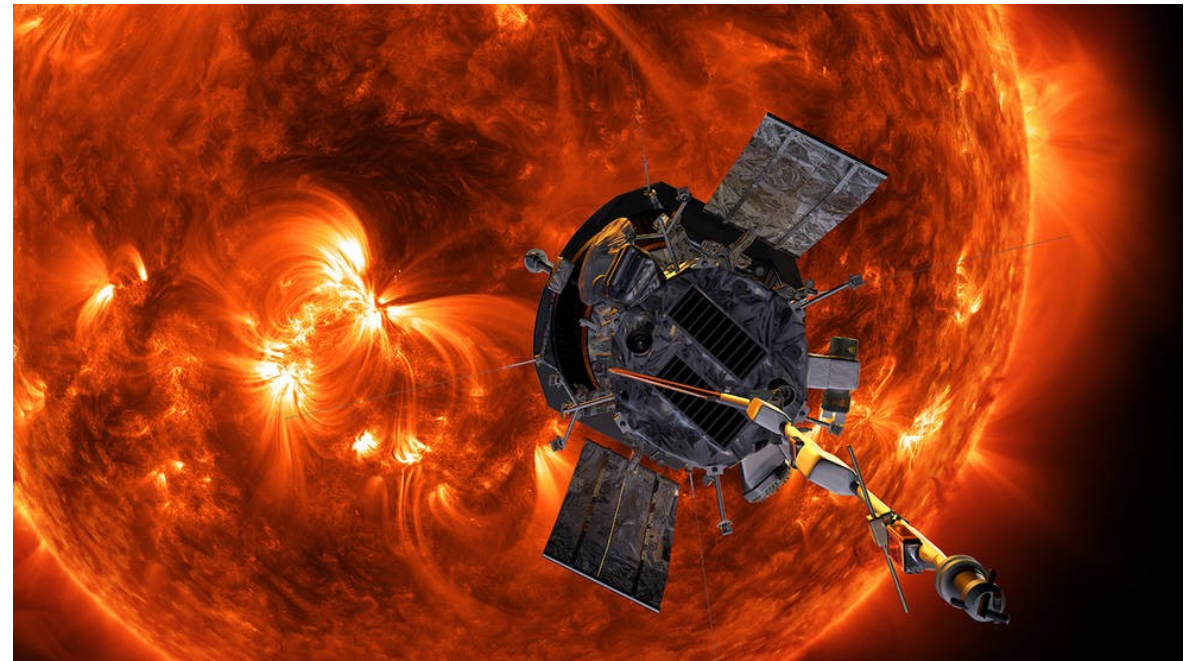
Orion Exploration Mission – 1 (EM-1)

Why Study Orbits?

It is important to understand orbits to determine the environment a spacecraft experiences, how long it takes to travel to the destination, etc.



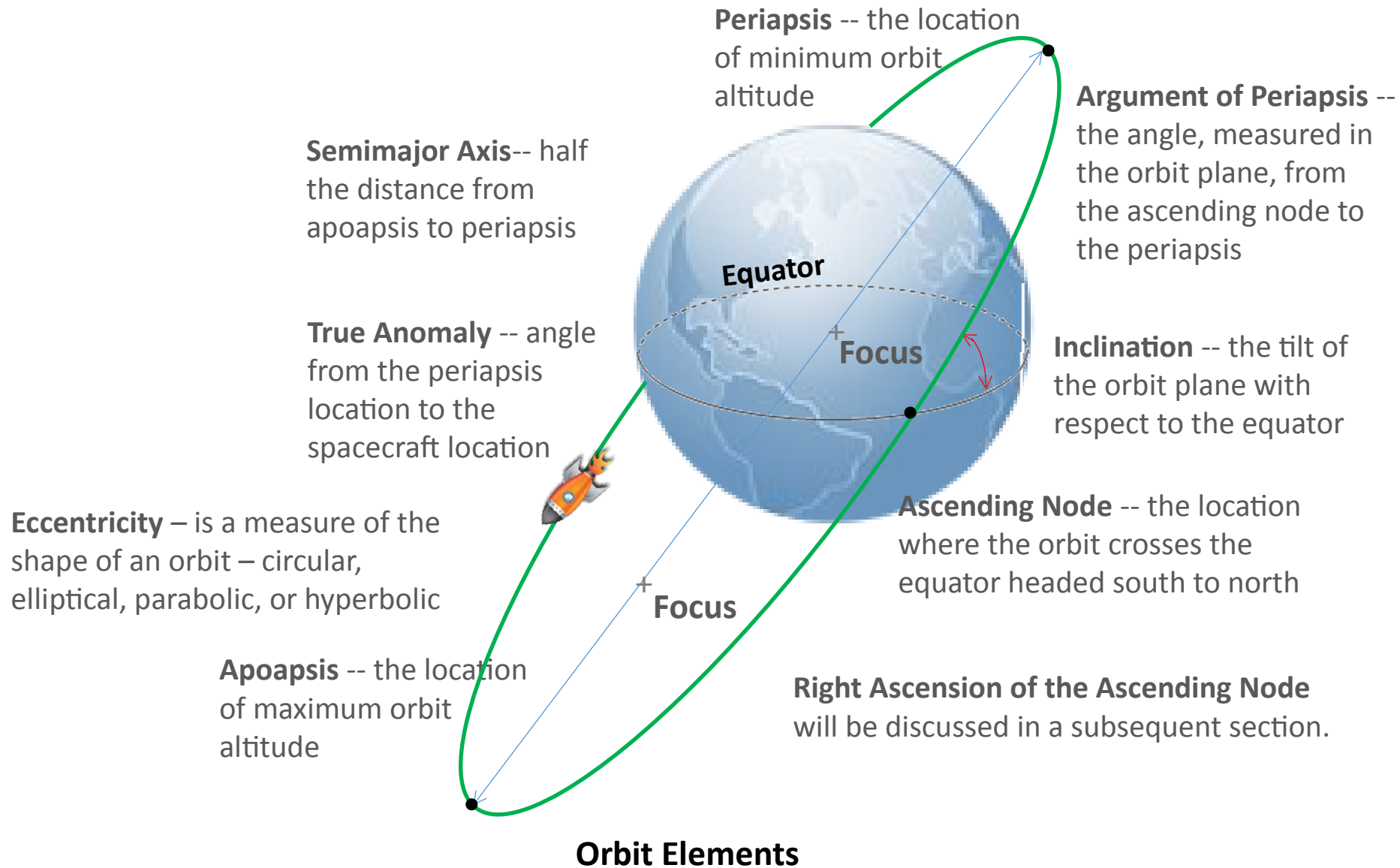
Parker Solar Probe Trajectory



Parker Solar Probe Spacecraft

Image Credits: <https://blogs.nasa.gov/parkersolarprobe/>
<https://www.nasa.gov/press-release/goddard/2018/scientist-to-discuss-heliophysics-parker-solar-probe>

Anatomy of an Orbit



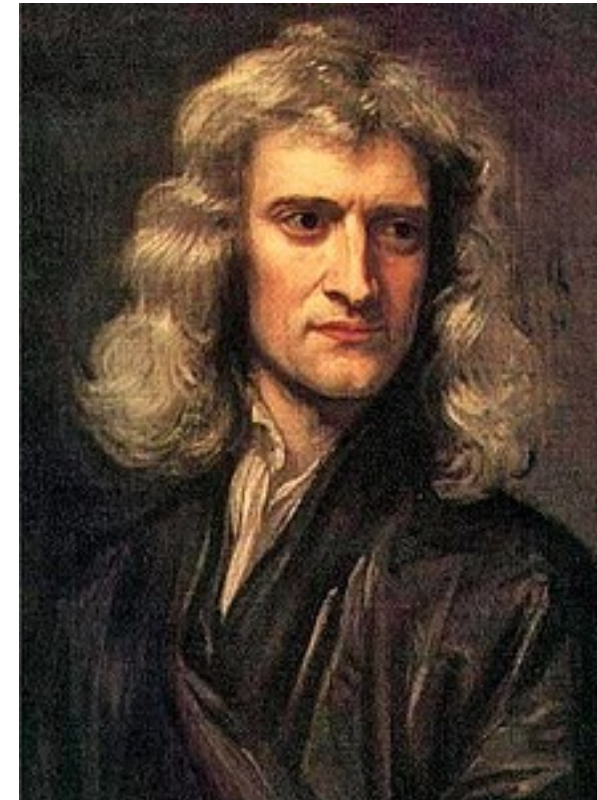
Johannes Kepler, Tycho Brahe, and Isaac Newton



Brahe, 1546-1601



Kepler, 1571-1630



Newton, 1643 (1642 O.S.) - 1727

Image Credits: https://en.wikipedia.org/wiki/Johannes_Kepler
https://en.wikipedia.org/wiki/Tycho_Brahe
https://en.wikipedia.org/wiki/Isaac_Newton

Kepler's First Law

The orbit of each planet is an ellipse*, with the sun as a focus.

*Actually, other orbit shapes are possible and are described by the “conic sections.”

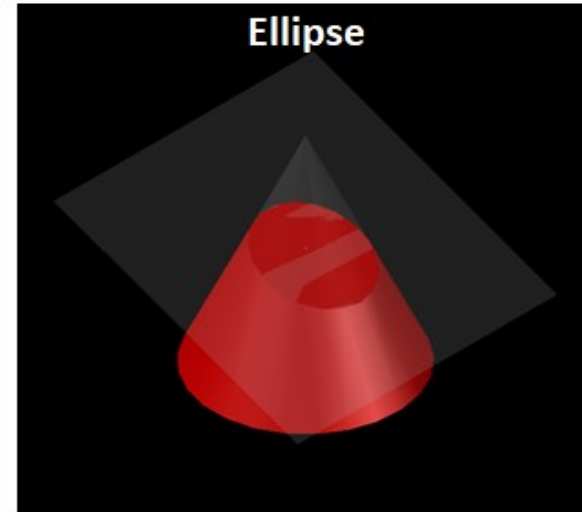
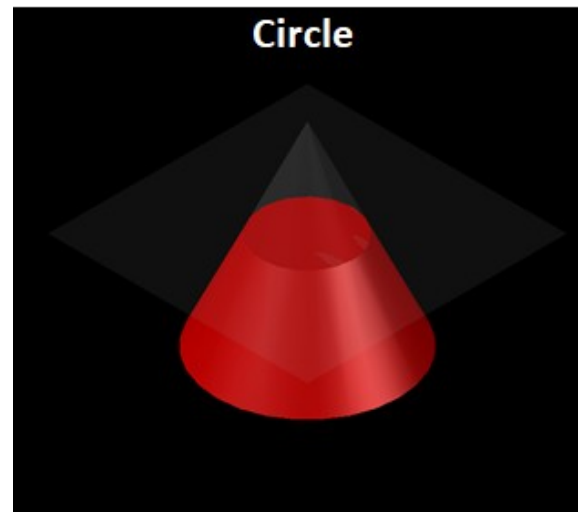
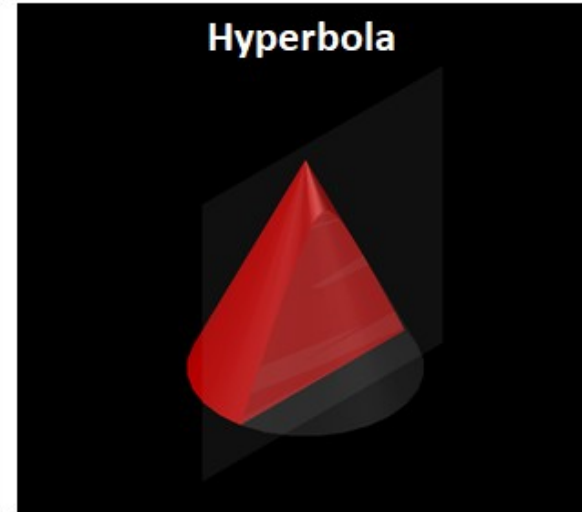
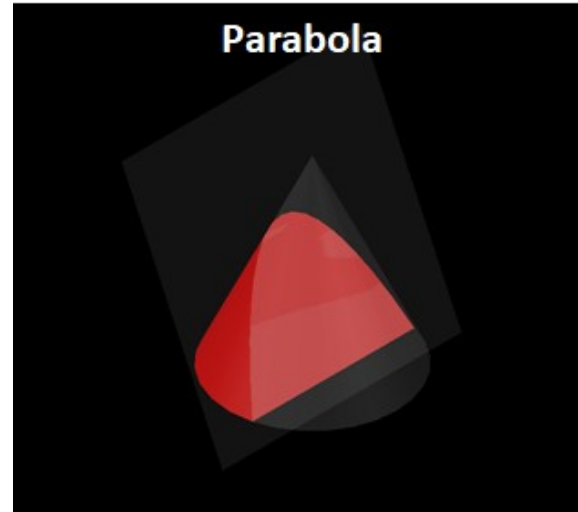


Orbits of the Inner Planets

Conic Sections

Take a cone and cut it with a plane at different angles

The shapes appearing at the cutting plane are also the shapes of the orbits.



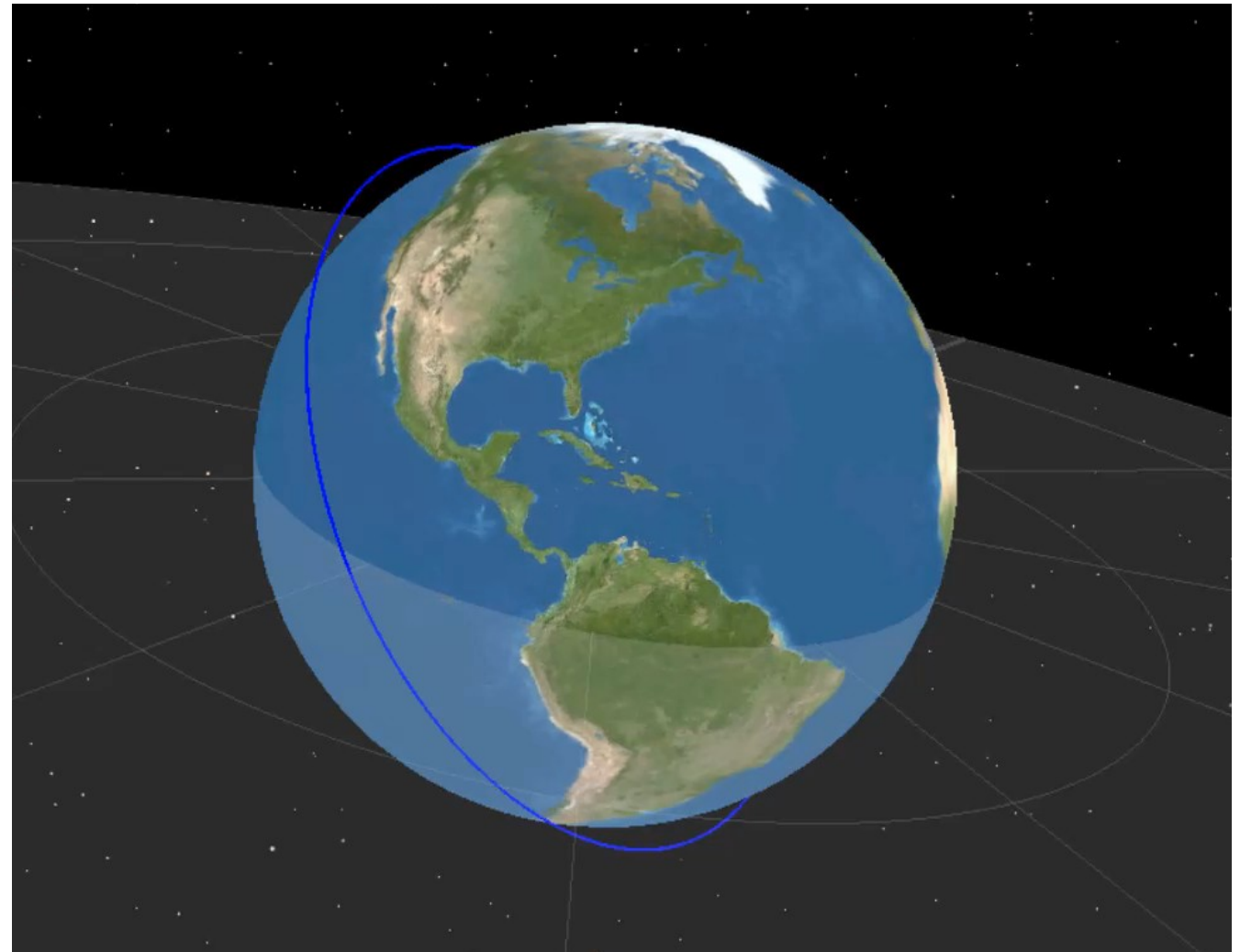
Circular Orbit

Circular orbits maintain a constant distance from their central body;

Orbit eccentricity, ;

Many Earth satellites have circular orbits;

The best example is the International Space Station.



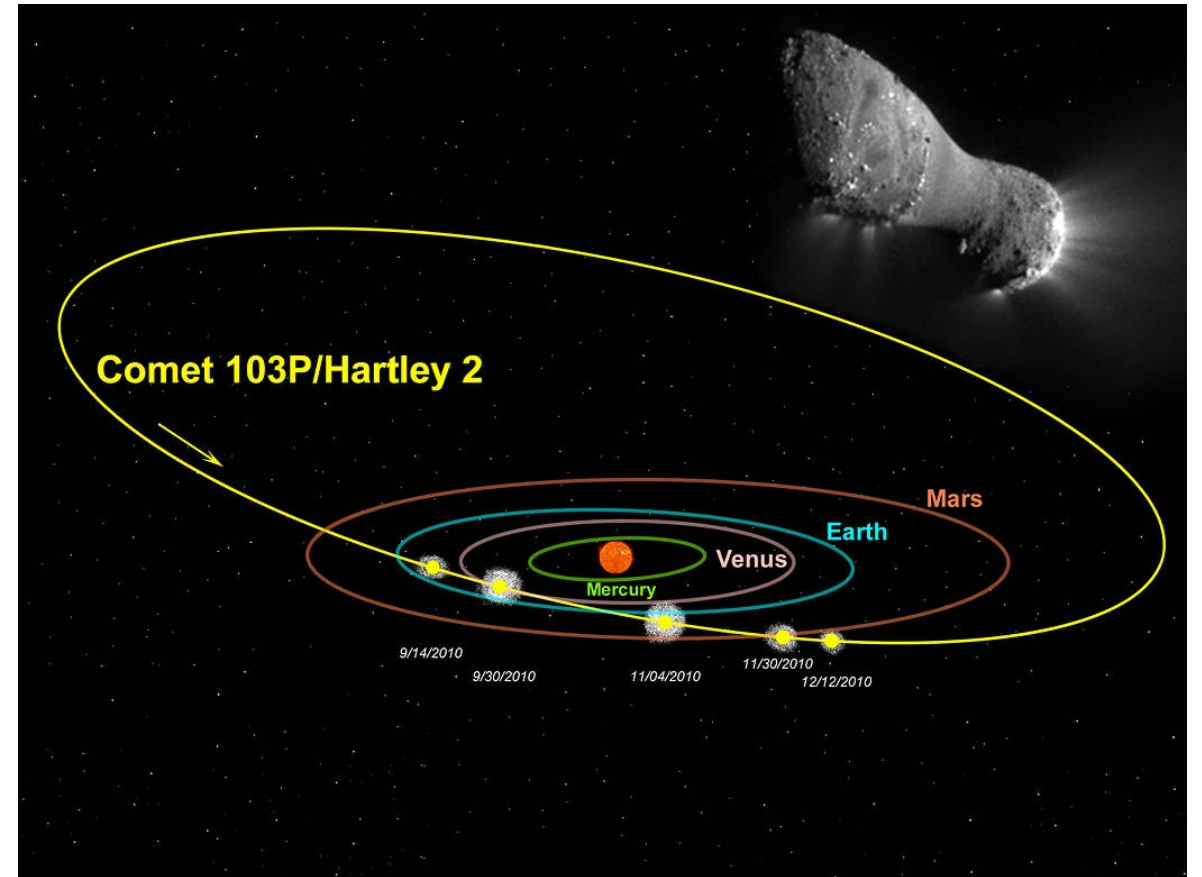
Example: International Space Station Orbit

Elliptical Orbit

Orbit eccentricity,

An elliptical orbit traces out an ellipse with the central body at one focus;

Comets such as 103P/Hartley 2 are in elliptical orbits with a period of 6.46 years (.

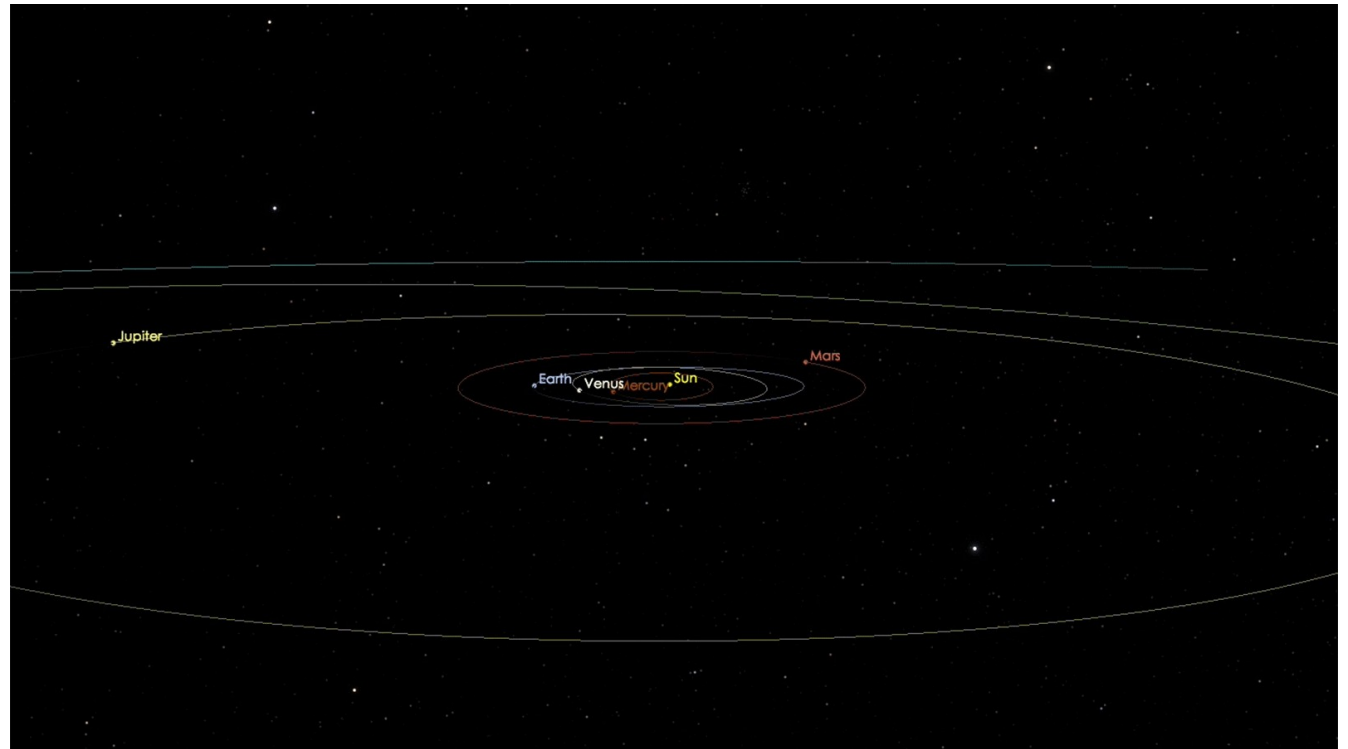


Example: Comet Hartley 2 Orbit

Hyperbolic Orbit

Orbit eccentricity, ;

For objects passing through the solar system, a hyperbolic orbit suggests an interstellar origin -- Asteroid Oumuamua was discovered in 2017 and is first and only object of this type .

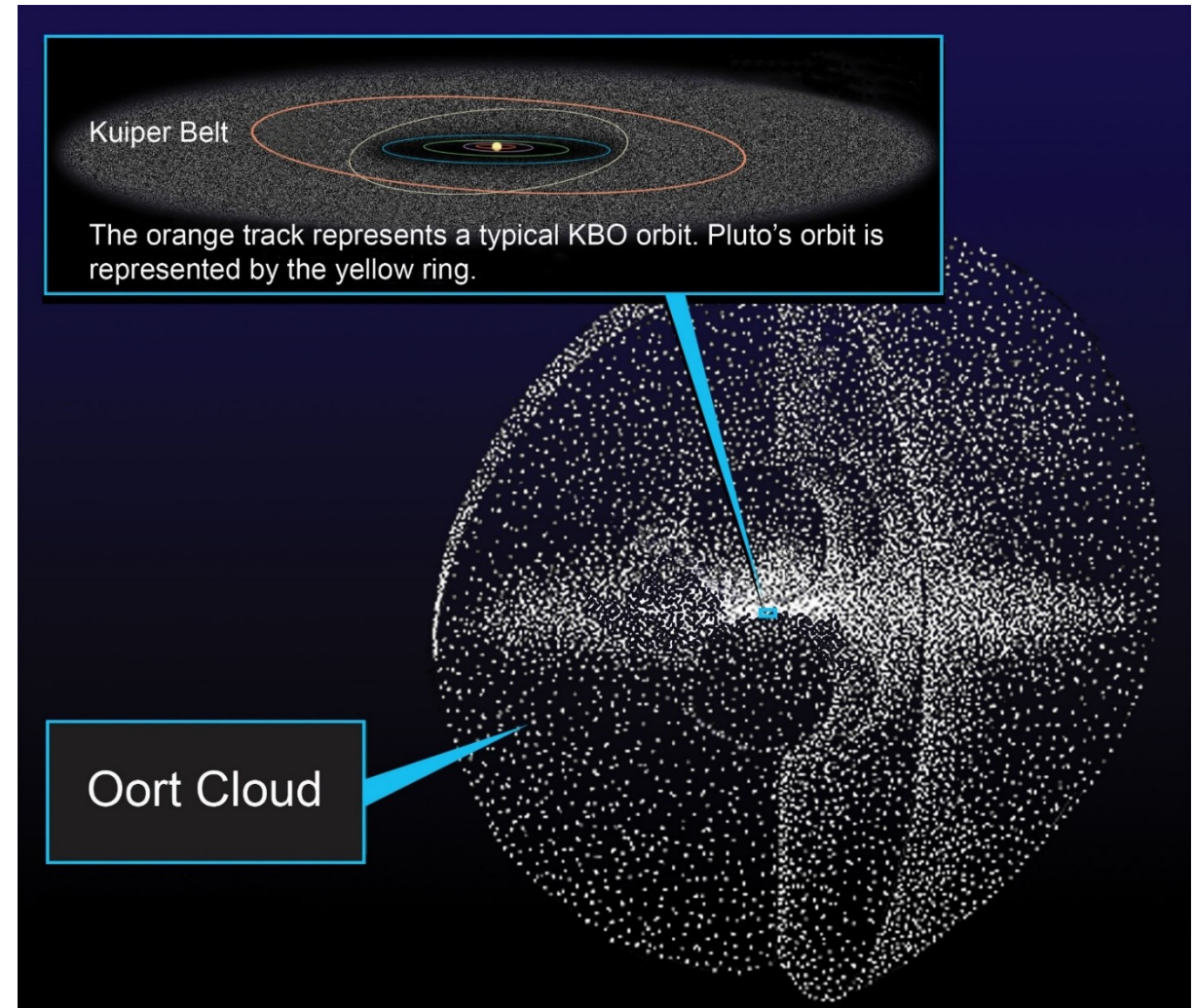


Example: Asteroid Oumuamua

Parabolic Orbit

Orbit eccentricity, ;

“Within observational uncertainty, long term comets all seem to have parabolic orbits. That suggests they are not truly interstellar, but are loosely attached to the Sun. They are generally classified as belonging the *Oort cloud* on the fringes of the solar system, at distances estimated at 100,000 AU.”



The Oort Cloud

Source: <https://www-spod.gsfc.nasa.gov/stargaze/Scometes.htm>

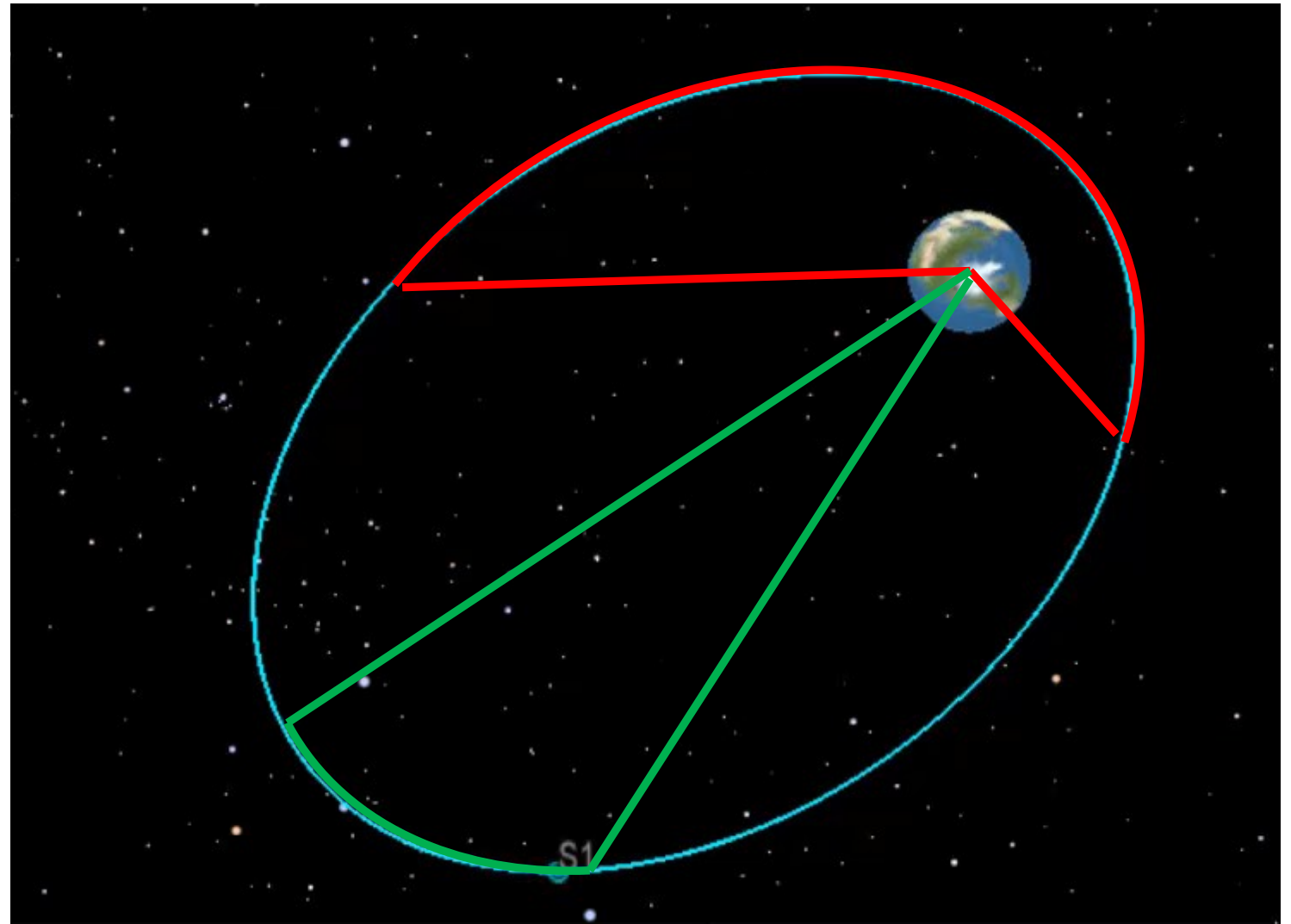
Image Credit: <https://solarsystem.nasa.gov/resources/491/oort-cloud/>

Kepler's Second Law

The line joining the planet to the sun sweeps out equal areas, in equal times, .

$$\Delta t_1 = \Delta t_2$$

$$A_1 = A_2$$

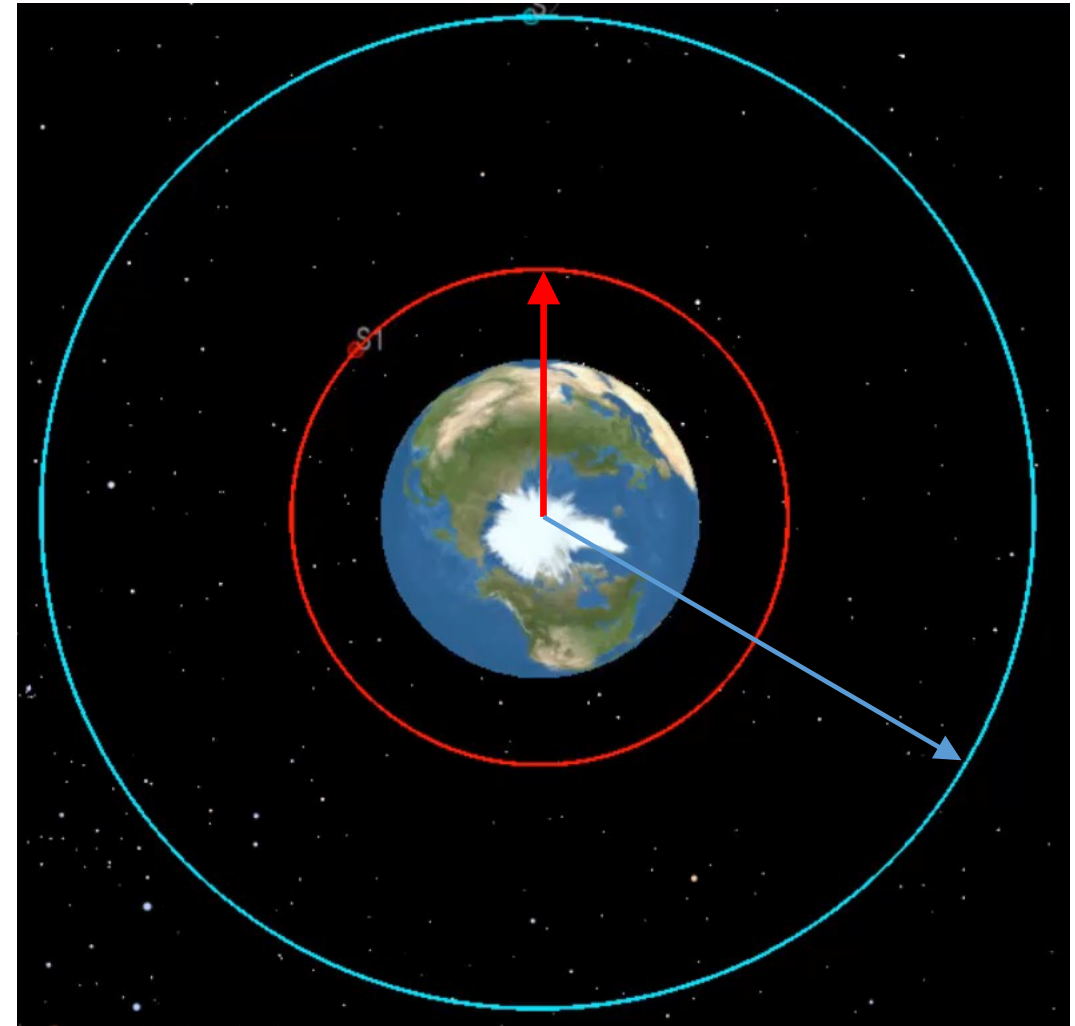


Demonstration of Constant "Areal" Velocity

Kepler's Third Law

The square of the period, of a planet is proportional to the cube of its mean distance, to the sun (or its central body).

For the orbits at the right:

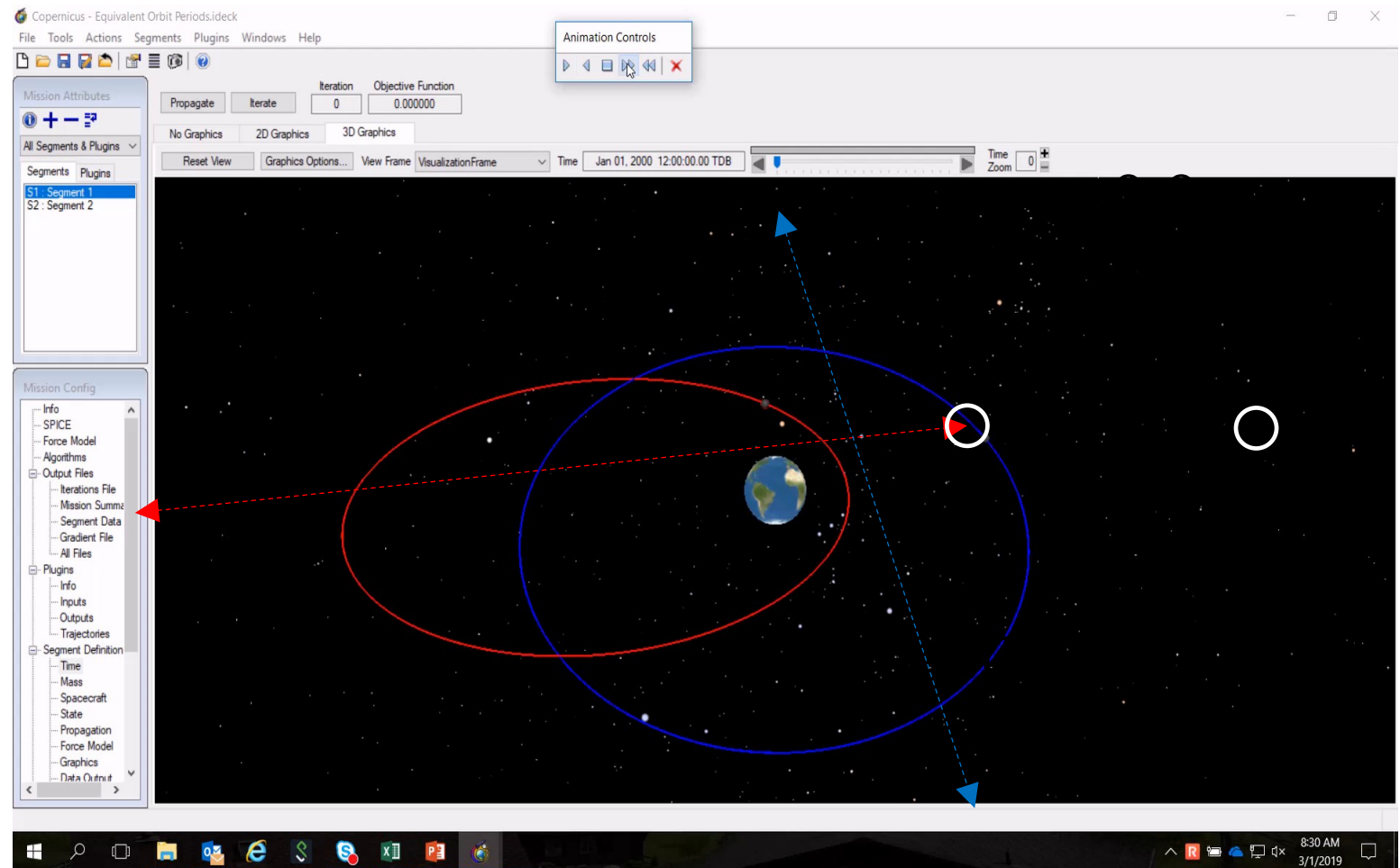


Orbits with Different Semimajor Axes

Kepler's Third Law

As long as the semimajor axis, is the same, the orbit period will be the same;

Each orbit has a different eccentricity, but both orbits have the same .



Two Orbits with the Same Period



Thank You, Sir Isaac Newton!

The governing differential equation for two body astrodynamics is derived from two laws originated by Sir Isaac Newton.

Newton's Second Law

Newton's Law of Gravitation



Thank You, Sir Isaac Newton!

For two bodies that are moving only under gravitational force, we can equate both expressions:

and we can express the acceleration, in terms of radial acceleration, :



Thank You, Sir Isaac Newton!

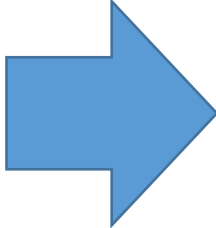
Rearrange...

Simplify noting that $\frac{1}{x}$ cancels, $\frac{1}{x^2}$ combines in the denominator and :



Thank You, Sir Isaac Newton!

There's A LOT of information to be squeezed out of this equation including...

$$\ddot{\mathbf{r}} + \frac{\mu}{r^3} \mathbf{r} = 0$$


- Conservation of Specific Mechanical Energy

$$\mathcal{E} = \frac{v^2}{2} + \left(c - \frac{\mu}{r} \right)$$

- Conservation of Specific Angular Momentum

$$\bar{\mathbf{h}} = \bar{\mathbf{r}} \times \bar{\mathbf{v}}$$

- Kepler's 1st Law: Trajectory

$$r = \frac{a(1 - e^2)}{1 + e \cos \nu}$$

- Kepler's 2nd Law: Constant "Areal" Velocity

$$\frac{1}{2} r^2 \dot{\theta} = \text{constant}$$

- Kepler's 3rd Law: Orbit Period

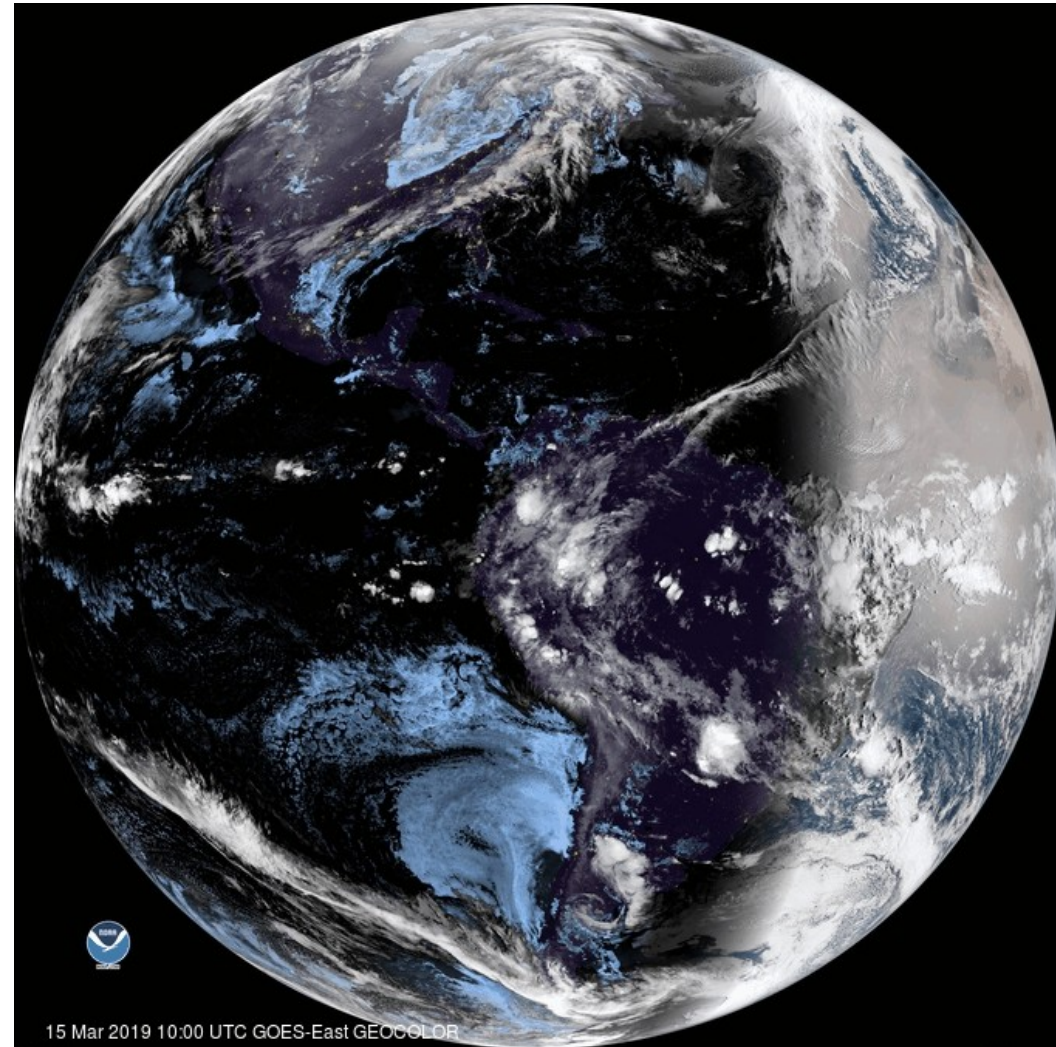
$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

Example: Geostationary Orbit

A geostationary orbit has an orbit period of 24 hours with an orbit inclination of 0 degrees;

In this orbit, the spacecraft appears fixed over a specific location on Earth's equator;

Geostationary orbits are used for communications satellites and weather satellites.



Earth as Seen from GOES 16

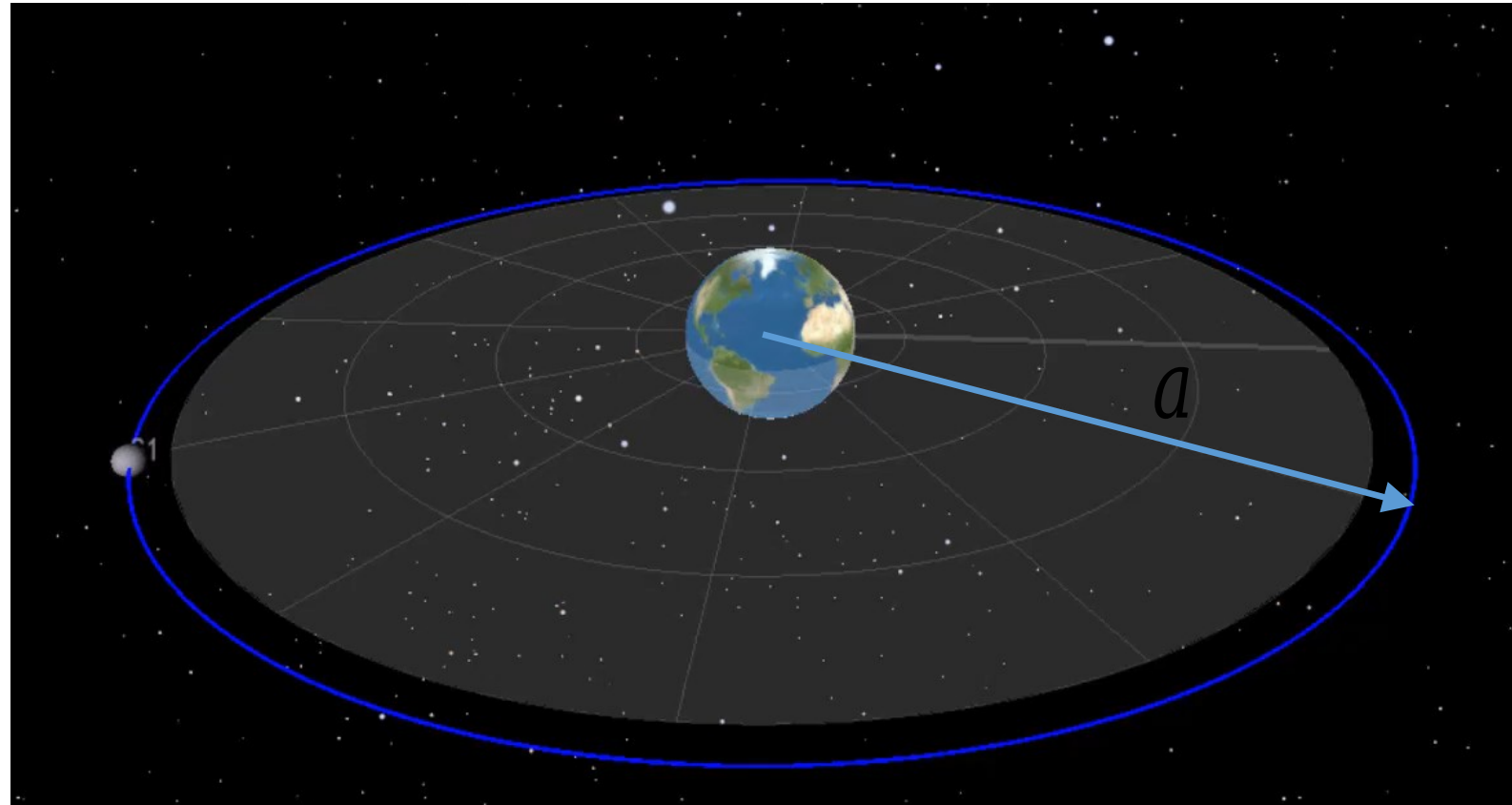
Example: Geostationary Orbit

At what altitude must the satellite be positioned to be geostationary?

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

$$a = \sqrt[3]{\frac{\mu T^2}{4\pi^2}}$$

$$h = a - r_e = 35786 \text{ km}$$



Geostationary Orbit



Perturbed Orbits

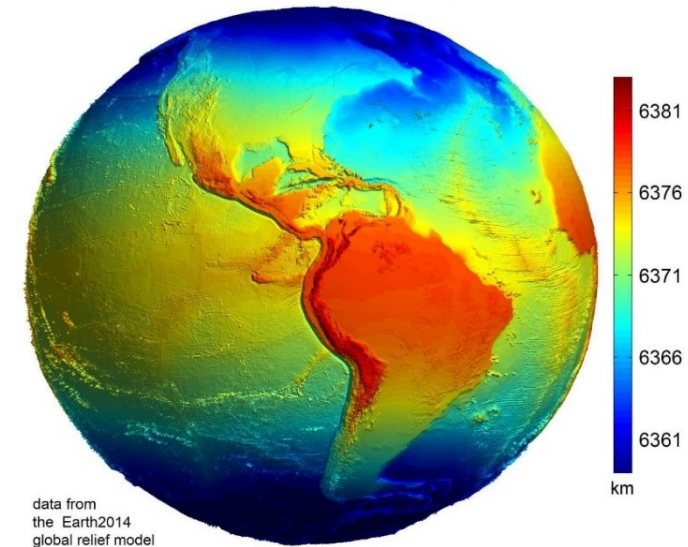
Recall our previous equation was derived for a body moving under the influence of ONLY the gravity of a central body:

Some interesting things happen when there is a perturbing force such that:

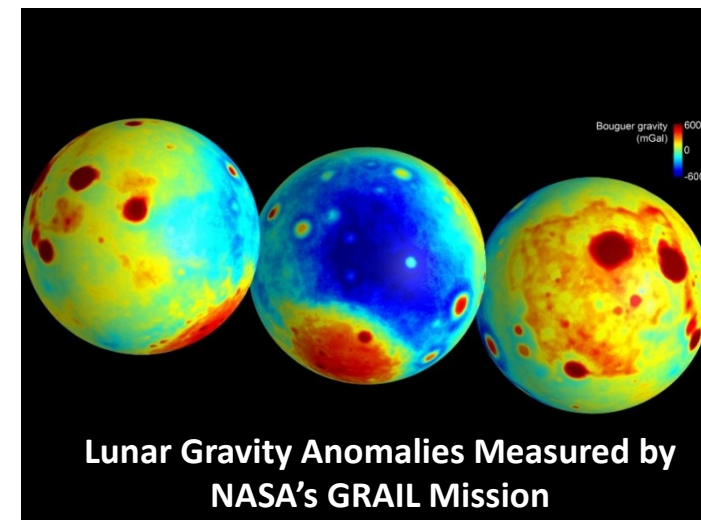
Perturbed Orbits

There are many forces that can perturb an orbit including:

- Spherical harmonics
- Drag
- Radiation pressure
- Other celestial bodies
- Tides
- Mass concentrations
- etc.



Equatorial Bulge from Earth 2014 Global Relief Model



Perturbations

Earth is not a perfect sphere -- it is oblate and has a slight bulge in the equatorial region and this imperfection gives rise to some major orbit perturbations;

Precession of the Ascending Node:

$$\frac{d\Omega}{dt} = \dot{\Omega} = \frac{-3 J_2 n r_e^2 \cos i}{2 a^2 (1 - e^2)^2}$$

Precession of the Periapsis:

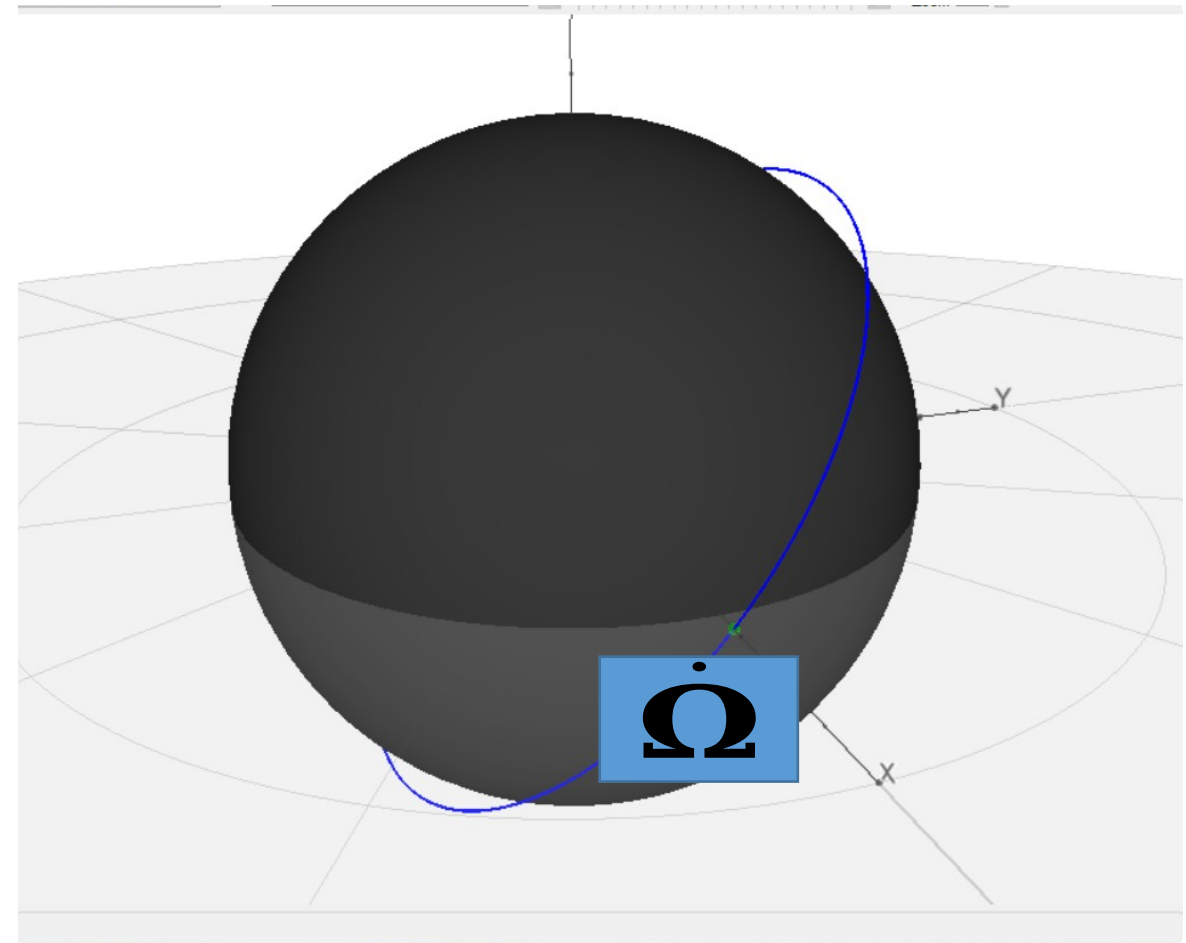
$$\frac{d\omega}{dt} = \dot{\omega} = \frac{3 J_2 n r_e^2}{4 a^2 (1 - e^2)^2} (4 - 5 \sin^2 i)$$

Note: For Earth,

Perturbations: Precession of the Ascending Node

The oblateness perturbation causes the ascending orbit ascending node to precess at the rate:

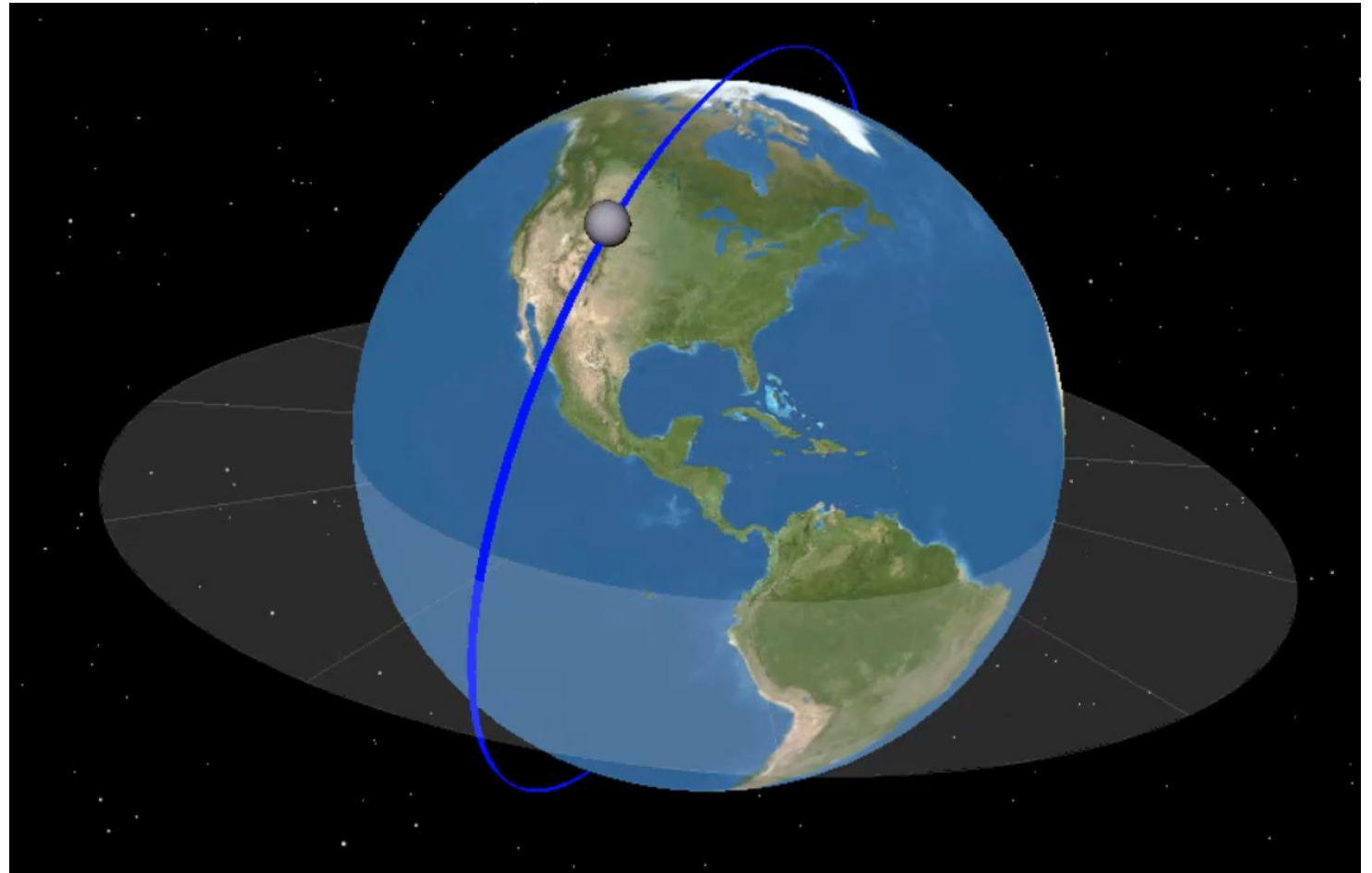
For orbit inclinations, $i < 90^\circ$, precession is westward – when $i > 90^\circ$, precession is eastward.



Precession of the Orbit Ascending Node

Example: Sun Synchronous Orbit

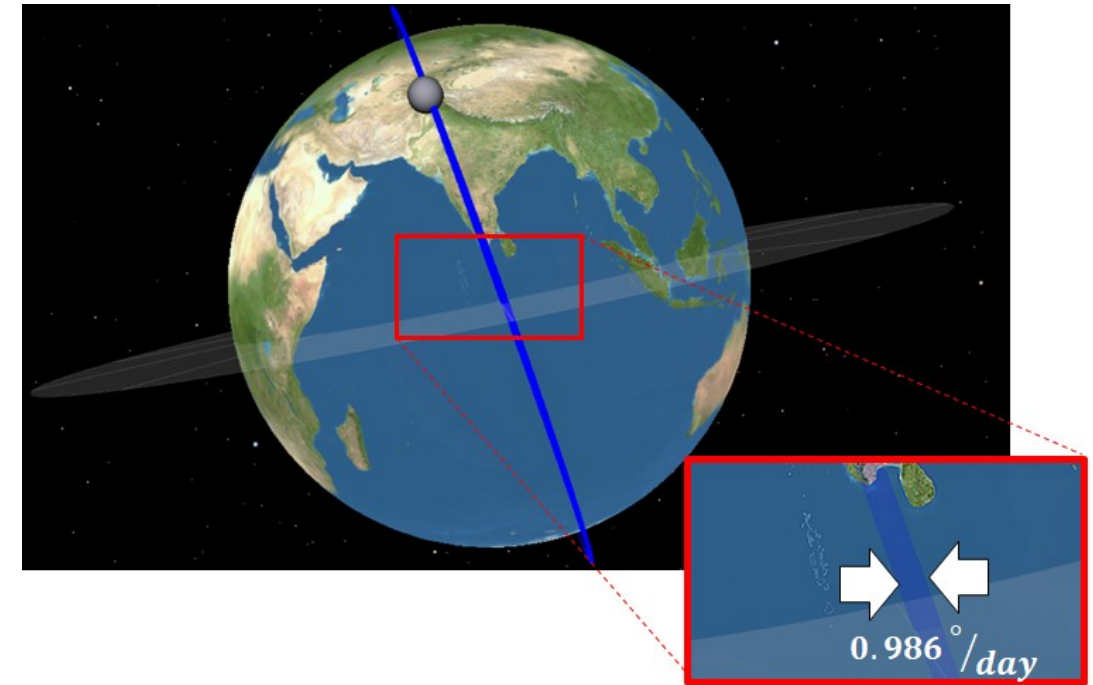
Sun synchronous orbits are useful for Earth observation spacecraft because they are designed to pass over sunlit portions of the planet at the same “local solar” time – this results in consistent illumination conditions for observations.



Sun Synchronous Orbit

Example: Sun Synchronous Orbit

To achieve this, the orbit ascending node needs to maintain a consistent offset from the orbit subsolar point – this is accomplished by moving the orbit ascending node at the same rate the sun appears to move across the celestial sphere --to meet this condition:



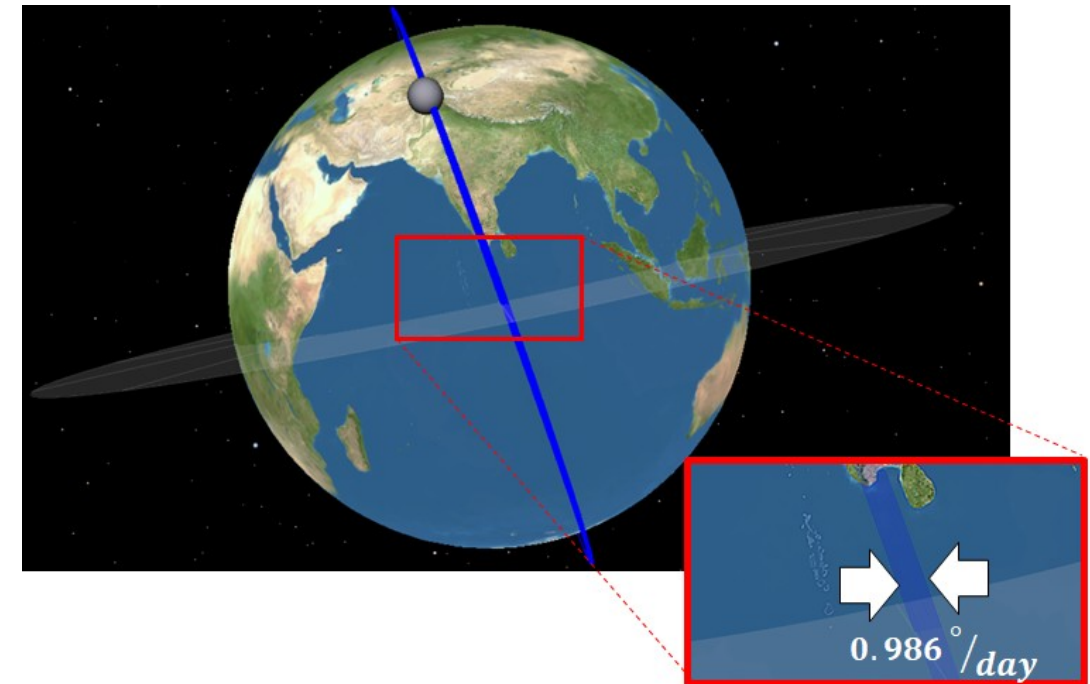
Daily Precession of the Ascending Node

Example: Sun Synchronous Orbit

Assuming a circular orbit we see that combinations of a and i may be used to specify the desired orbit.

$$\dot{\Omega} = \frac{-3 J_2 n r_e^2 \cos i}{2 a^2 (1 - e^2)^2}$$

One such combination is $a = 7000$ km and $i = 98.6^\circ$ and



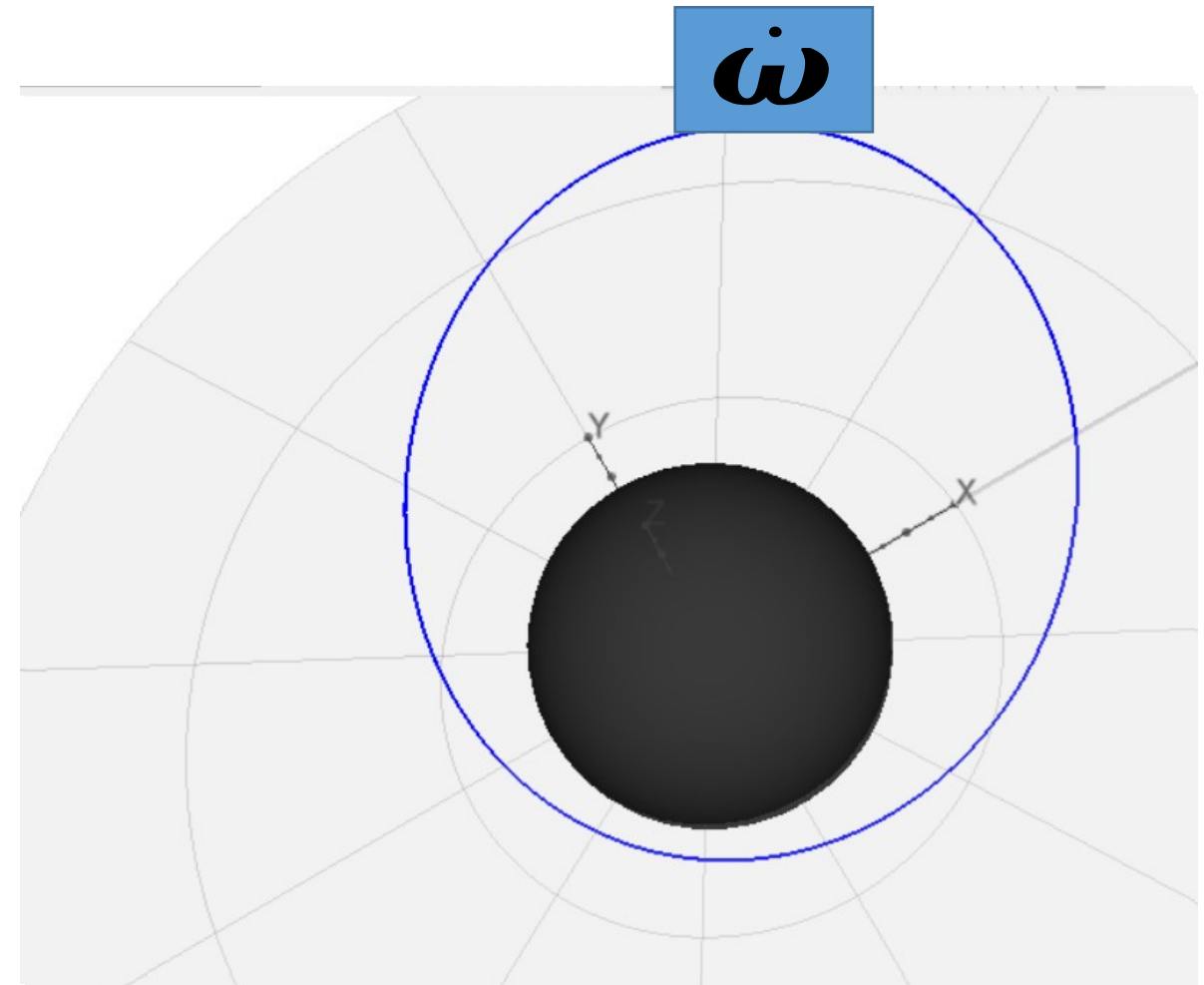
Daily Precession of the Ascending Node

$$0.986 \frac{^\circ}{day}$$

Perturbations: Precession of the Periapsis

The oblateness perturbation also causes the periapsis and apoapsis to precess at the rate:

Precession is positive when $\dot{\omega} > 0$ and negative when $\dot{\omega} < 0$.



Precession of the Orbit Periapsis



Example: Molniya Orbit

Communication satellites in geostationary orbits over the equator are of little use to those living at higher latitudes because they appear low in the sky;

A satellite orbiting at a higher inclination is desired;

However, it won't appear to remain over the same point on the ground;

A Molniya orbit may be used to cause the spacecraft to dwell at nearly the same point for long periods of time.



Example: Molniya Orbit

In order to “lock” the location of the apoapsis and periapsis in place, we desire an orbit where the rate of movement of the periapsis goes to zero:

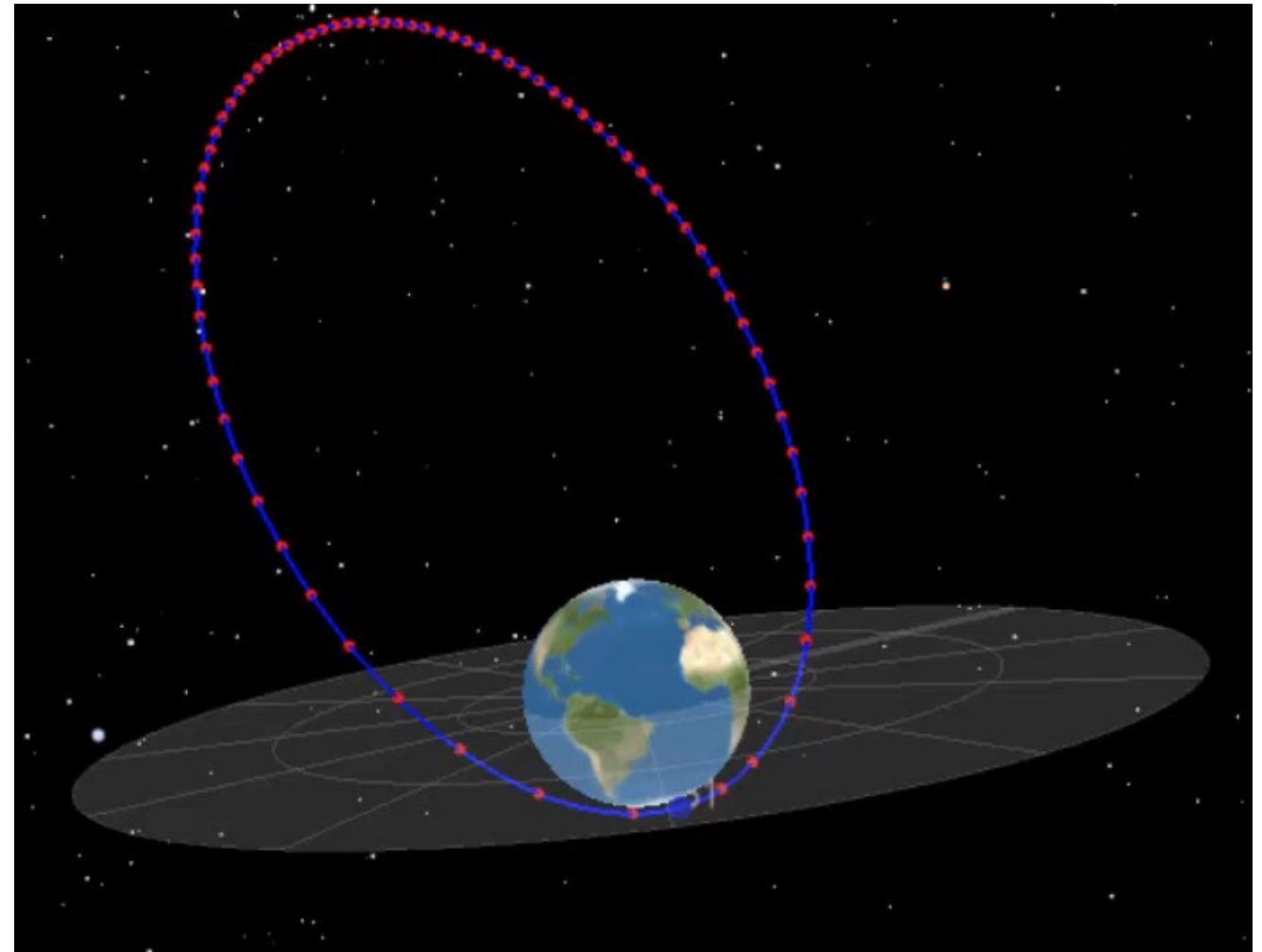
We see from the equation that this happens when:

This is true when the inclination is

Example: Molniya Orbit

The spacecraft spends much of its orbit at high altitude, at high latitude, moving slowly -- appearing nearly stationary when near apoapsis;

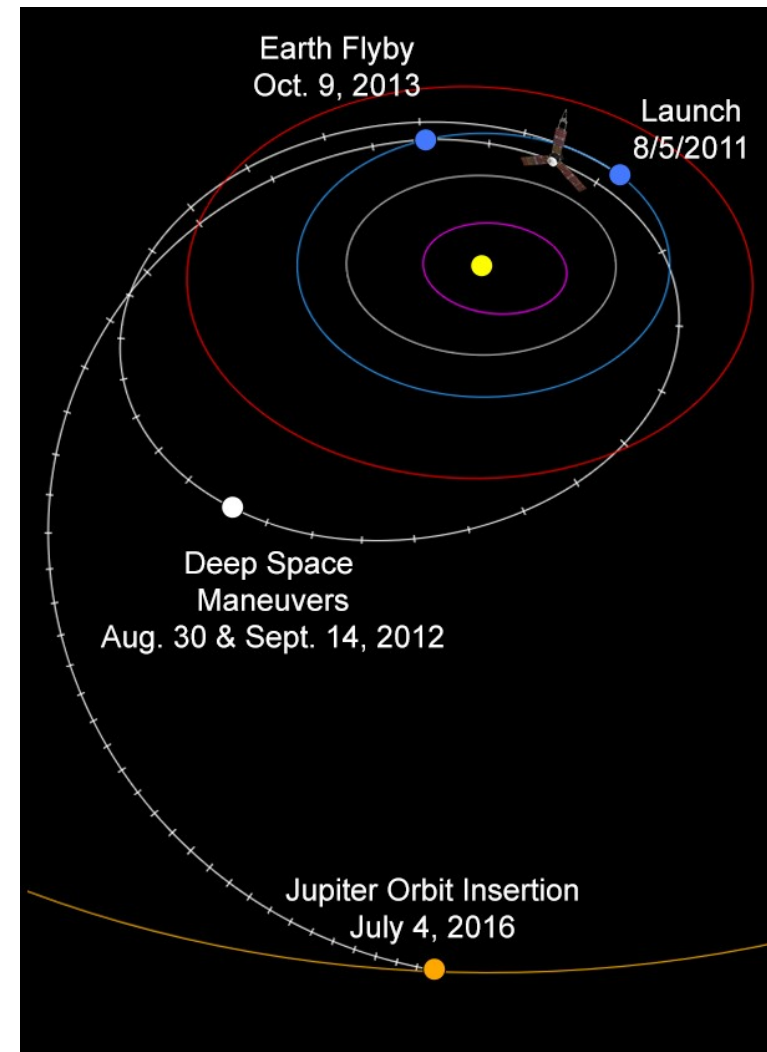
Orbit is designed so that apoapsis stays “locked” into the same position over time.



Molniya Type Orbit (Time points in red are 10 minutes apart)

Other Orbits: Gravity Assist Orbit

Spacecraft orbits may be redirected using gravity assist maneuvers where a close fly-by of a planet is used to change the direction of and orbit and add energy to it.

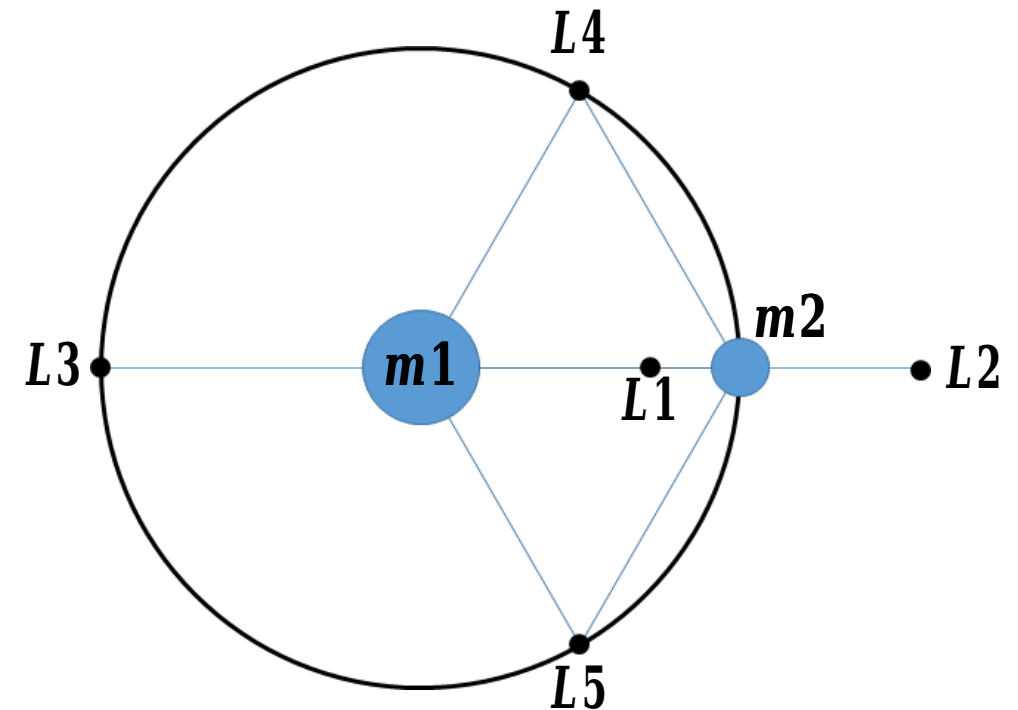


Juno Spacecraft Trajectory

Other Orbits: The Restricted Three-Body Problem

When two large masses, m_1 and m_2 , are orbiting one another, regions in space can serve as gravitational nodes where spacecraft or other celestial bodies can collect – these are called Lagrange points;

L_1 , L_2 , and L_3 are unstable.
 L_4 and L_5 are stable.

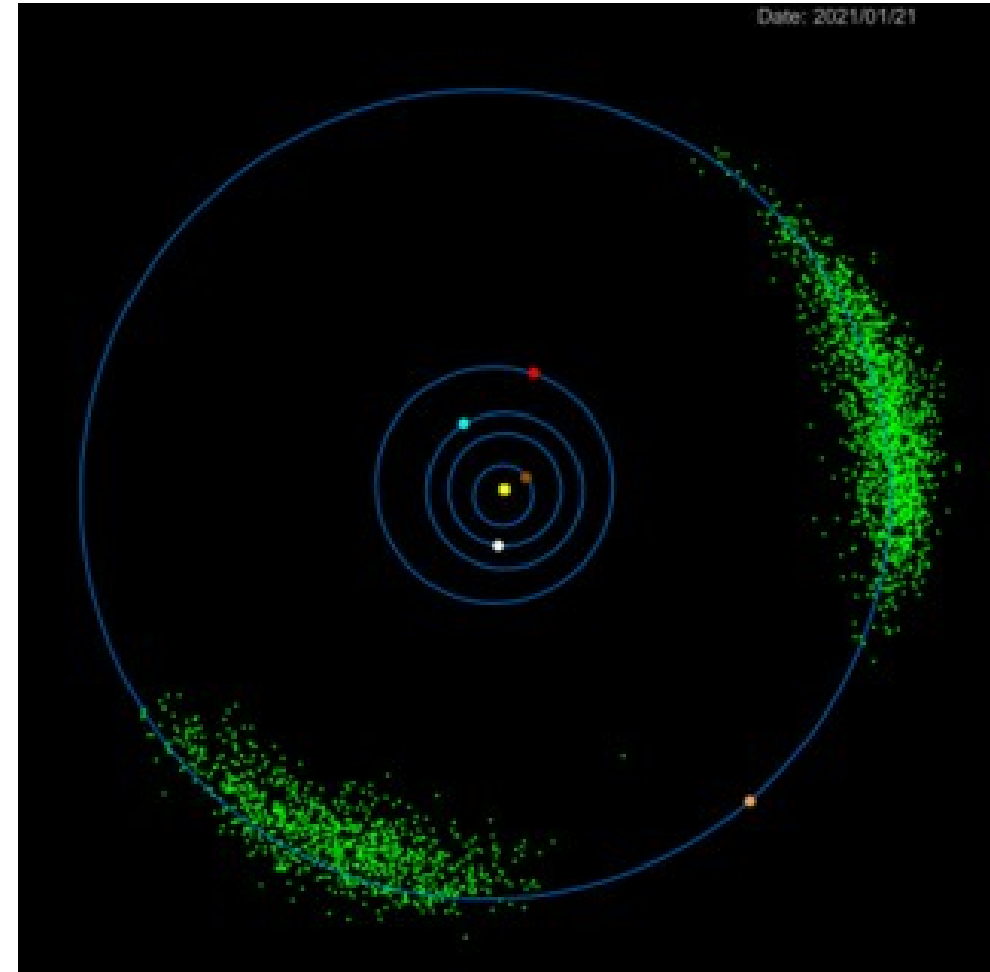


Dynamics of the Three-Body System

Other Orbits: Three-Body Orbits

In 1772, using three-body assumptions, Joseph-Louis Lagrange believed that, because the L4 and L5 points are stable, asteroids might be trapped near these points;

The first confirmed observation of a Jupiter Trojan was made by Max Wolf in 1906.

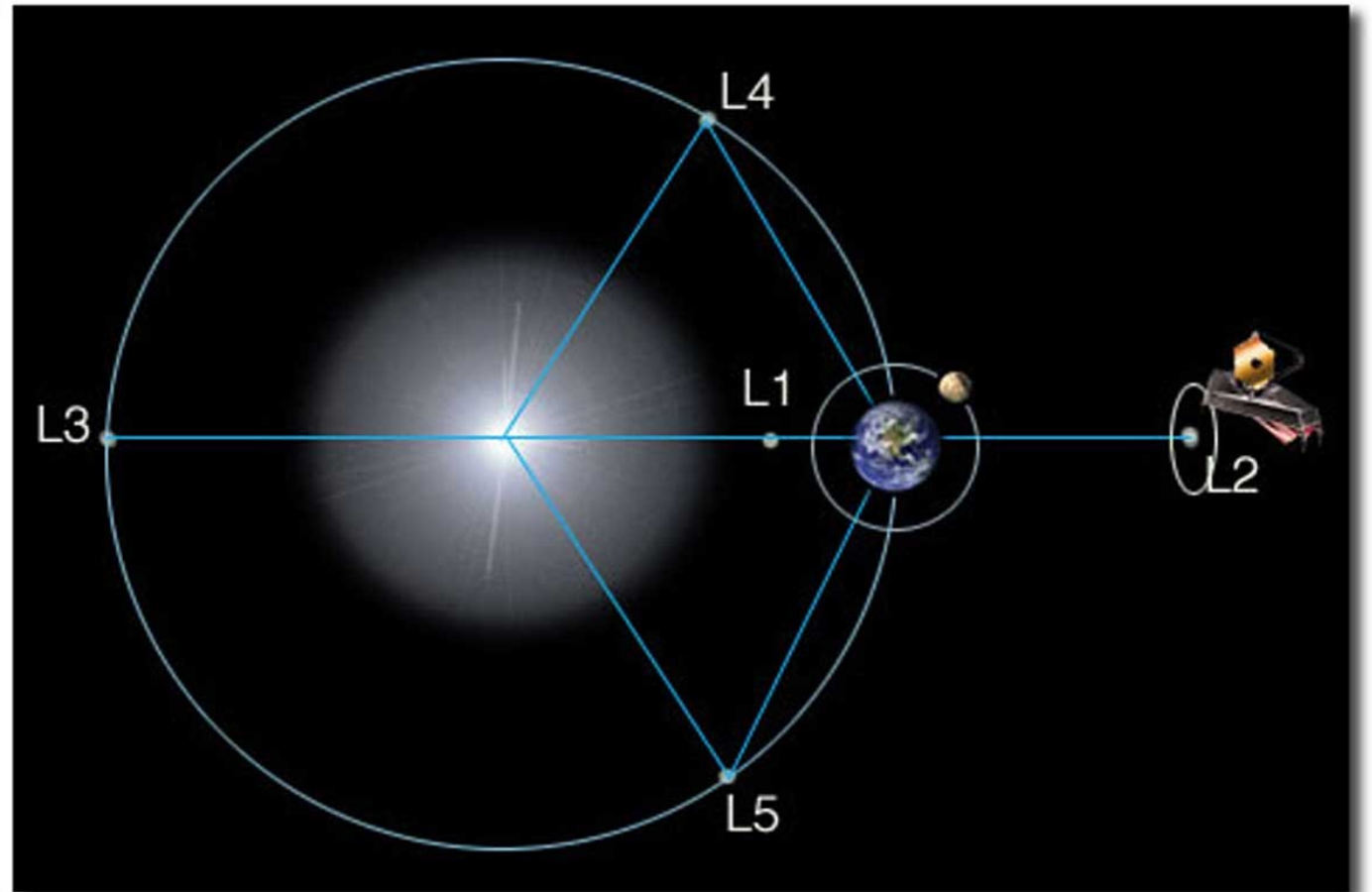


Jupiter's Trojan Asteroids

Other Orbits: Three-Body Orbits

Lagrange points are also used for spacecraft;

The James Webb Space Telescope (JWST) will be located at the Earth-Moon L2 point.



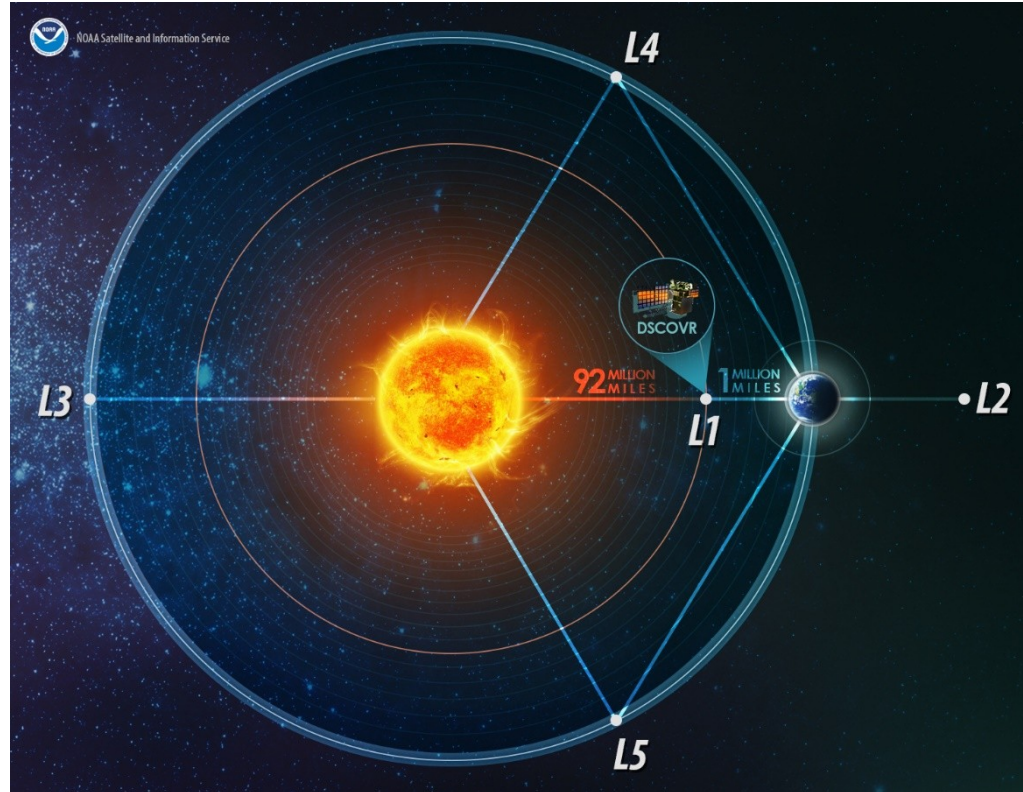
JWST Orbit at the Earth-Moon L2 Point

Image Credit: NASA

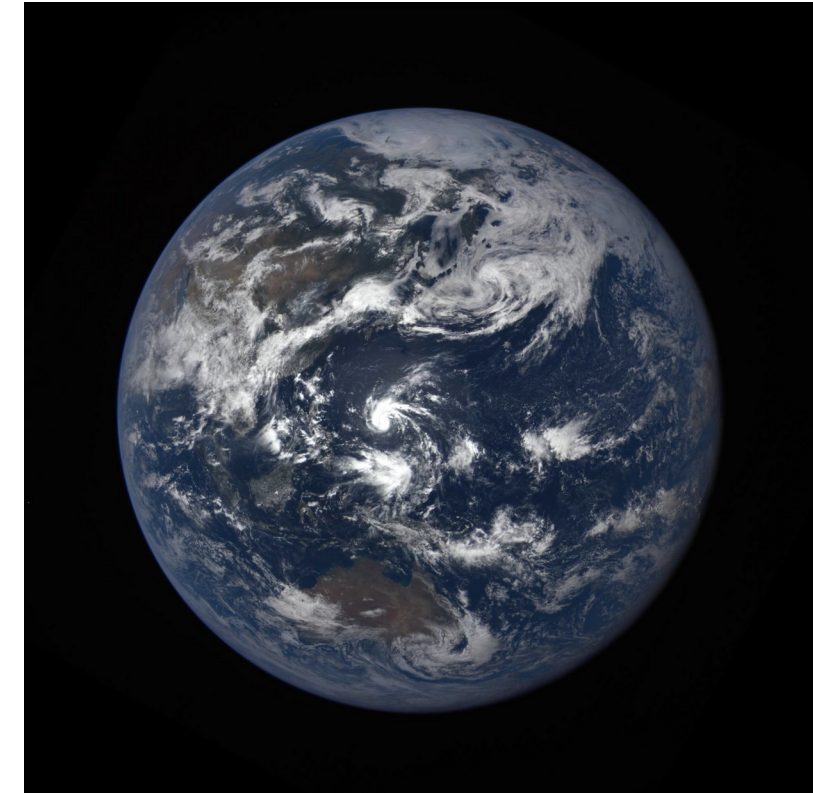
https://www.nasa.gov/images/content/463480main_lagrange_point_lg_1.jpg

Other Orbits: Three-Body Orbits

The DSCOVR spacecraft is located at the Sun-Earth L1 point.



DSCOVR Spacecraft at the Sun-Earth L1 Point



The Earth-Moon System as Seen from the DSCOVR Spacecraft

Image Credit: NOAA

Video Credit: DSCOVR: EPIC Team



Questions?