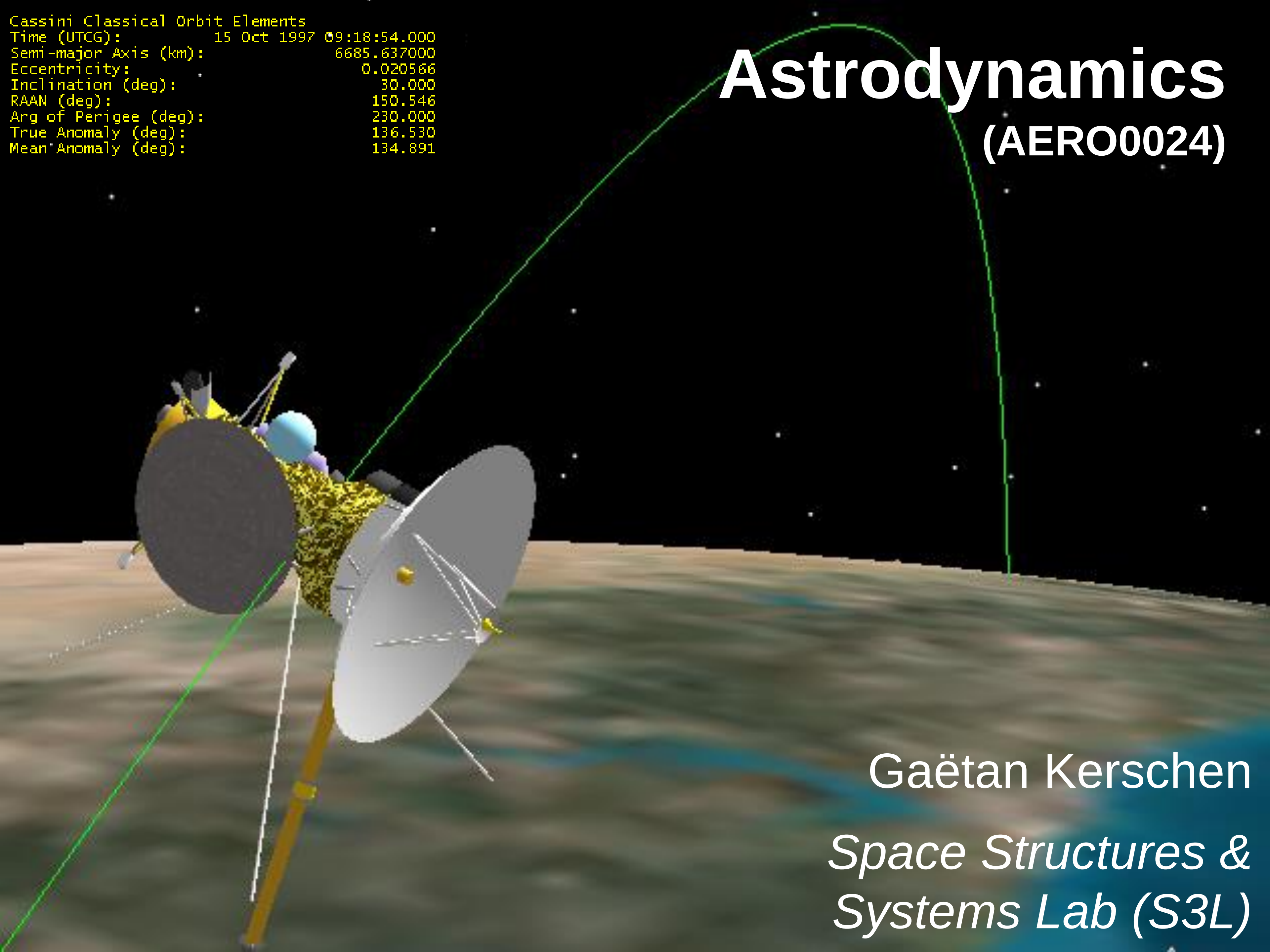
Astrodynamics

(AERO0024)



Gaëtan Kerschen

Space Structures & Systems Lab (S3L)

Instructors — Gaëtan Kerschen

Contact details

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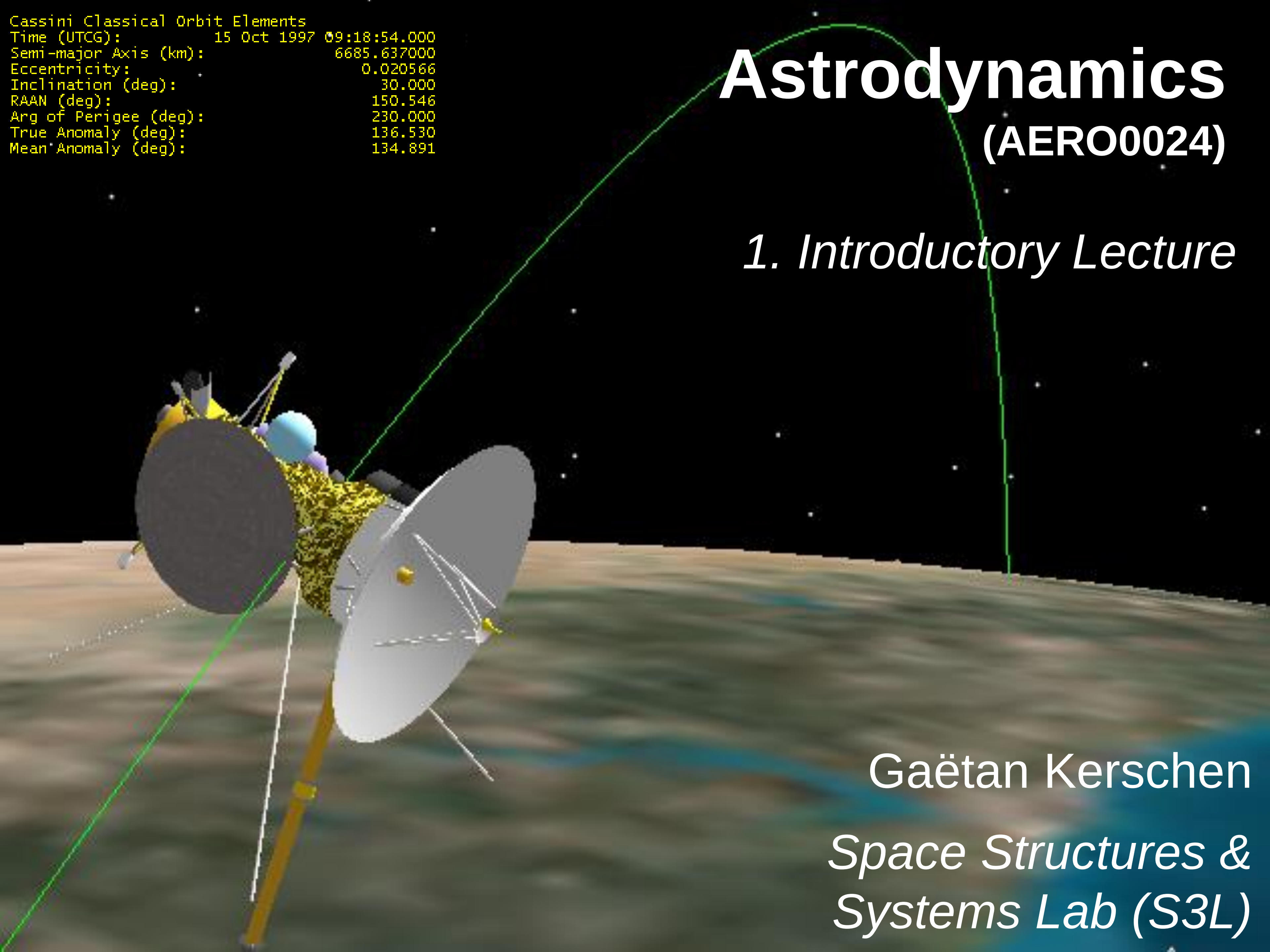
Course Organization

See web site.



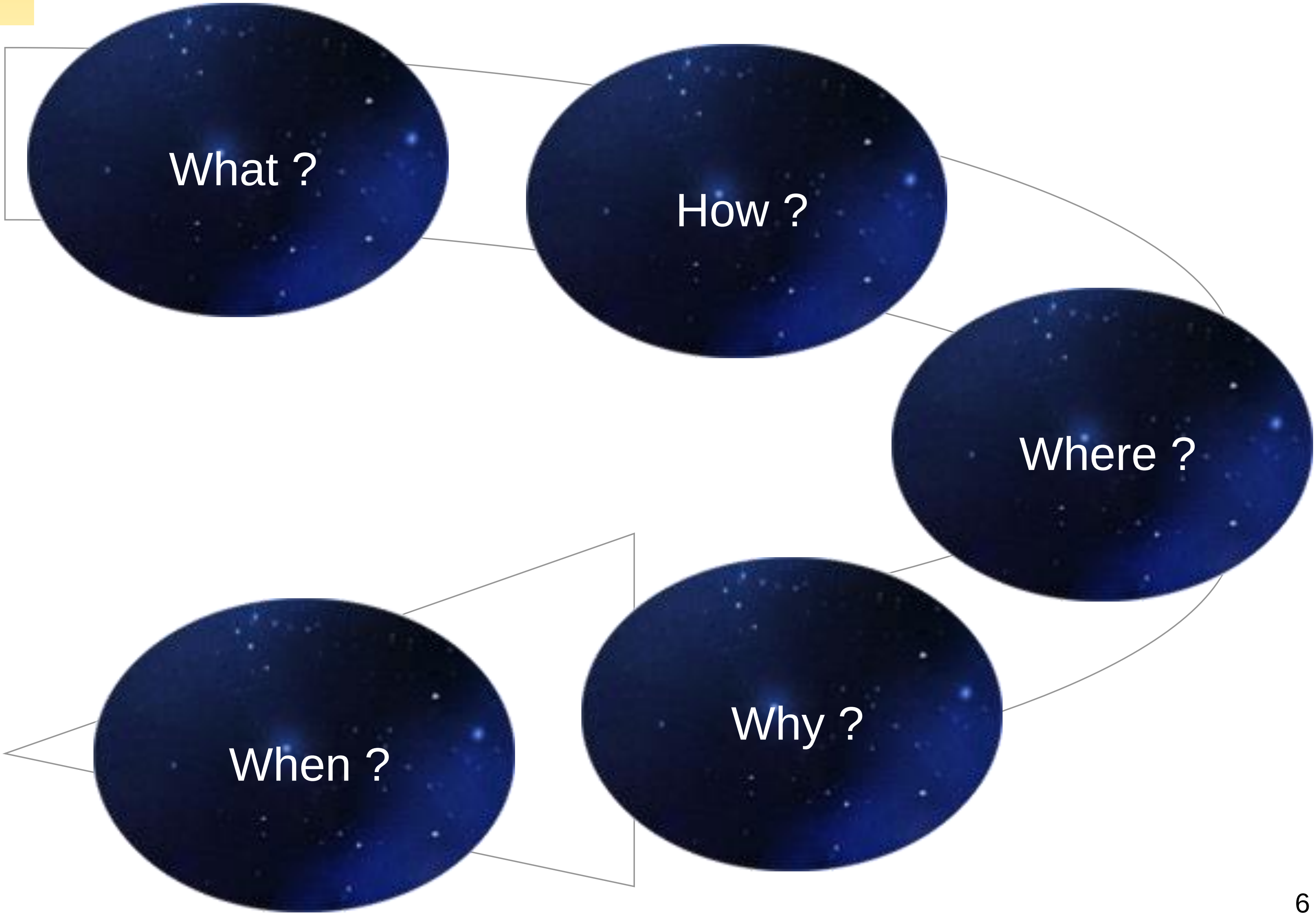
Astrodynamics
(AERO0024)

1. Introductory Lecture

Gaëtan Kerschen

Space Structures & Systems Lab (S3L)

Introductory Lecture

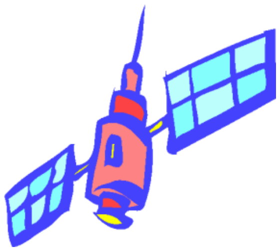


Space Mechanics

Space mechanics is the science concerned with the description of the motion of bodies in space.

Astrodynamics

Motion of spacecraft



Celestial mechanics

Motion of natural bodies

Astrodynamics

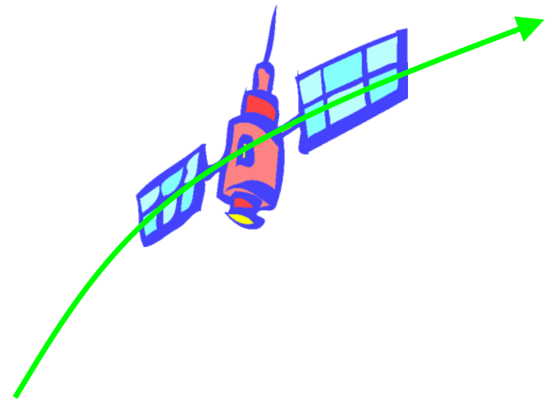
Astrodynamics is the study of the motion of man-made objects in space subject to both **natural** and **artificially** induced forces.

- *Unpowered flight*: Same basic theory as the one for of a small, natural body — close link with celestial mechanics !
- *Powered flight*: Launch vehicle, orbital maneuvers and interplanetary transfer

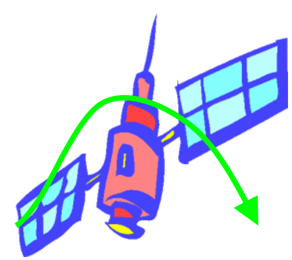
Astrodynamics

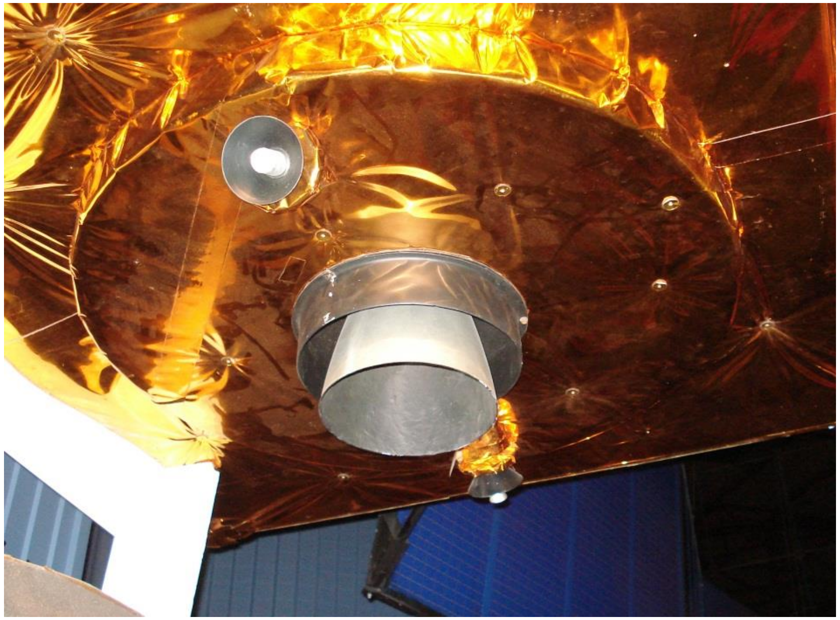
Astrodynamics is commonly divided into orbital motion and attitude motion.

Motion of the center of mass

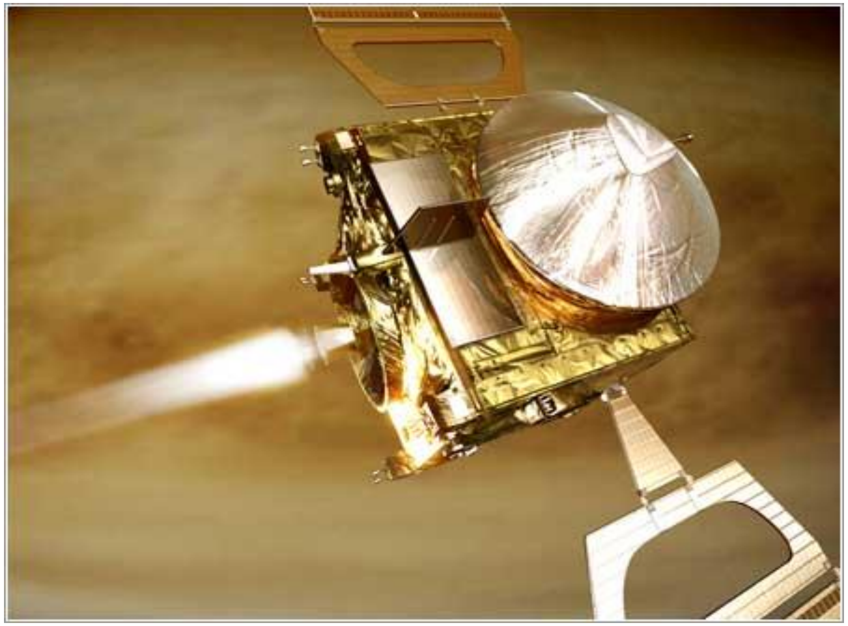


Motion about the center of mass

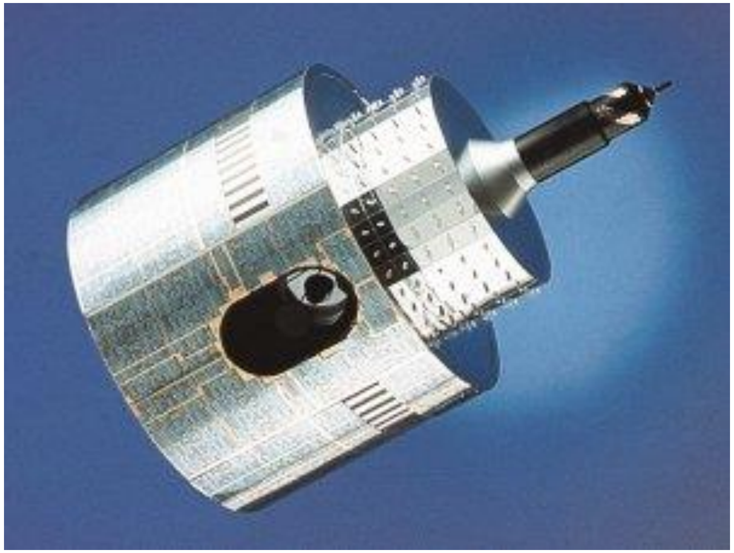




Apogee motor for orbit circularization (Eutelsat)

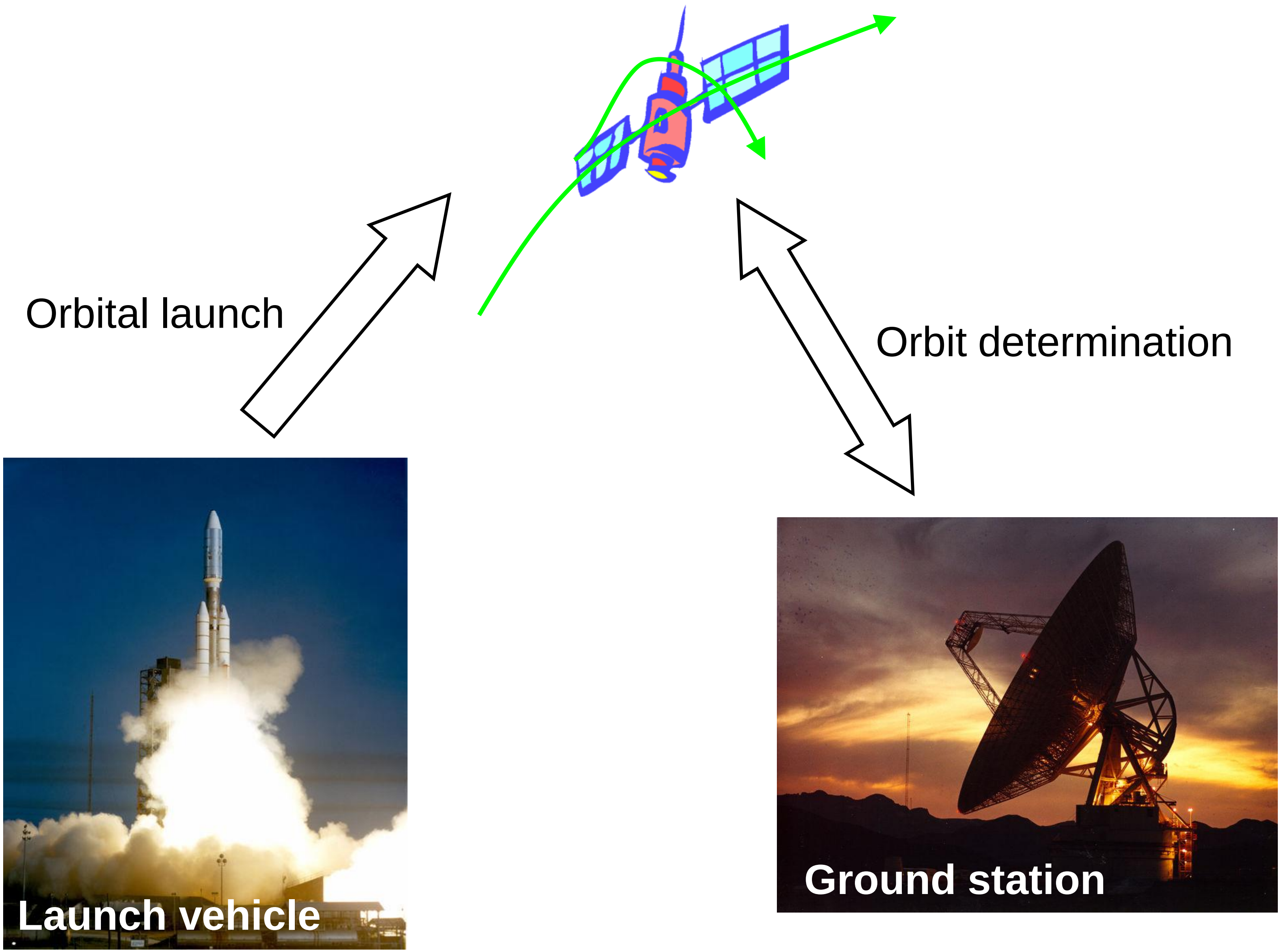


Braking maneuver (Venus Express)



Meteosat: 6 thrusters for orbit maintenance

The Whole Story…



Course Objective

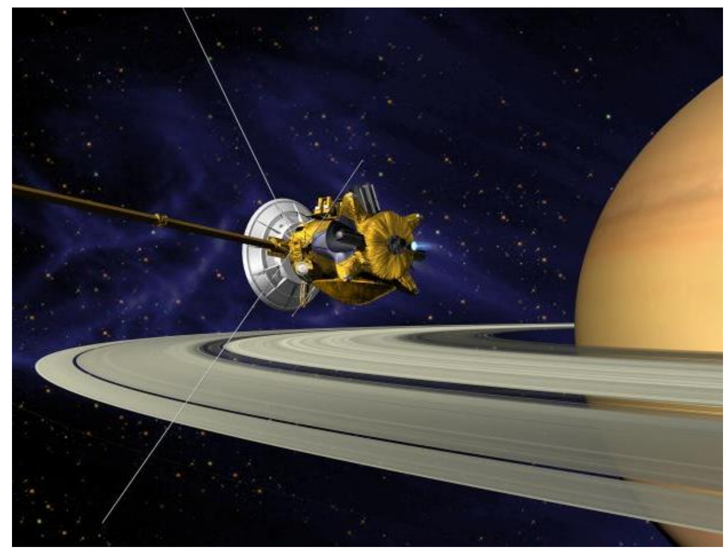
Develop a ***fundamental*** and ***comprehensive*** knowledge of ***astrodynamics***:

⇒ Celestial mechanics will not be our primary focus.

⇒ Orbital motion will be covered in great detail, and attitude motion will not be touched upon.

Course Objective

COURSE OBJECTIVE

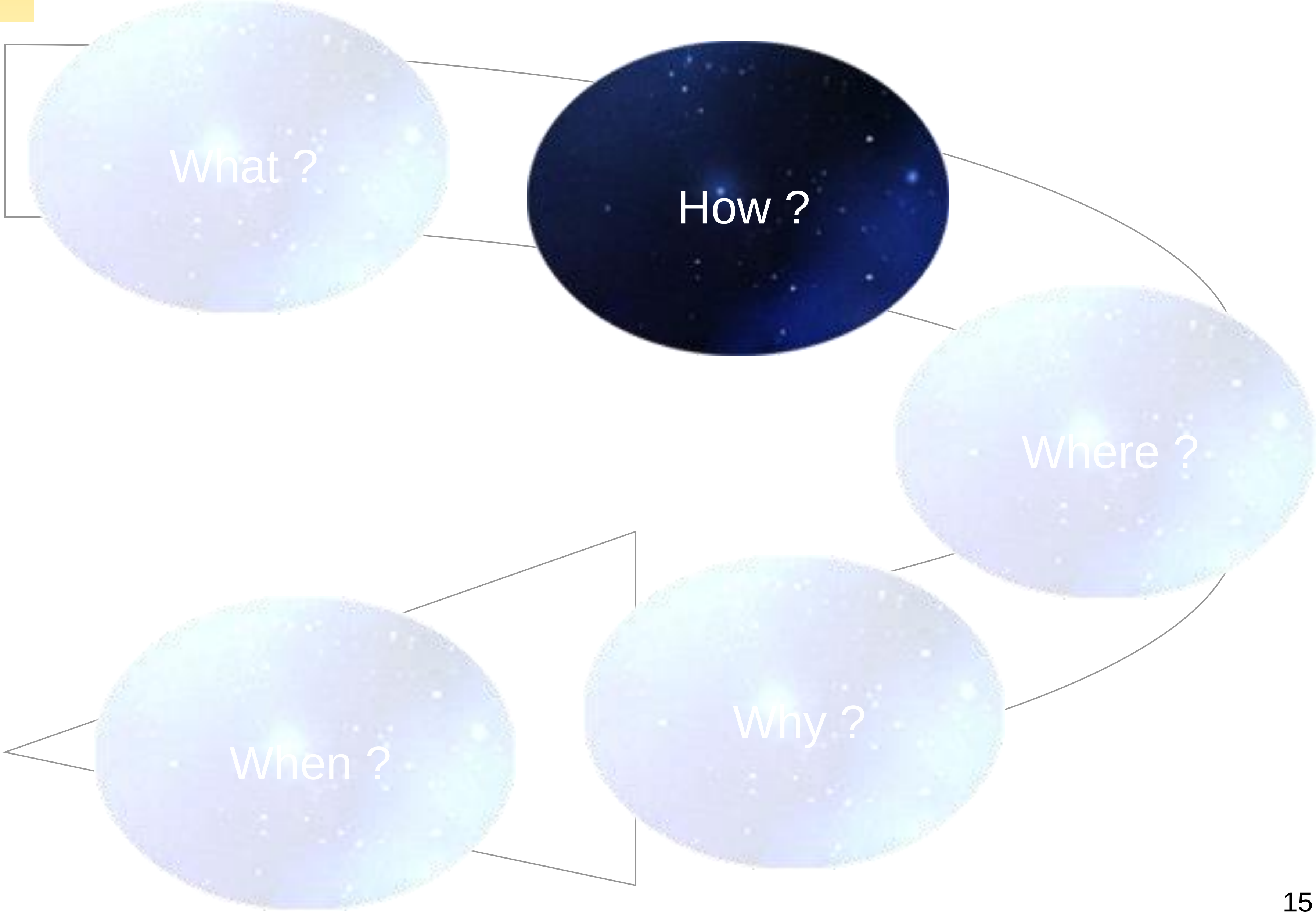


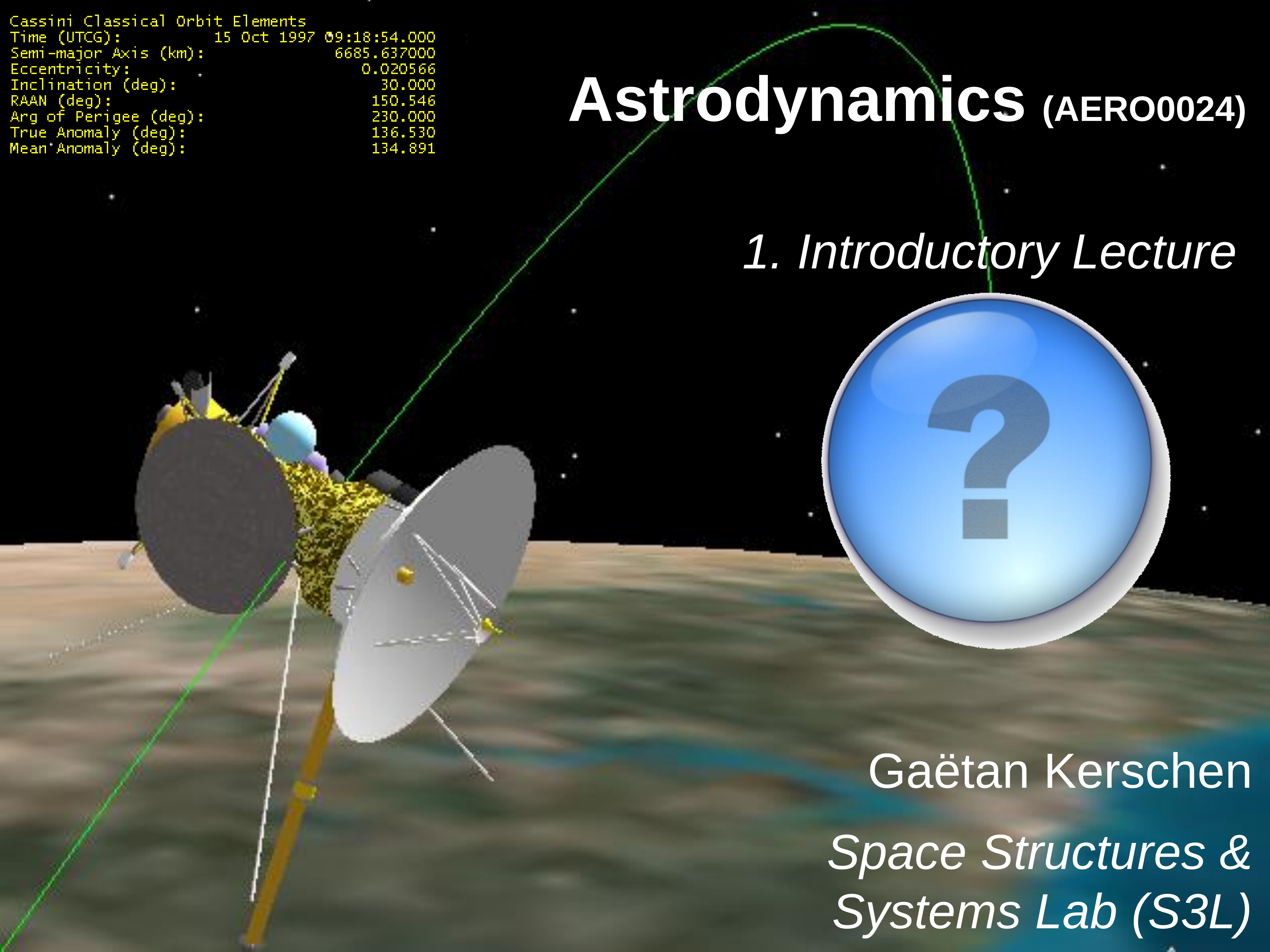
Expected Learning Outcomes

Upon completion of this course, you will be able to:

1. Understand the key features of common satellite orbits
2. Develop a detailed knowledge of the two-body problem
3. Calculate orbital parameters of satellites
4. Estimate orbit perturbations and their effects
5. Design maneuvers to accomplish desired change of orbit
6. Design interplanetary trajectories
7. Solve basic and more advanced orbital mechanics problems using Matlab

Introductory Lecture





Astrodynamics (AERO0024)

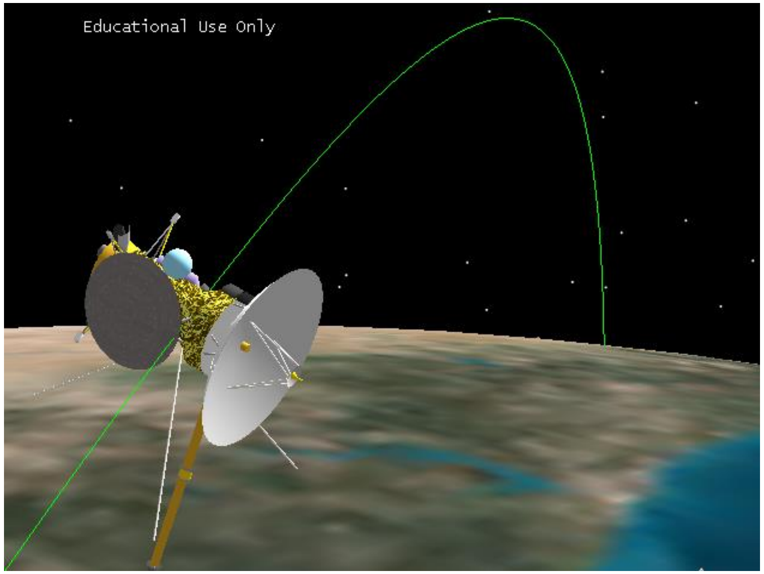
1. Introductory Lecture

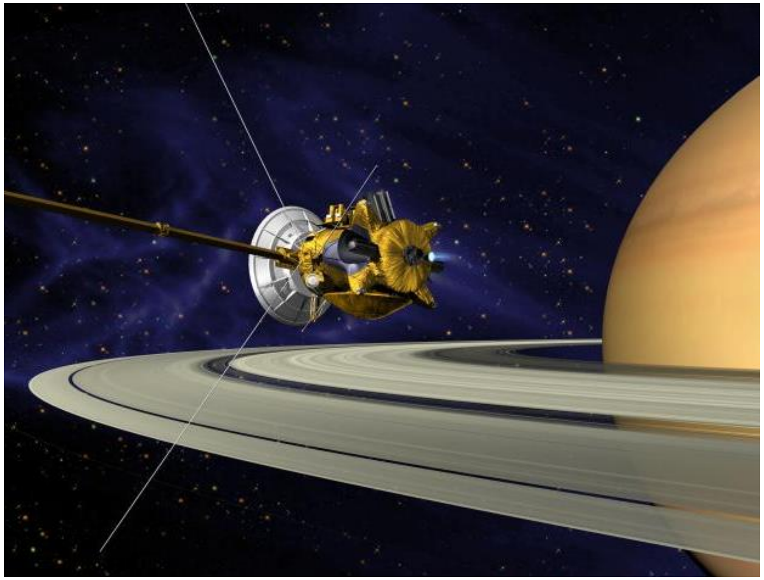
Gaëtan Kerschen

Space Structures & Systems Lab (S3L)

Cassini-Huygens Mission

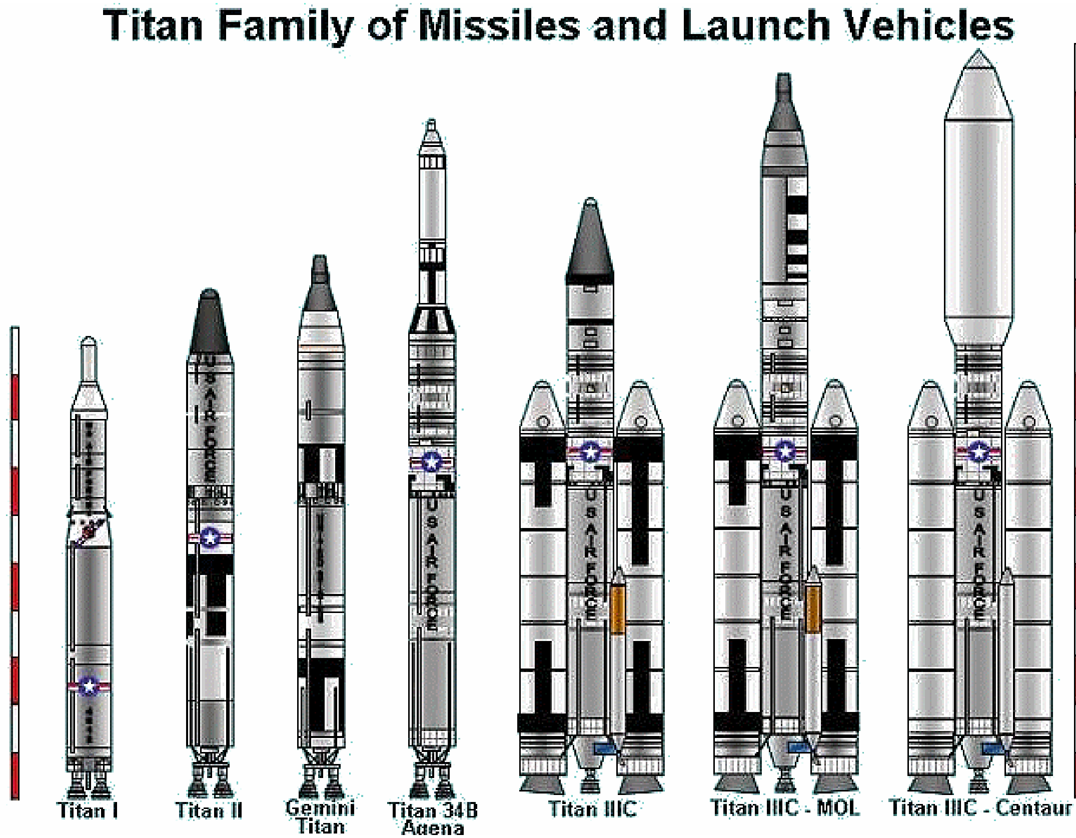
Mission to Saturn … but…. the spacecraft is in earth parking orbit (170 x 445 km, i=30°)





Launch

Oct. 15, 1997, 08:55 UTC:	lift-off from Cape Canaveral (30-day launch window)
T+2m11, 58.5 km:	stage 1 ignition
T+2m23, 68.3 km:	solid rocket boosters separation
T+3m27, 101.4 km:	fairing jettisoning
T+5m23, 167.3 km:	stage 2 ignition & stage 1 separation
T+9m13, 206.7 km:	Centaur separation and first burn
T+11m13, 170x445 km:	end of first burn (parking orbit)
T+28m13, 170x445 km:	second burn
T+36m13 $\Rightarrow$ VENUS:	Cassini separation with C/CAM (hyperbolic trajectory, C_3=16.6km^2/s^2)


Titan Family of Missiles and Launch Vehicles
U S AIR FORCE
Titan I
Titan II
Gemini Titan
Titan 34B Agena
Titan IIIC
Titan IIIC - MOL
Titan IIIC - Centaur


Centaur

En Route for Venus

There is no launch vehicle powerful enough to send Cassini on a direct path to Saturn

$\Rightarrow$ Thematic unit 2

Mostly An Unpowered Flight But…

TCM/ OTM (1)	Date (2)	Event (3)	Duration [s] (4)	Delta v [m/s] Actual Bi (5)	Delta v [m/s] Actual Mono (6)	Propellant Remaining [kg] Mono (11)	Propellant Remaining [kg] Bi (12)	Propellant Remaining [kg] Bi Used (13)
1	09.11.97	V1-Launch	34,13	2,70		131,86	3.000,00	5,05
2	25.02.98	V1			0,18		2.994,95	
3	Canceled	V1					2.994,95	
4	Canceled	V2-CA					2.994,95	
5	03.12.98	V2-DSM	5.275,23	450,00		129,61	2.994,95	780,08
6	04.02.99	V2	125,21	11,55		129,25	2.214,88	18,52
7	18.05.99	V2			0,23		2.196,36	
8	Canceled	V2					2.196,36	
9	06.07.99	Earth	466,91	43,49		128,37	2.196,36	69,04
10	19.07.99	Earth	54,63	5,13		128,30	2.127,32	8,08
11	02.08.99	Earth	383,78	36,29		128,21	2.119,24	56,75
12	11.08.99	Earth	128,46	12,25		128,16	2.062,49	19,00
13	31.08.99	Earth-CA	69,90	6,69		128,05	2.043,49	10,34
14	14.06.00	Flush	5,74	0,55		126,39	2.033,15	0,85
15	Canceled	Jupiter					2.032,30	
16	Canceled	Jupiter					2.032,30	
17	28.02.01	Flush	5,32	0,51		124,89	2.032,30	0,79
18	01.04.02	Flush	9,85	0,89		122,60	2.031,30	1,46
19	01.05.03	Flush	17,53	1,58		120,32	2.029,84	2,59
20	27.05.04	Phoebe	362,00	34,70		118,06	2.027,25	53,53
21	17.06.04	Phoebe-CA	38,38	3,68		117,94	1.973,72	5,68
22	Canceled	Pre SOI						
Cruise				609,99	0,40			1.031,74

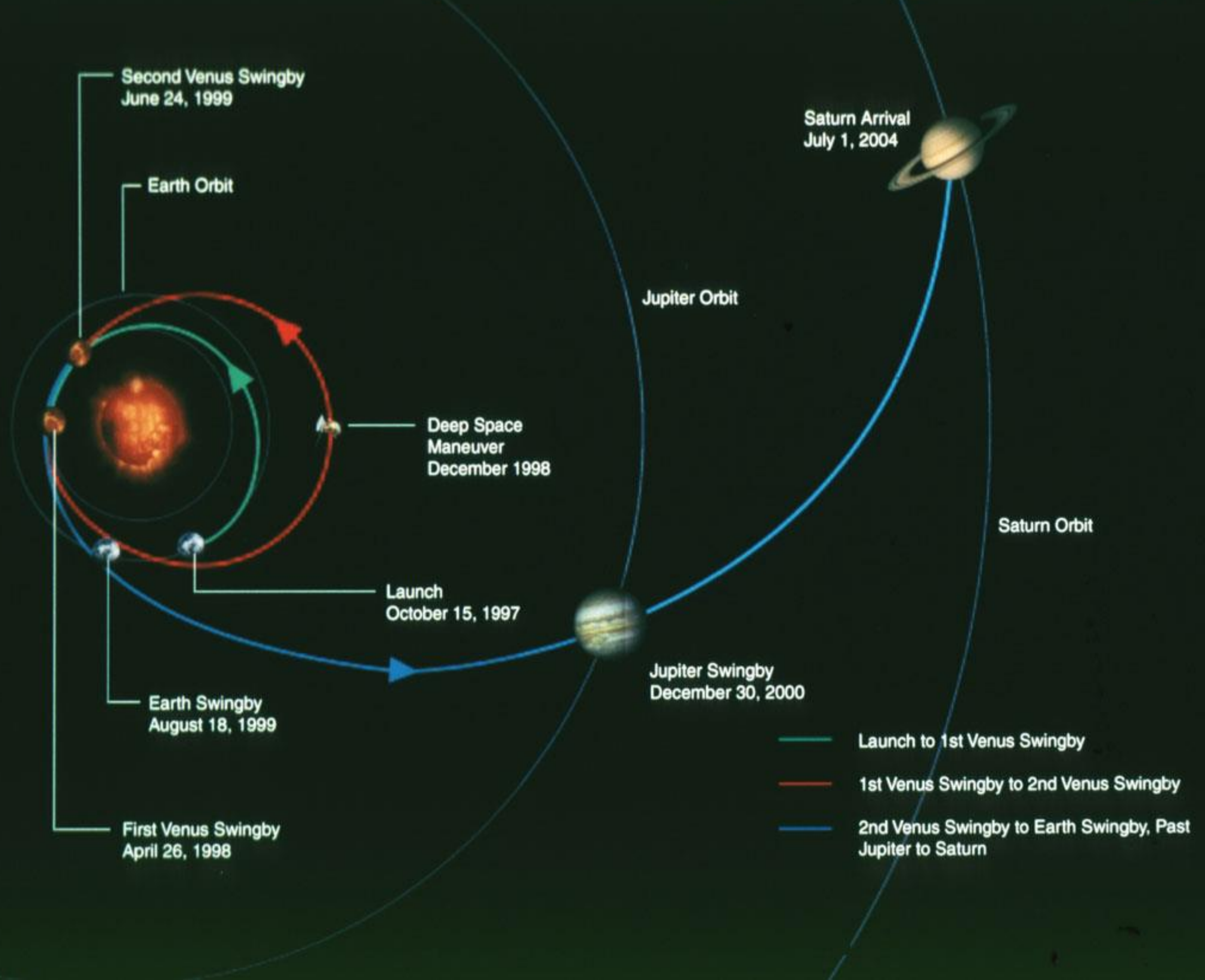
Two Venus Swingby

TCM-1 (*):	correct errors due to launch
TCM-2:	very small corrections before Venus encounter
TCM-3 and TCM-4:	cancelled (mission redesign !)
⇒ Venus swingby #1	minimum altitude of 284 km
TCM-5:	deep-space maneuver
TCM-6, TCM-7:	bias removal due to redesign
TCM-8:	cancelled
⇒ Venus swingby #2	

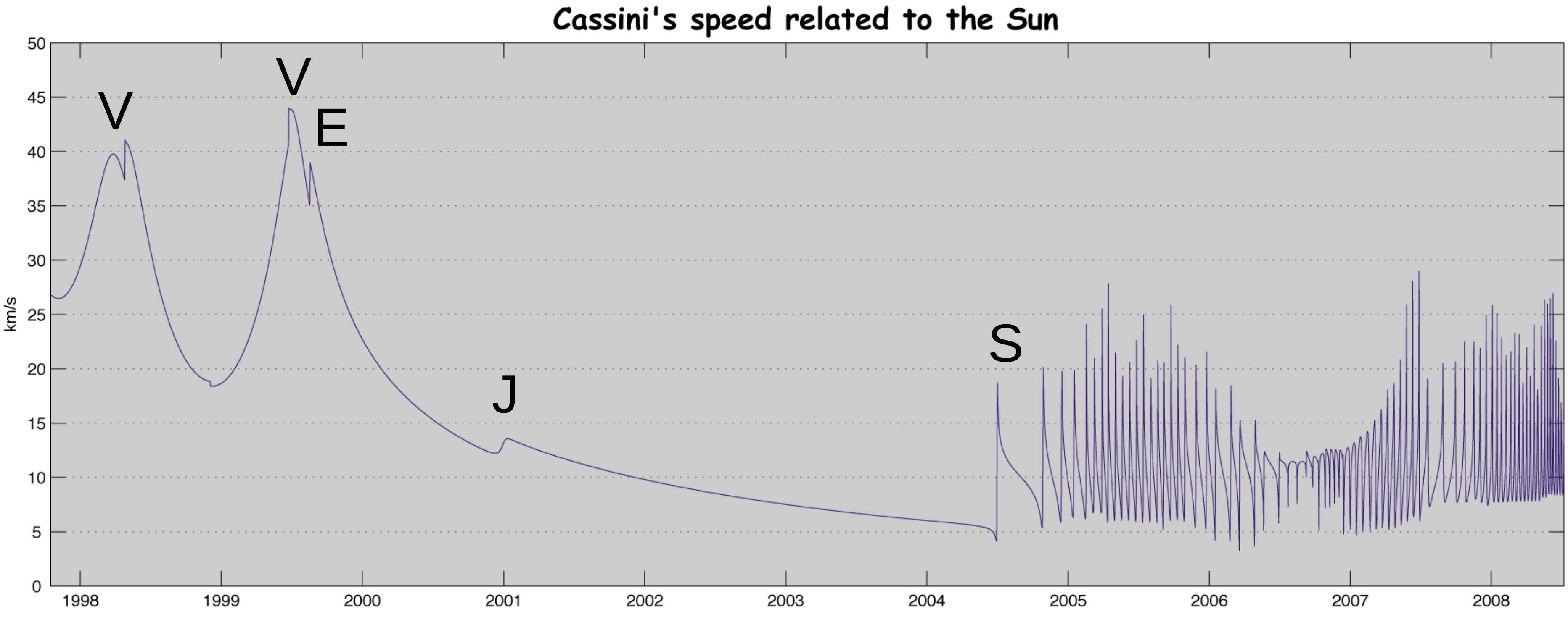
(*) HGA pointed toward the sun (thermal shield) and use of the LGA for communications

Cassini Interplanetary Trajectory

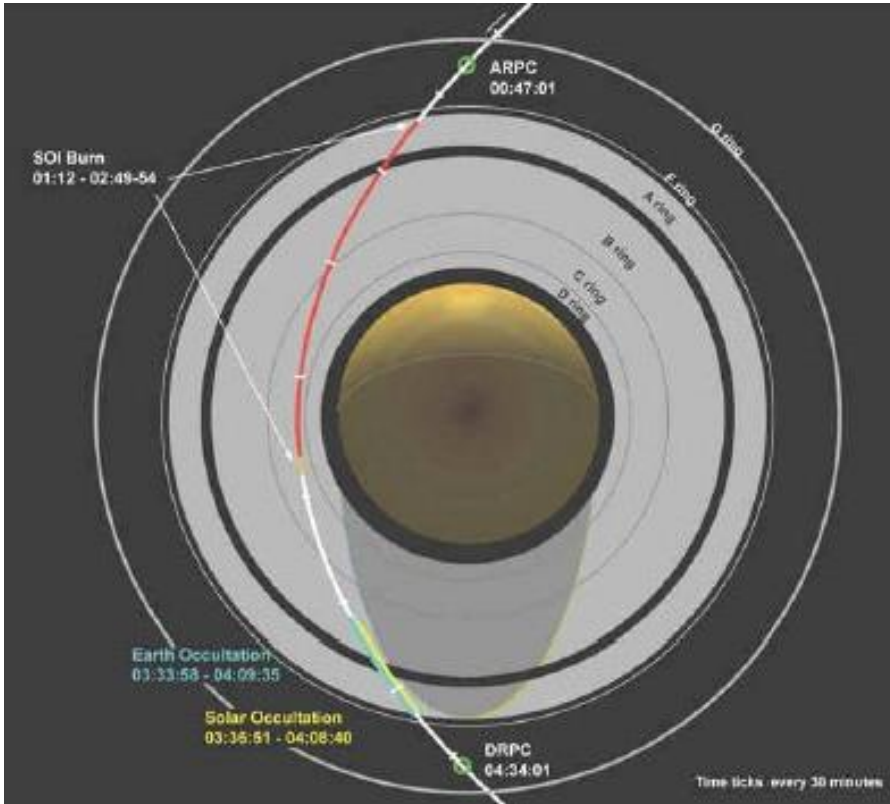
V
V
E
J
G
A



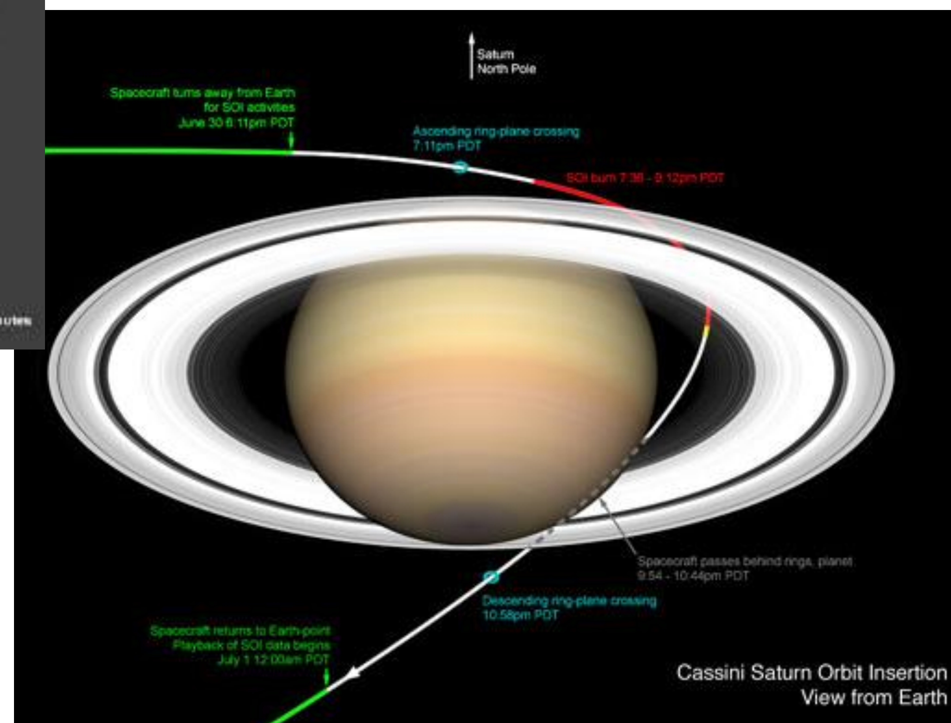
Swingby Effects



Saturn Orbit Insertion (SOI)



ΔV=633 m/s ⇒
periapsis=1.3 Rs, i=16.8°, T=148d
(initial orbit)

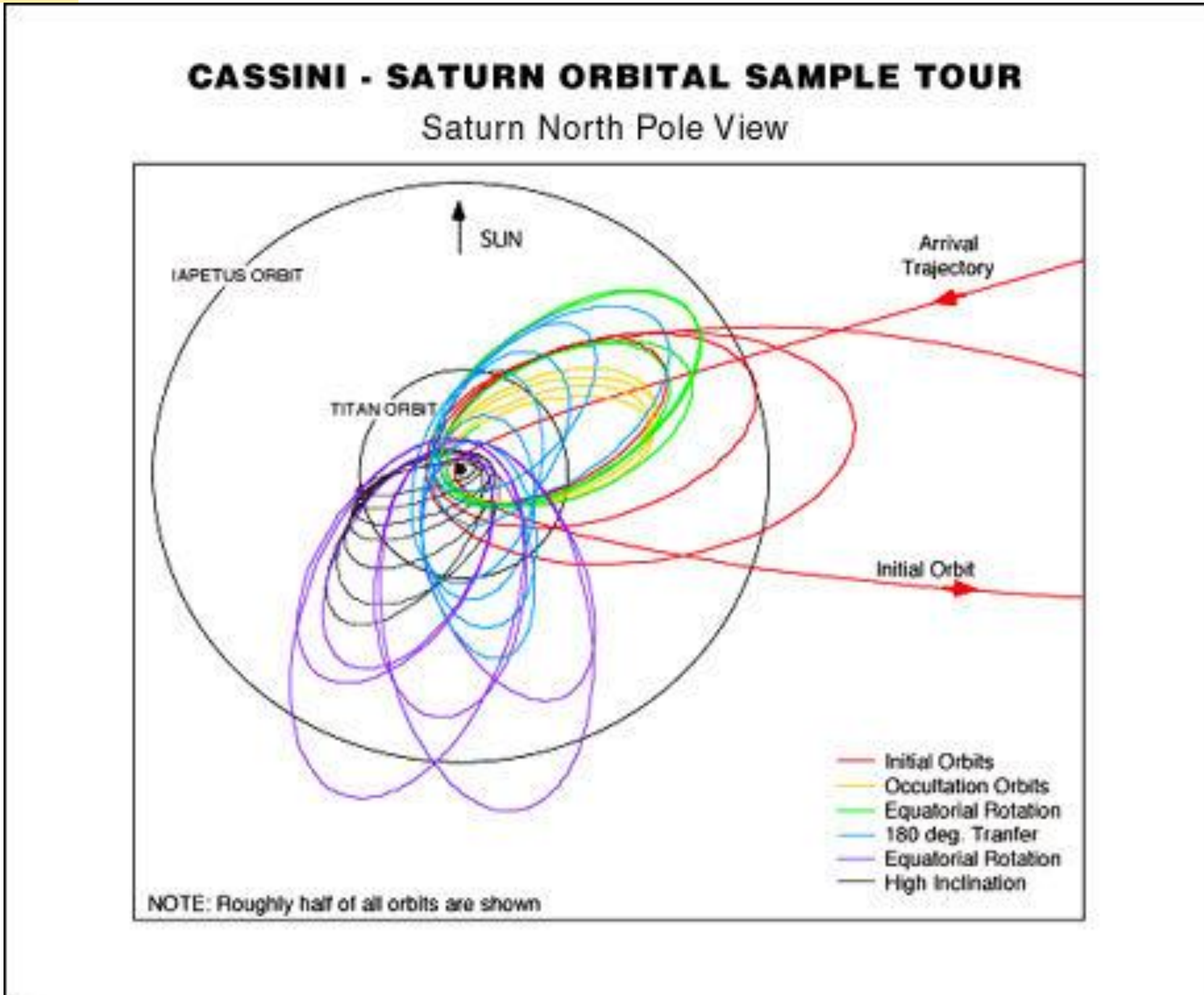


Saturn Orbit Insertion

http://www.esa.int/esaMI/Cassini-Huygens/SEMUIE25WVD_0.html

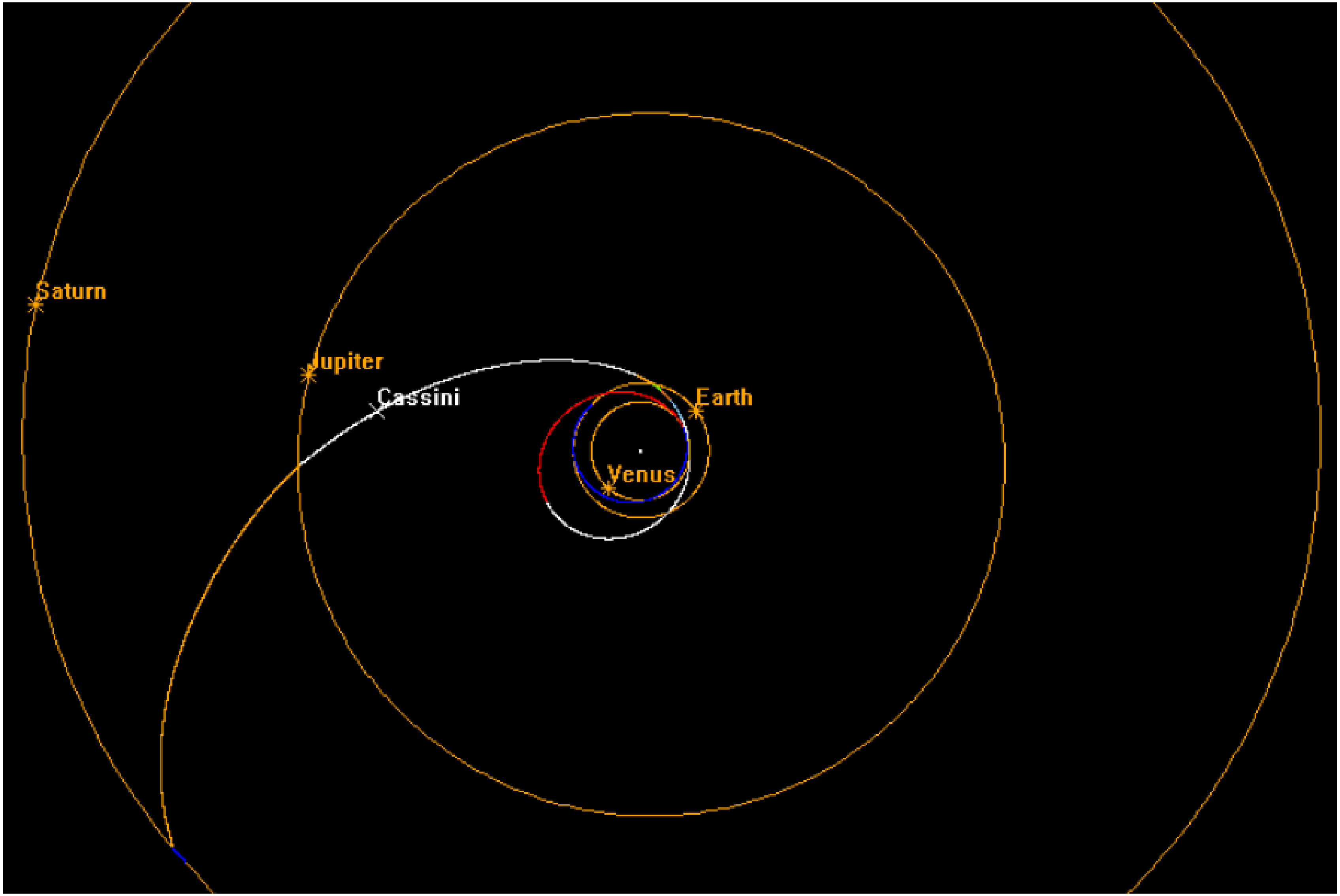
EDT	Cassini Saturn Orbit Insertion Timeline
08:51 PM	Switch to LGA antenna 1; telemetry off; carrier only
09:11 PM	Turn to protective attitude
10:11 PM	**Ascending ring plane crossing (D=98,500 miles)**
10:21 PM	Turn to burn attitude (10-minute turn; 6 spare minutes)
10:35 PM	Open latch valves for helium pressurization
10:36 PM	**SOI burn begins; dV=1,400 mph; dT=96.4 minutes**
10:59 PM	Cassini moves behind F ring as seen from Earth
11:06 PM	Cassini moves behind A ring; begin 25-minute comm loss
11:31 PM	6 minutes of comm through Cassini division
11:37 PM	Cassini moves behind B ring; possible 28-minute comm loss
11:54 PM	Minimal orbit achieved; not useable
12:03 AM	Saturn closest approach. D=12,400 miles from cloudtops
12:05 AM	Spacecraft moves behind C ring; comm resumes
12:12 AM	**Saturn orbit Insertion burn ends**
12:15 AM	Begin turn to Earth pointing; comm reconfig
12:18 AM	Spacecraft HGA pointed toward Earth
12:24 AM	Spacecraft moves behind D ring; communications still likely
12:30 AM	Switch to HGA comm
12:31 AM	Spacecraft turns off Earth point for science observations
12:39 AM	Jettison Ion and Neutral Mass Spectrometer cover
12:54 AM	Cassini moves behind C ring; no comm possible
12:57 AM	Spacecraft passes behind Saturn; remains in science attitude
01:32 AM	Turn to protective attitude for descending ring plane crossing
01:33 AM	Spacecraft emerges from behind Saturn; no comm
01:44 AM	Spacecraft emerges from behind A ring; no comm
01:58 AM	**Descending ring plane crossing (D=98,500)**
03:00 AM	Spacecraft turns to Earth; SOI data playback
03:12 AM	Main engine cover opened for post SOI maneuver
06:49 AM	Switch to reaction wheel attitude control
08:39 AM	First SOI images downlinked

Orbits Around Saturn: The "Petal Tour"



Movie

Cassini-Huygens using STK



Introductory Lecture

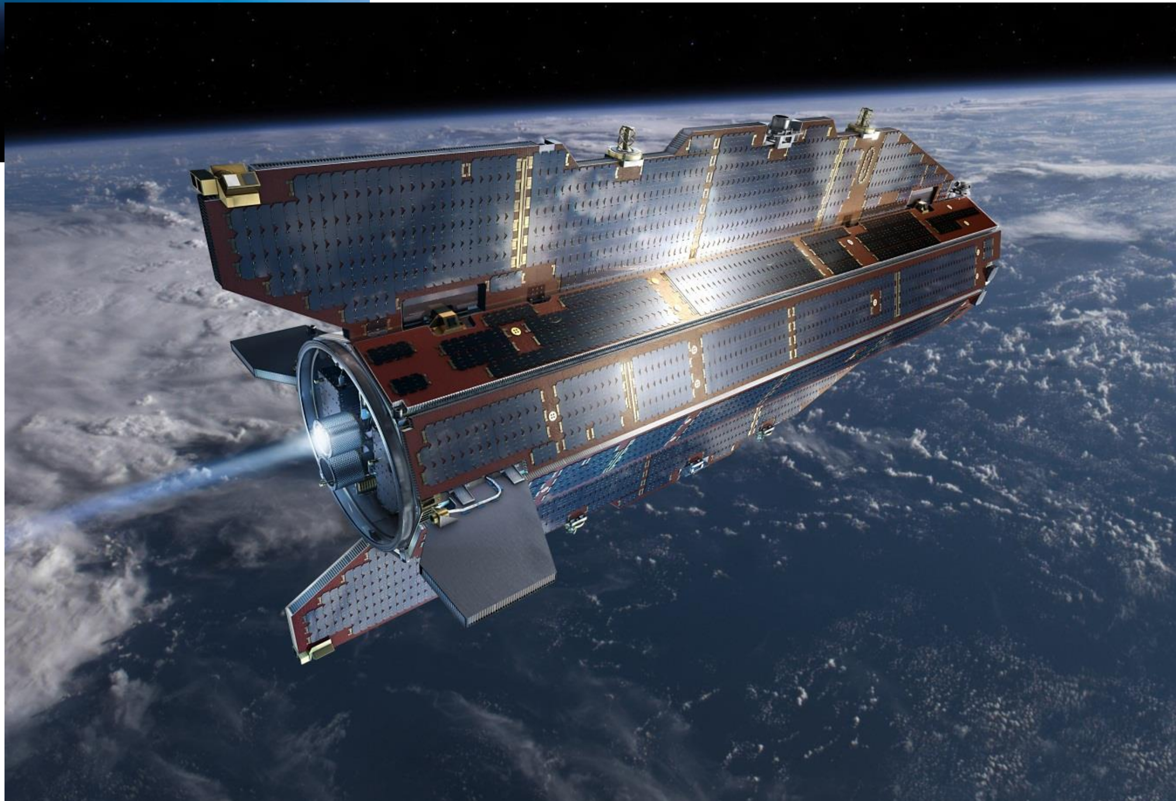
GOCE (ESA)

Payload: gravity mission (gravity field and geoid). The gravitational signal is stronger closer to the earth. Orbit as low as possible, but keep non-gravitational accelerations to a minimum:

250 kms, SSO (i=96.5°)

Very demanding *environment*: atmosphere

Satellite: propulsion system, 20 months mission

GOES (NOAA)

Payload: earth monitoring with a continuous coverage

35800 kms, GEO (60°W, 75°W, 105°W, 135°W, i=0°)

Demanding *orbit*: GTO, station-keeping and link budget

Satellite: propellant, apogee motor

Movie

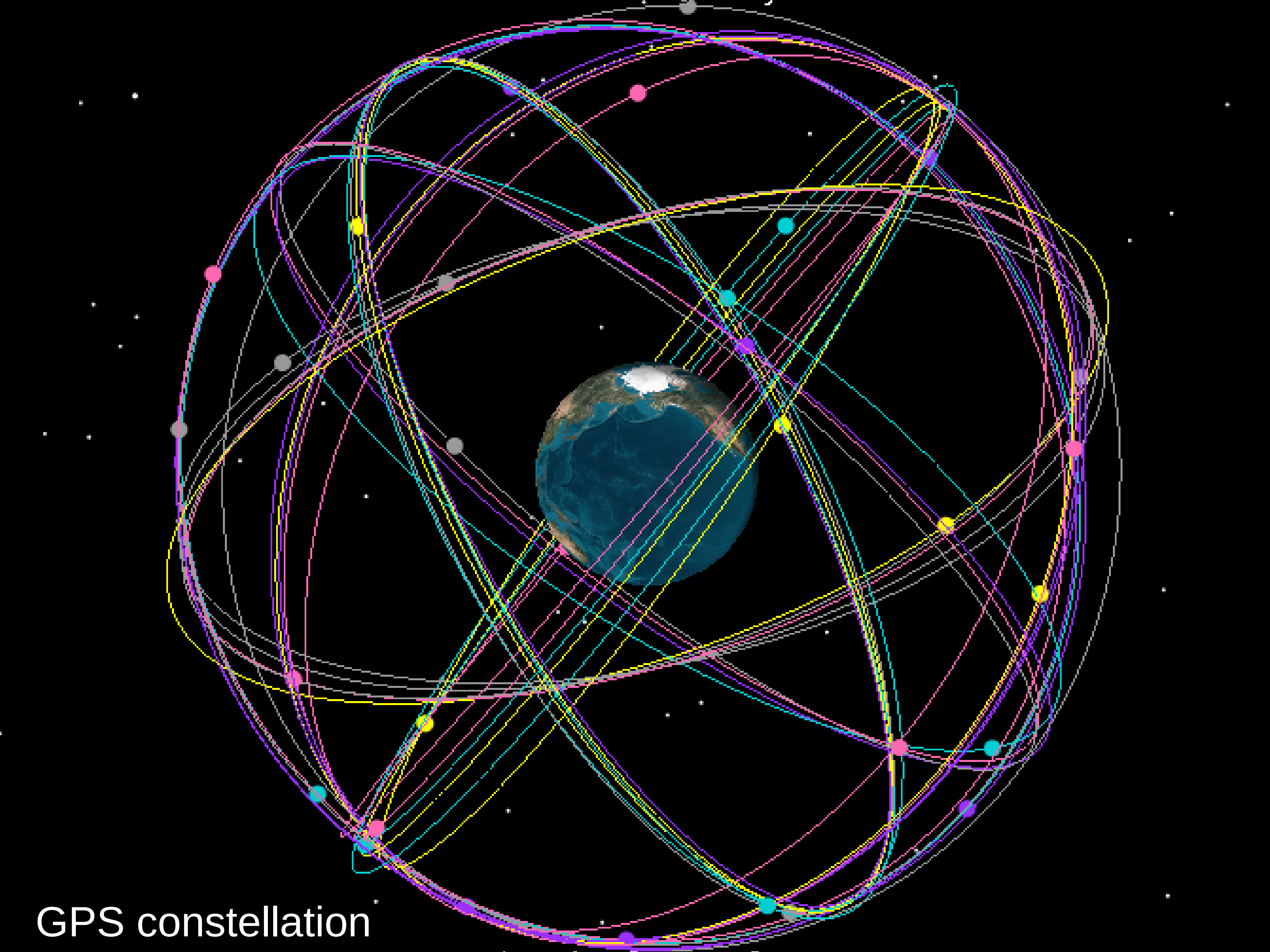
GPS (USA)

Payload: navigation. At least 4 satellites visible, at all sites on the globe, and at all times:

Constellation (24), 20200 kms, MEO (i=55°)

Demanding *environment*: radiation (outer belt)

Satellite: shielding


GPS constellation

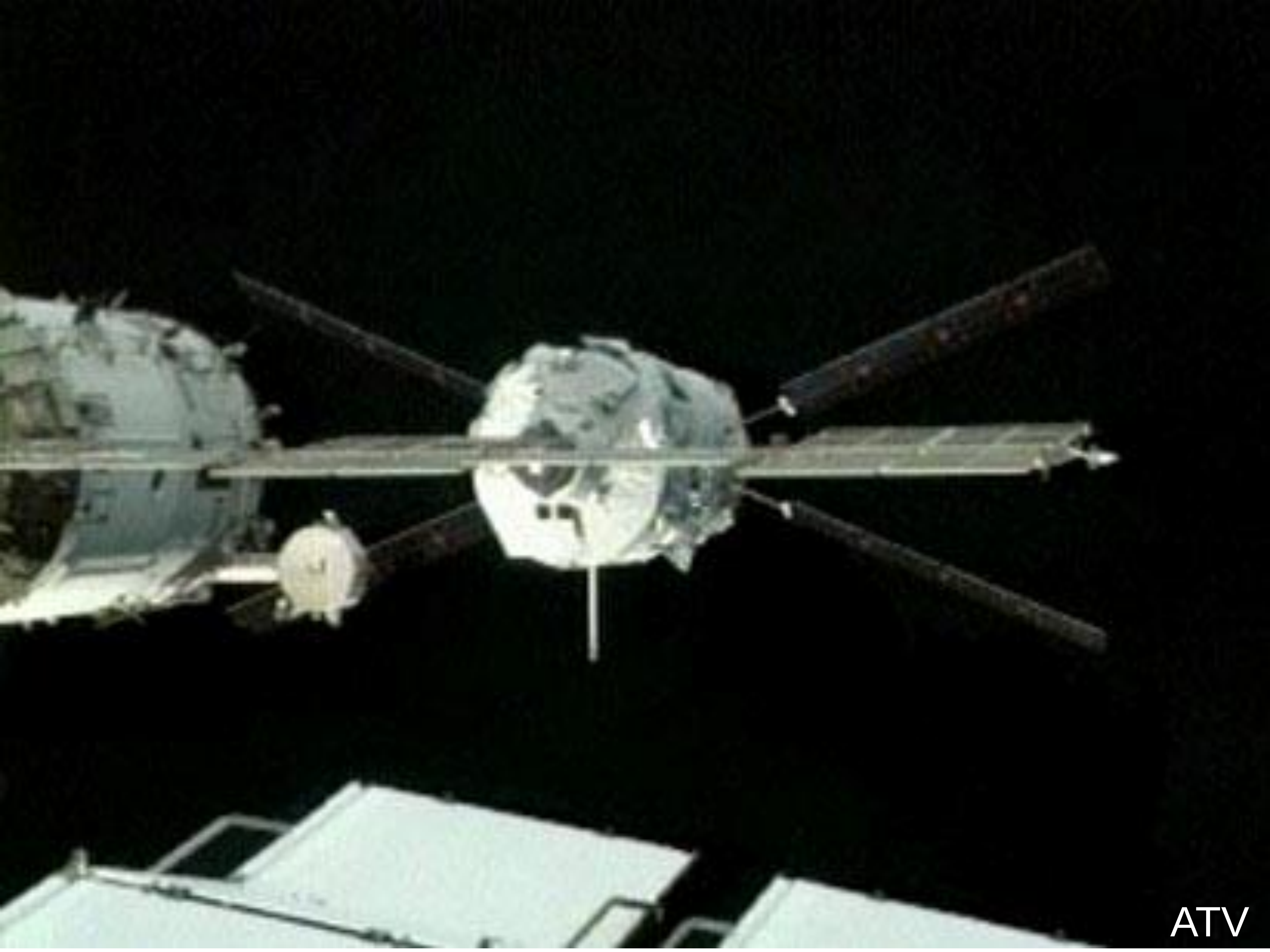
International Space Station (International)

Payload: scientific experiments. Lifetime and access are key issues:

350 kms, LEO (i=51°)

Demanding *environment*: atmosphere

Satellite: reboost necessary



ATV

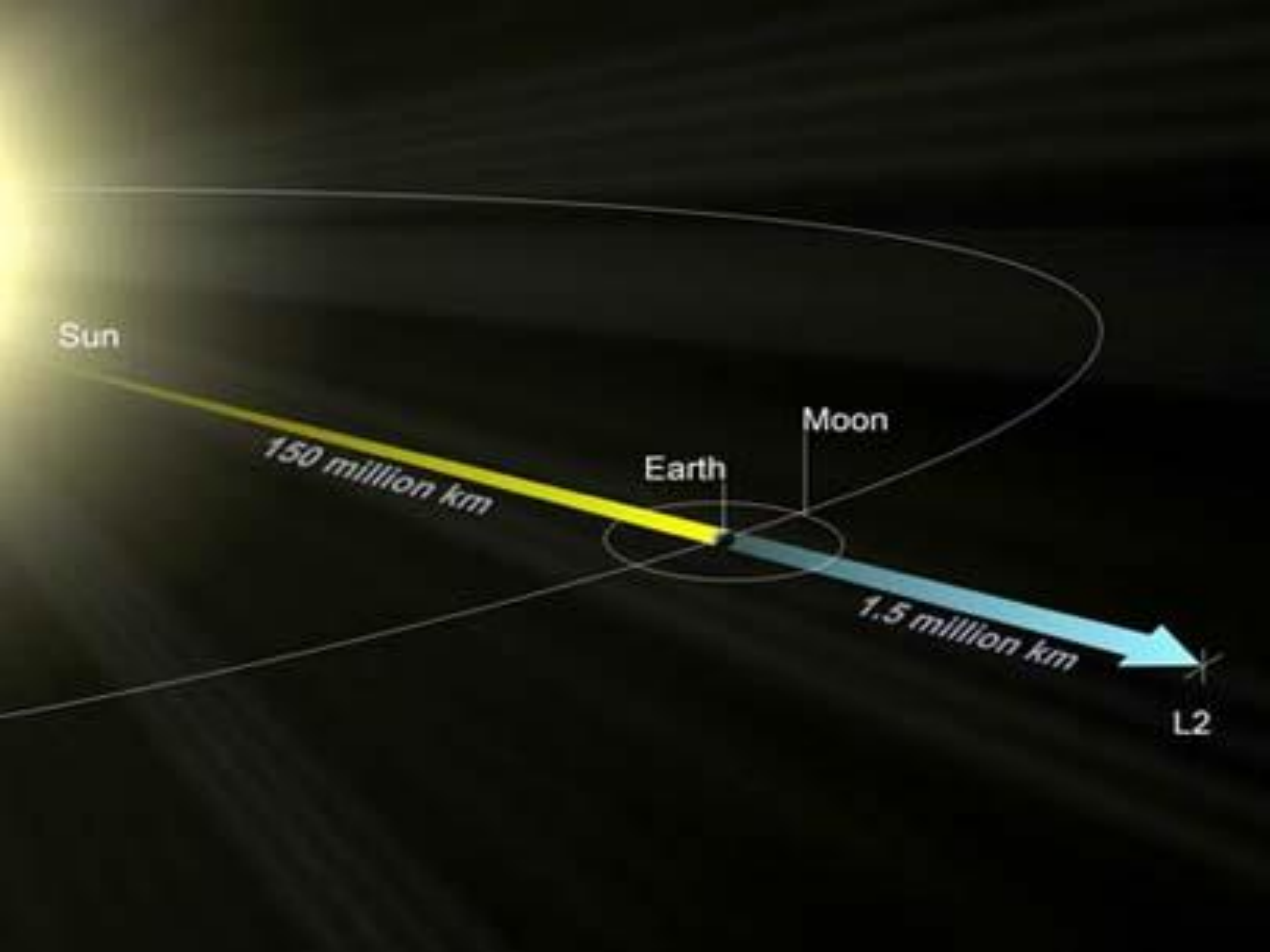
J. Webb Space Telescope (ESA-NASA)

Payload: infrared telescope. Thermal stability is an issue:

Sun-Earth L_2 halo orbit (1.5 millions km)

Benign and unchanging *environment* (small station-keeping maneuvers)

Satellite: propellant


Sun
150 million km
Earth
Moon
1.5 million km
L2

Messenger (NASA)

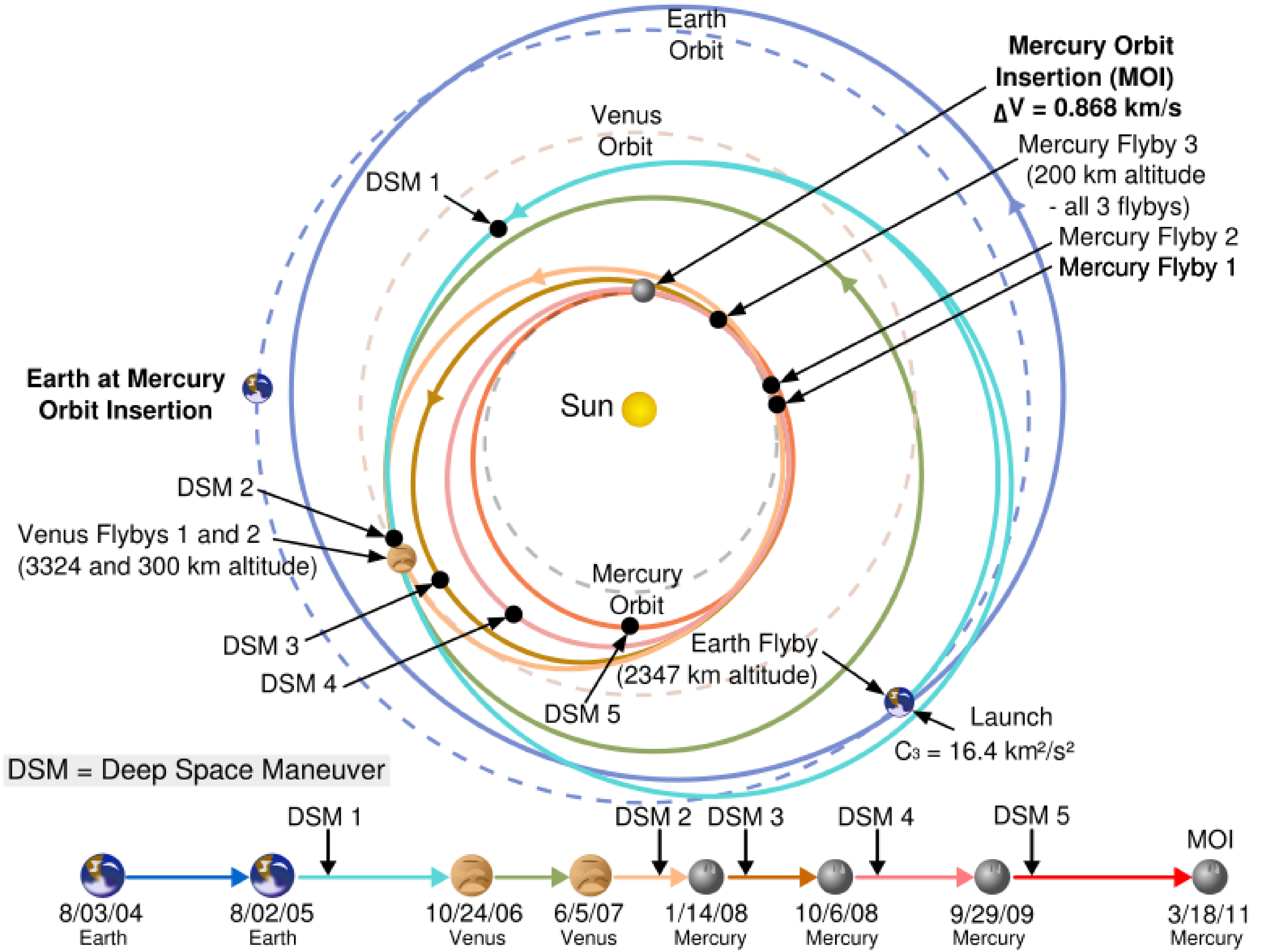
Payload: characteristic and environment of Mercury.

Orbit around Mercury

Demanding orbit: Mercury is difficult to reach (7 years)

Very demanding *environment*: intense heat

Satellite: sunshield, robustness



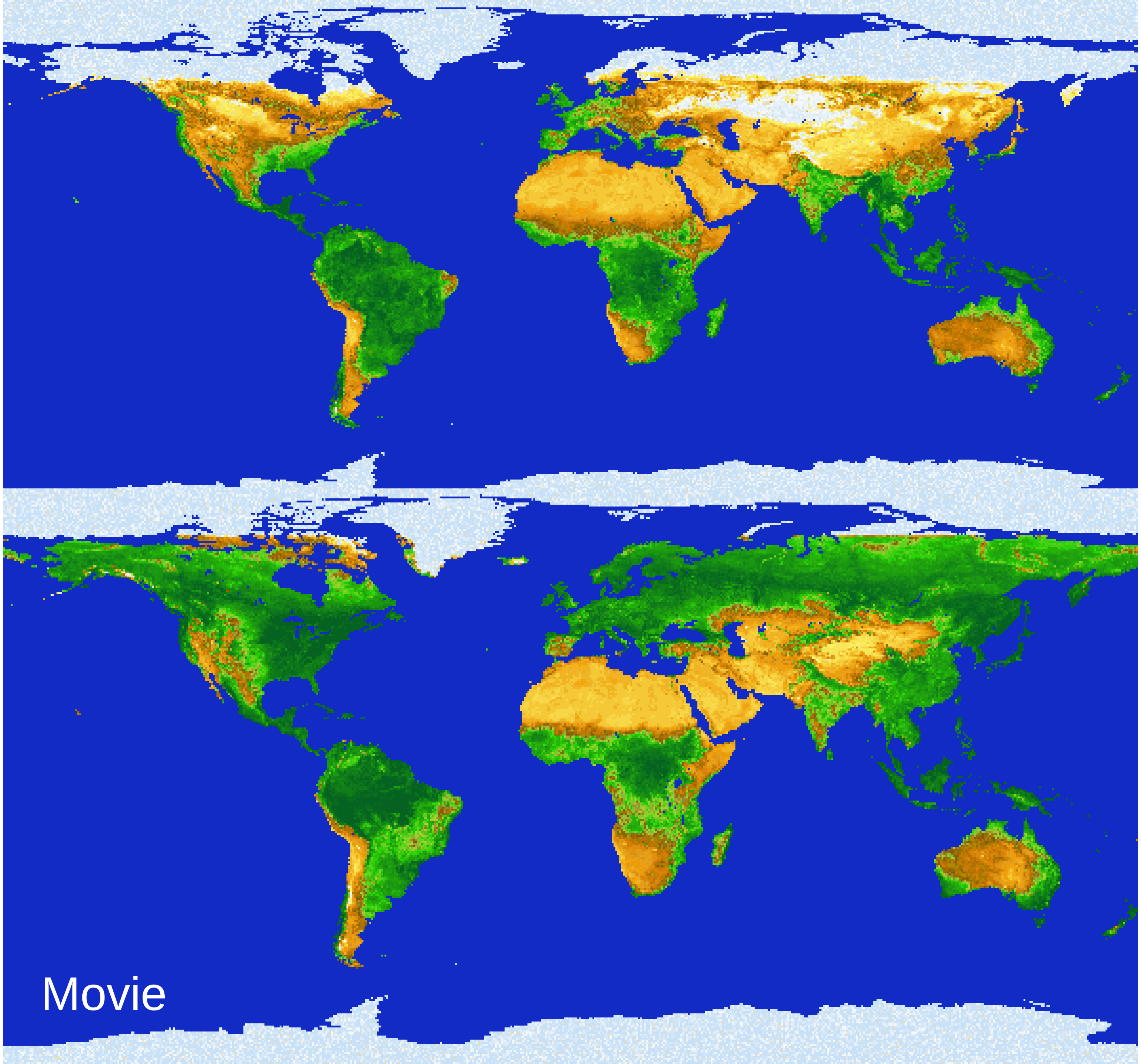
Earth Orbit
Mercury Orbit Insertion (MOI)
ΔV = 0.868 km/s
Venus Orbit
Mercury Flyby 3
(200 km altitude
- all 3 flybys)
DSM 1
Mercury Flyby 2
Mercury Flyby 1
Earth at Mercury Orbit Insertion
Sun
DSM 2
Venus Flybys 1 and 2
(3324 and 300 km altitude)
Mercury Orbit
DSM 3
Earth Flyby
(2347 km altitude)
DSM 4
DSM 5
Launch
C_3 = 16.4 km²/s²
DSM = Deep Space Maneuver
DSM 1
DSM 2
DSM 3
DSM 4
DSM 5
MOI
8/03/04
Earth
8/02/05
Earth
10/24/06
Venus
6/5/07
Venus
1/14/08
Mercury
10/6/08
Mercury
9/29/09
Mercury
3/18/11
Mercury

SPOT-5 (CNES)

Payload: daily monitoring of terrestrial vegetation cover. Constant ground illumination and passes above the same points on the ground at regular intervals

820 kms, phased-SSO (i=98.7°)

Satellite: nothing particular


Movie

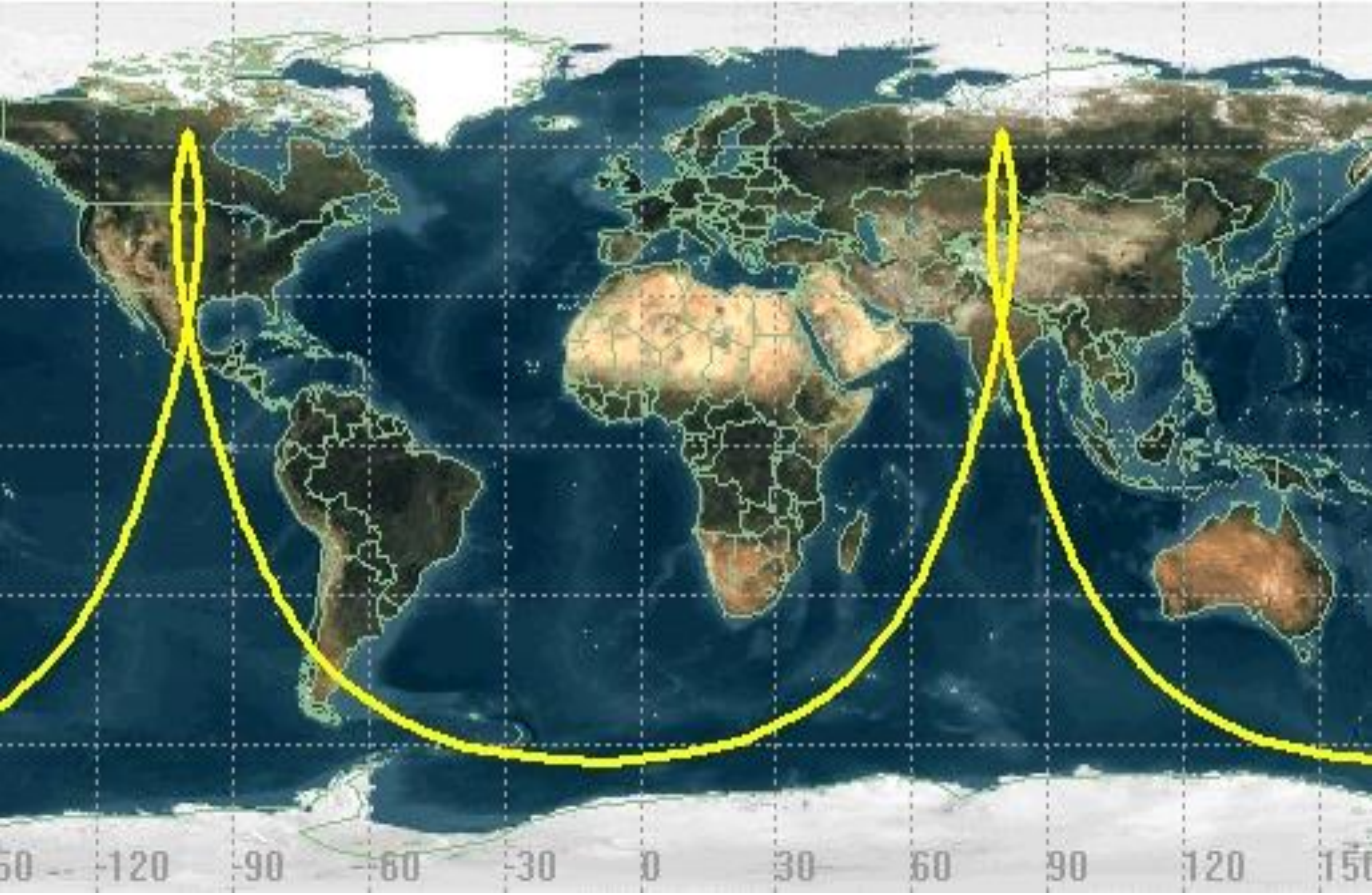
US-KS Satellites (Russia)

Payload: early warning detection of rocket launches from the US.

40000 x 600 kms, Molniya (i=63.4°, T=12h)

Demanding environment: radiation

Satellite: shut down electronic equipment



-120
-90
-60
-30
0
30
60
90
120

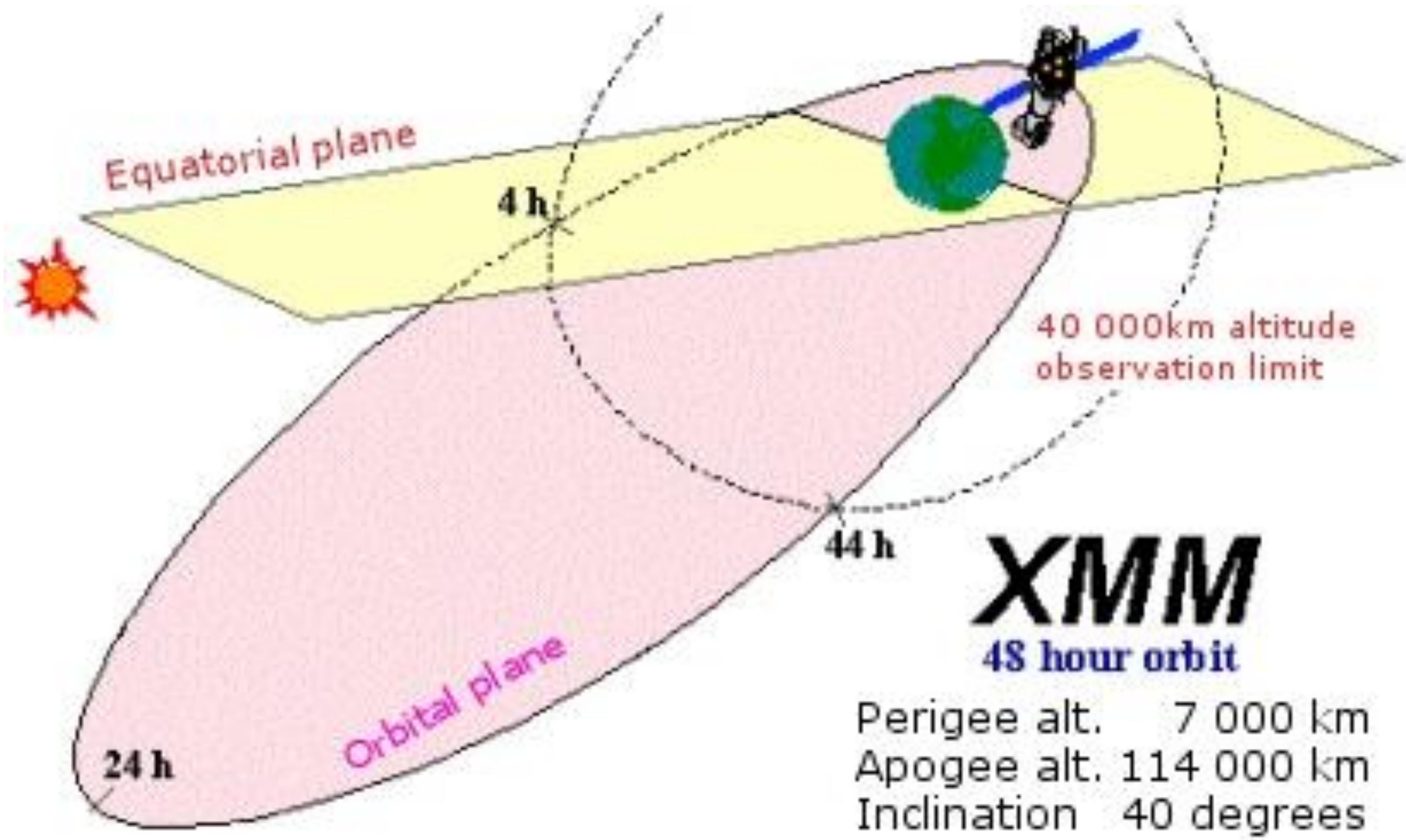
XMM (ESA)

Payload: X-ray observatory. Best visibility of the southern celestial hemisphere and long operational periods

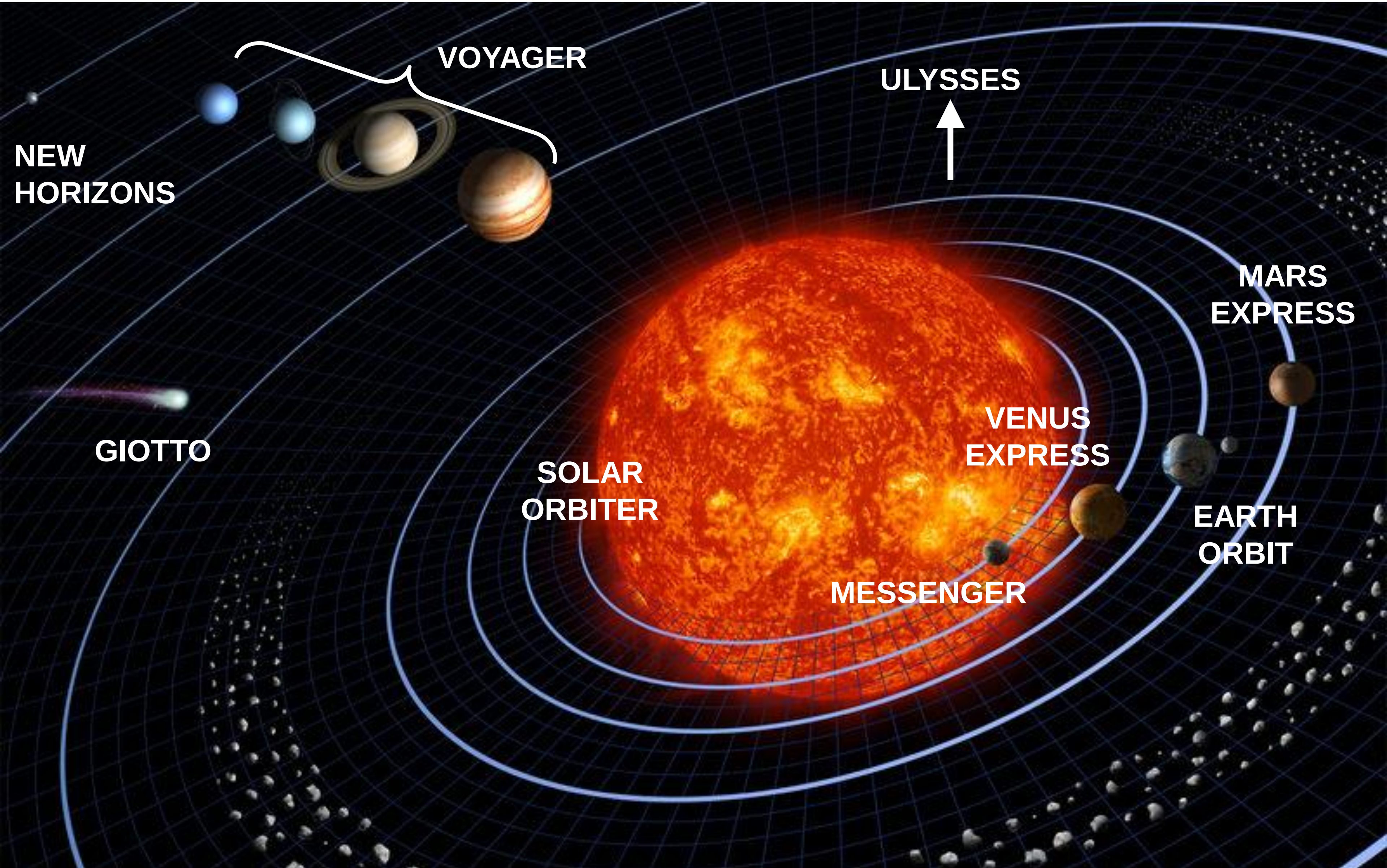
114000 x 7000 kms, i=40°, T=48h

Demanding environment: radiation

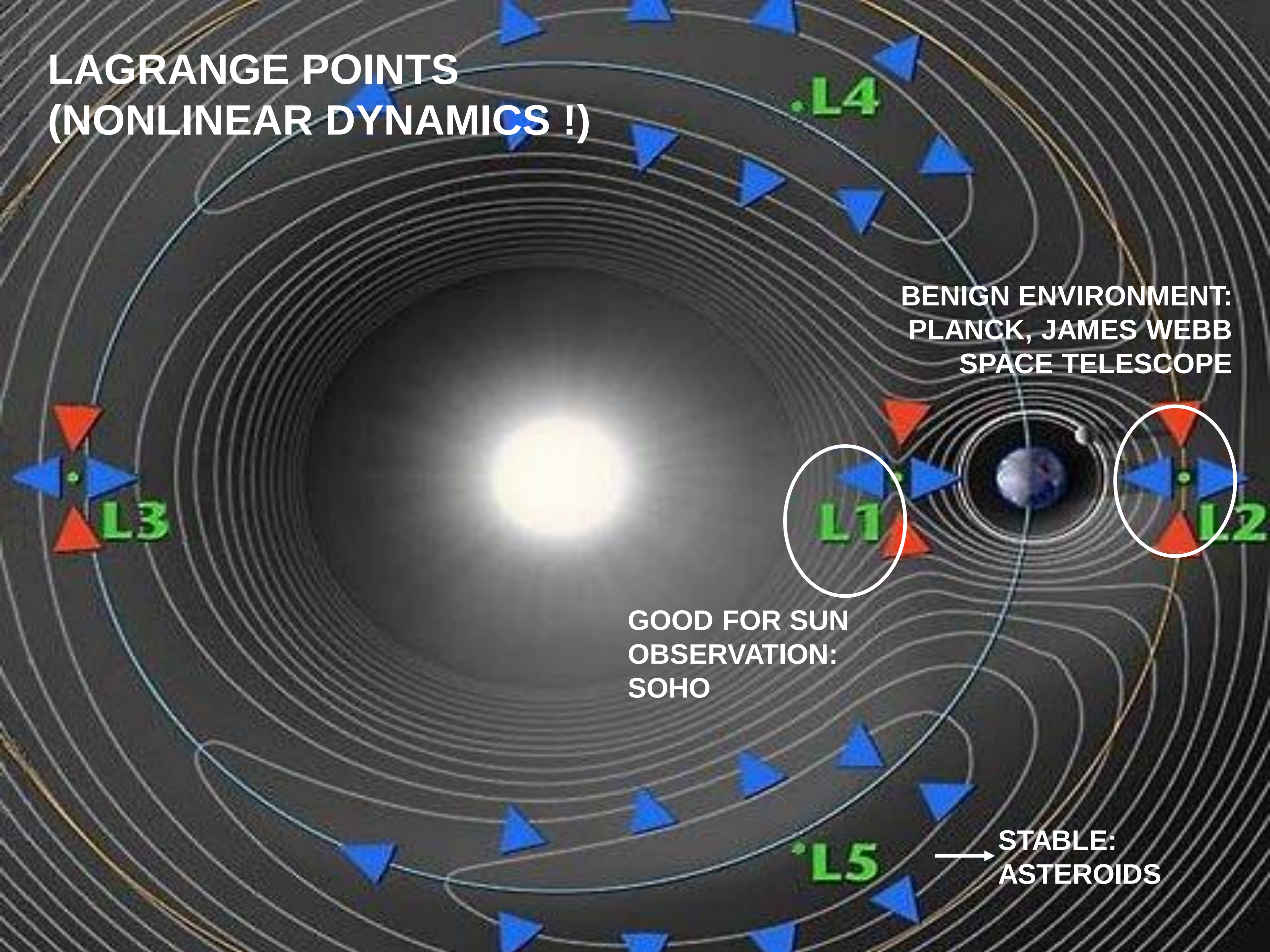
Satellite: shielding and shut down of the electronics


Equatorial plane
4 h
40 000km altitude
observation limit
44 h
XMM
48 hour orbit
Perigee alt. 7 000 km
Apogee alt. 114 000 km
Inclination 40 degrees
Orbital plane
24 h

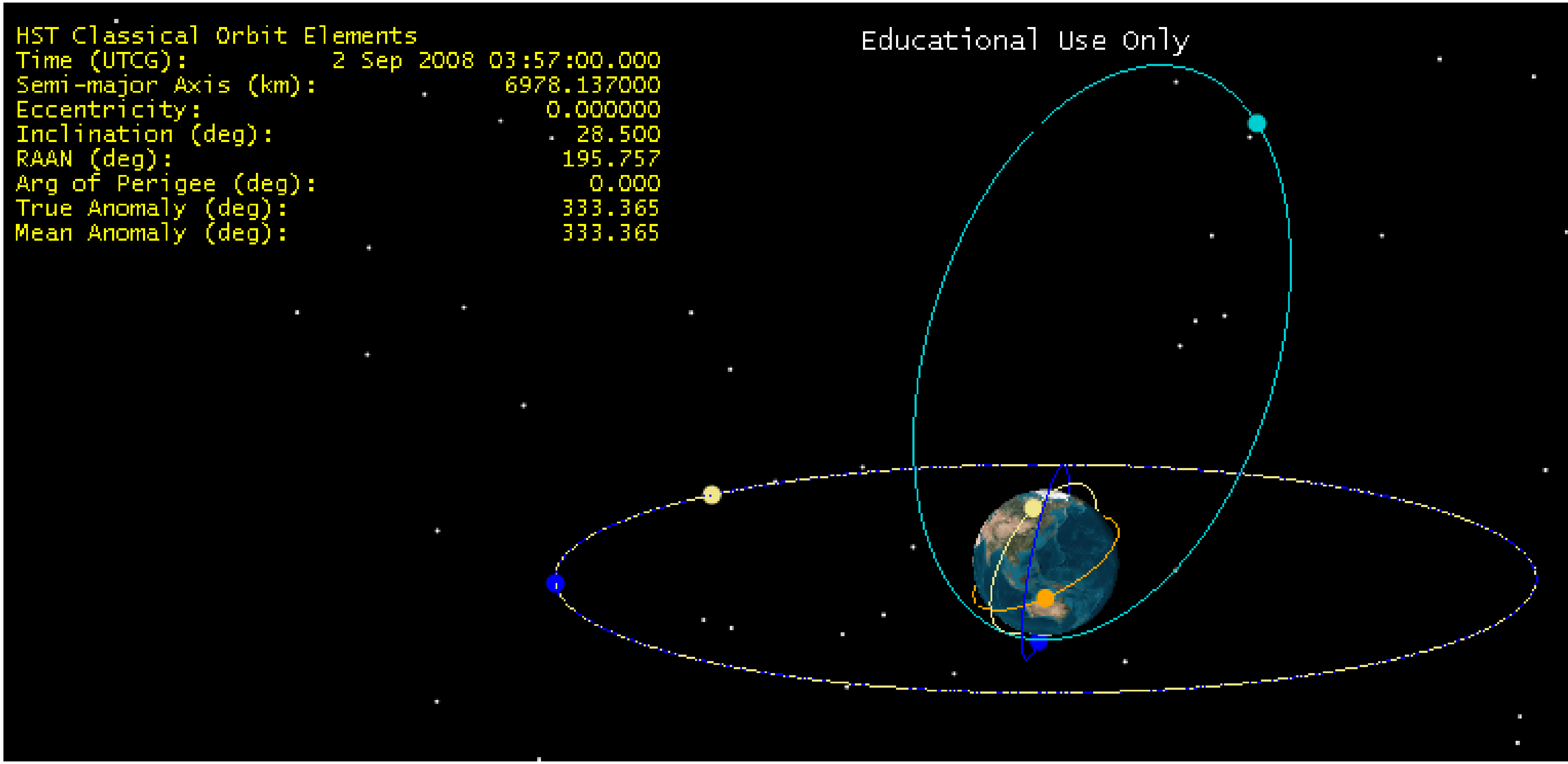
Conclusion 1: Satellites Are Everywhere



LAGRANGE POINTS
(NONLINEAR DYNAMICS !)

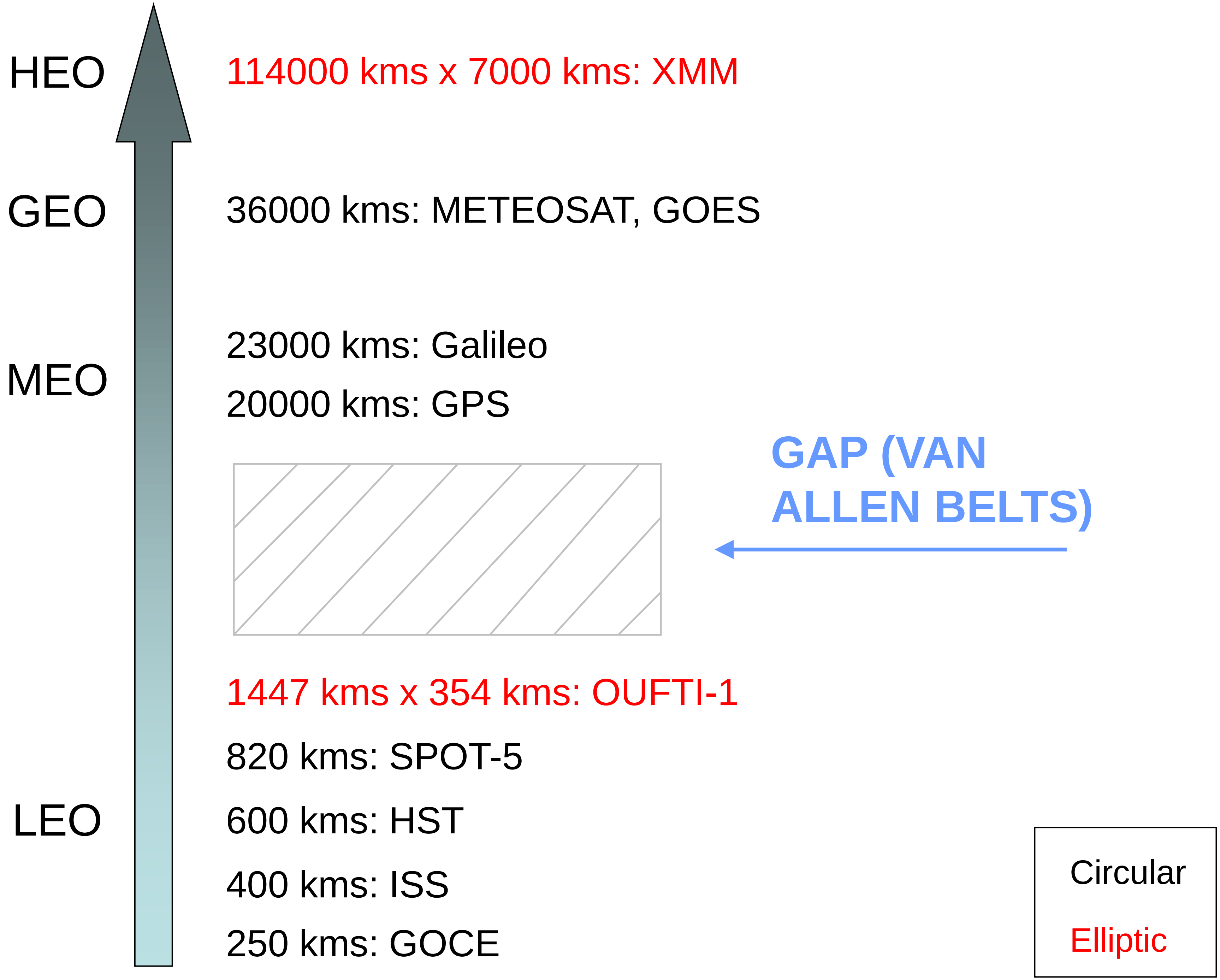


Conclusion 2: Orbits Are Varied



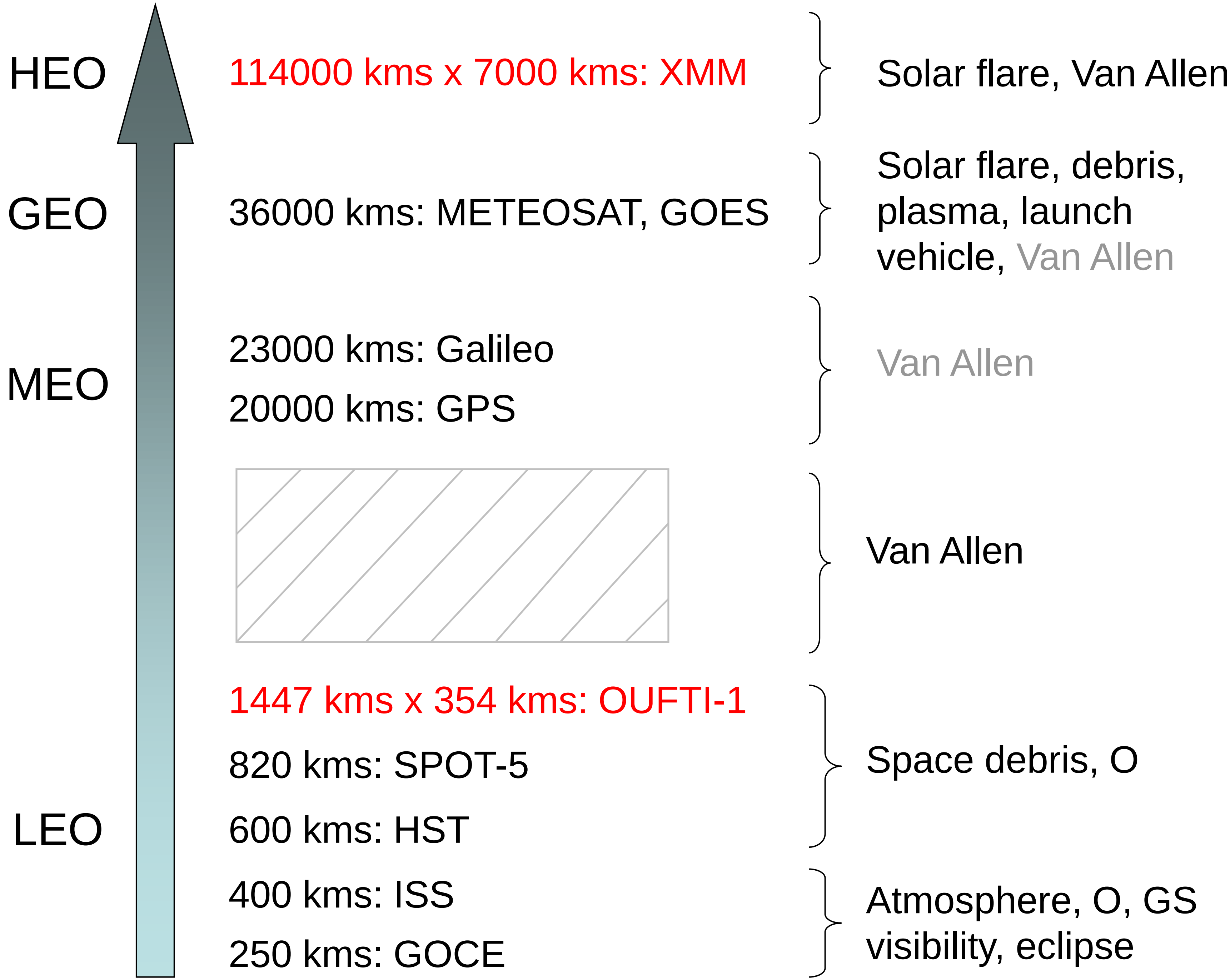
METEOSAT 6-7, HST, OUFTI-1, SPOT-5, MOLNIYA

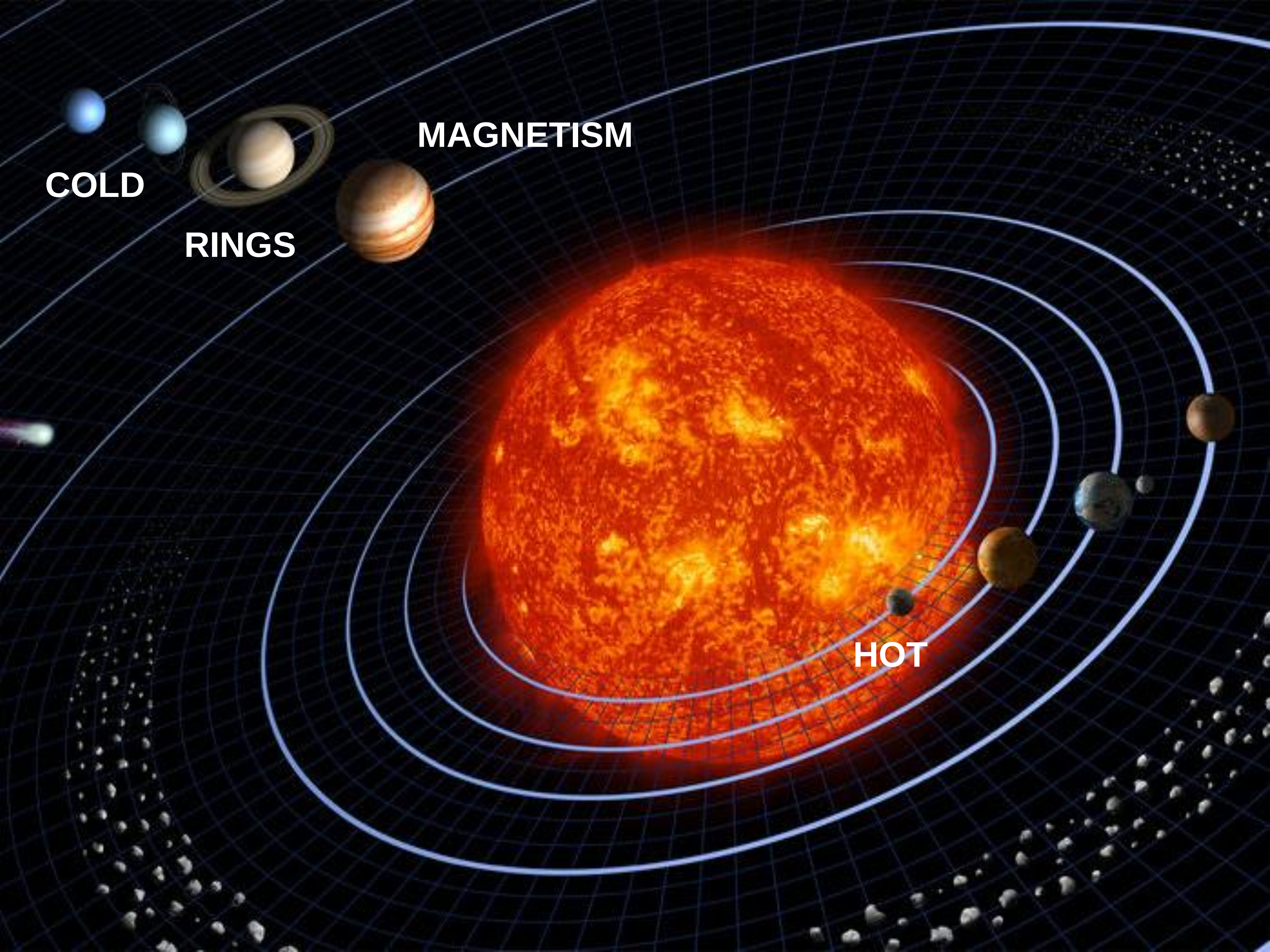
GEO	LEO	LEO	(LEO) SSO	Molniya
i=0	i=28.5	i=71	i=98.7	i=63.4


HEO
114000 kms x 7000 kms: XMM
GEO
36000 kms: METEOSAT, GOES
MEO
23000 kms: Galileo
20000 kms: GPS
GAP (VAN ALLEN BELTS)
1447 kms x 354 kms: OUFTI-1
820 kms: SPOT-5
LEO
600 kms: HST
400 kms: ISS
250 kms: GOCE
Circular
Elliptic

Conclusion 3: Orbit Constraints

Magnetic field, temperatures, atmosphere, launch vehicle, ground station visibility, eclipse duration, …


HEO
114000 kms x 7000 kms: XMM
Solar flare, Van Allen
GEO
36000 kms: METEOSAT, GOES
Solar flare, debris, plasma, launch vehicle, Van Allen
MEO
23000 kms: Galileo
20000 kms: GPS
Van Allen
Van Allen
1447 kms x 354 kms: OUFTI-1
820 kms: SPOT-5
600 kms: HST
Space debris, O
LEO
400 kms: ISS
250 kms: GOCE
Atmosphere, O, GS visibility, eclipse


MAGNETISM
COLD
RINGS
HOT

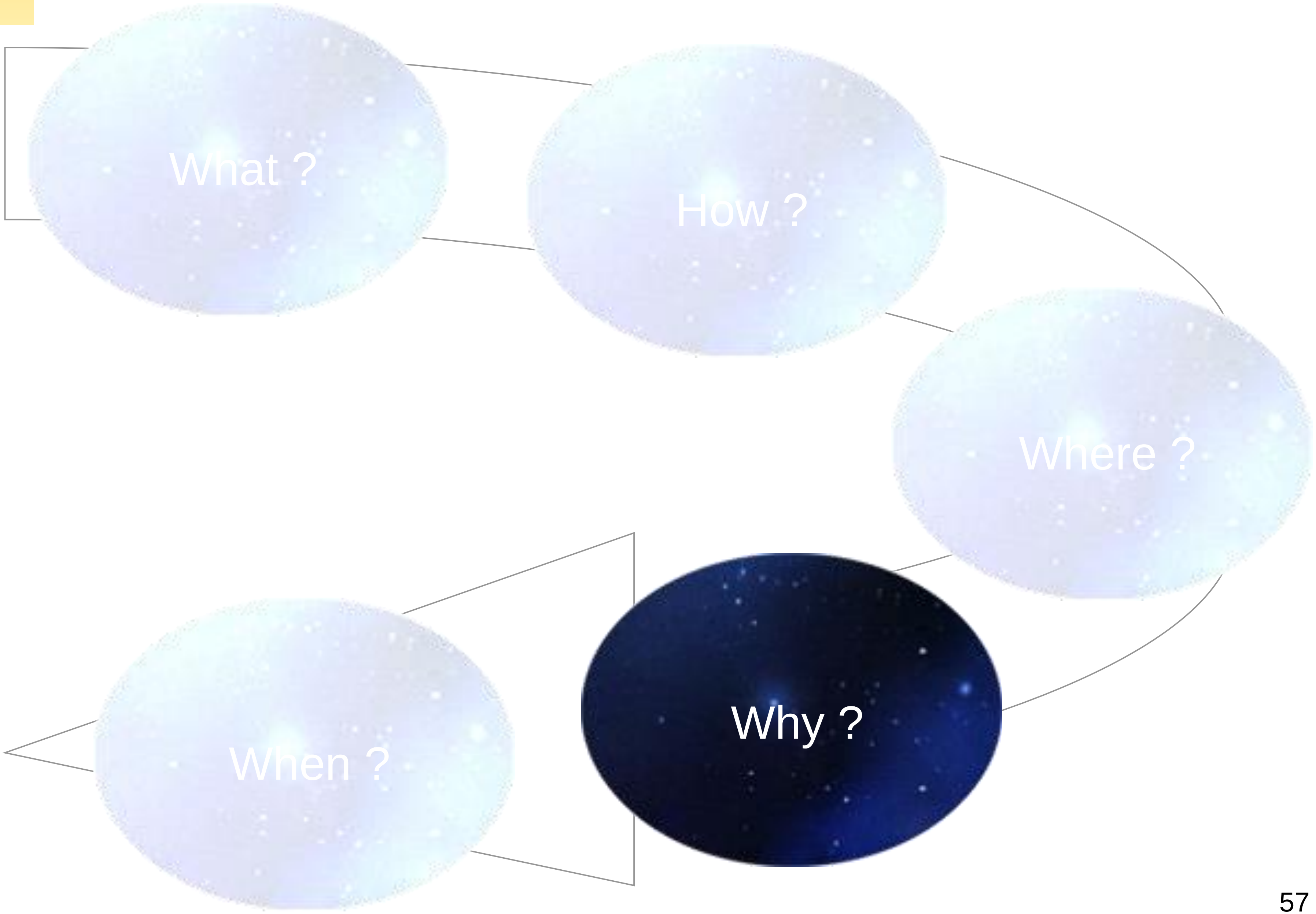
Conclusion 4: Why ? ⇔ Where ?

	LEO (<2000kms)	GEO (35800 kms)
+	High spatial resolution	High temporal resolution
+	Direct launch	Continuous, large coverage
+	Transmission time	Fixed ground antennas
+	SSO	
-	Low temporal resolution	Low spatial resolution
-	Limited duration of visibility	GTO
-	Atmospheric drag (<500km)	Signal round-trip transmission
-	Satellite tracking	

Conclusion 4: Why ? ⇔ Where ?

Communications	GEO (low latitudes) Molniya (high latitudes) Polar LEO (constellation for global coverage)
Weather	GEO (METEOSAT) or polar LEO (METOP)
Earth resources	Polar LEO for global coverage
Navigation	Inclined MEO for global coverage
Astronomy	LEO, HEO, GEO, Lagrange points
Space station	LEO for easy access

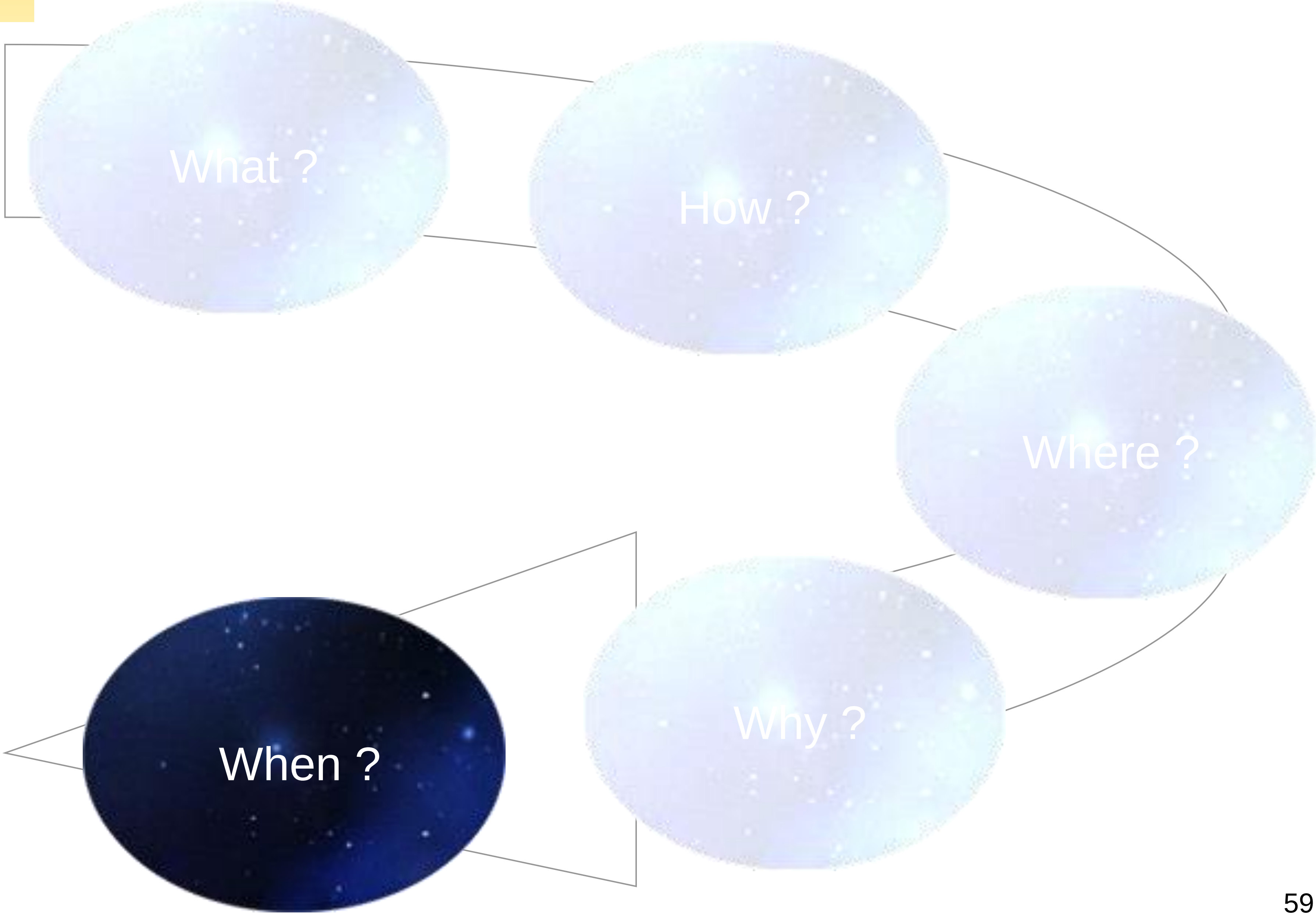
Introductory Lecture



Why ?

Already covered !

Introductory Lecture

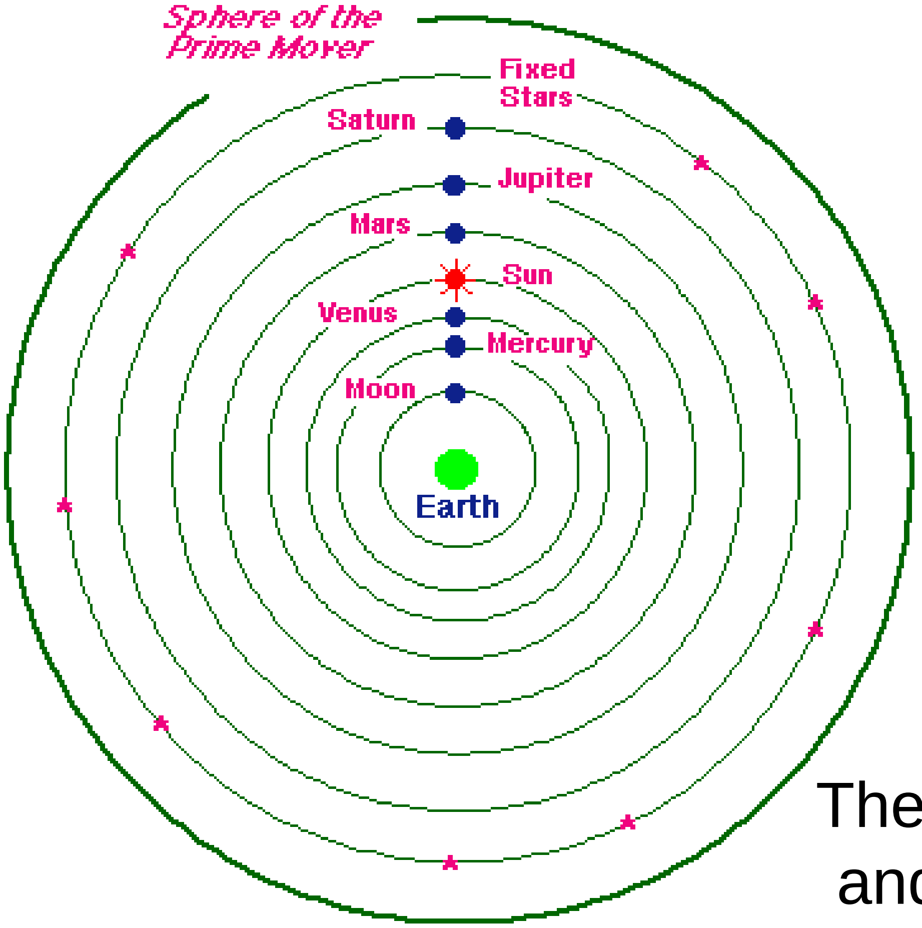


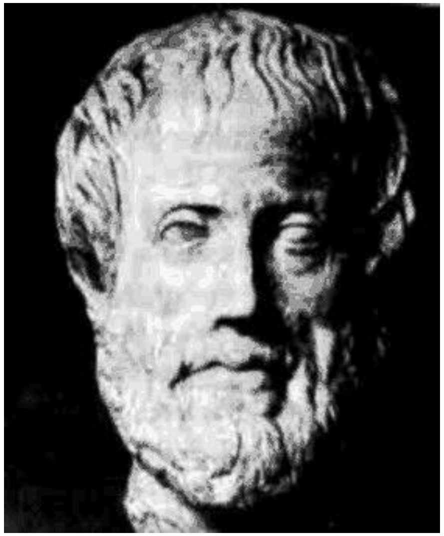
The Company We Keep

Aristotle, Ptolemaeus	*Geocentric theory*
Copernicus, Brahe, Galileo, Kepler, Newton, Halley, Euler, Lambert, Gauss, Lagrange.	*The golden age*
Poincaré, Tsiokolvski, Goddard, Von Braun, Korolev and … Coquilhat	*The modern age*
Sputnik & co…	*The satellite era*

Aristotle (300 BC)

Earth at the center of the universe & uniform circular motion.

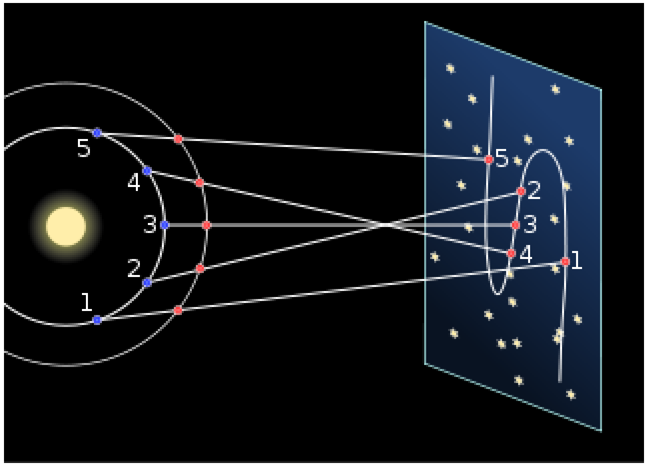


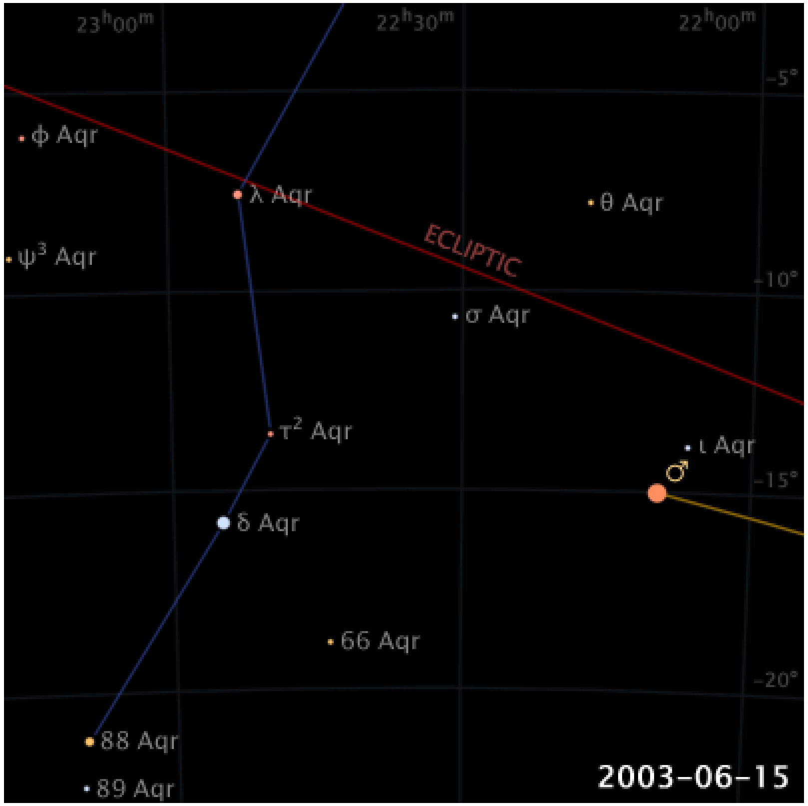


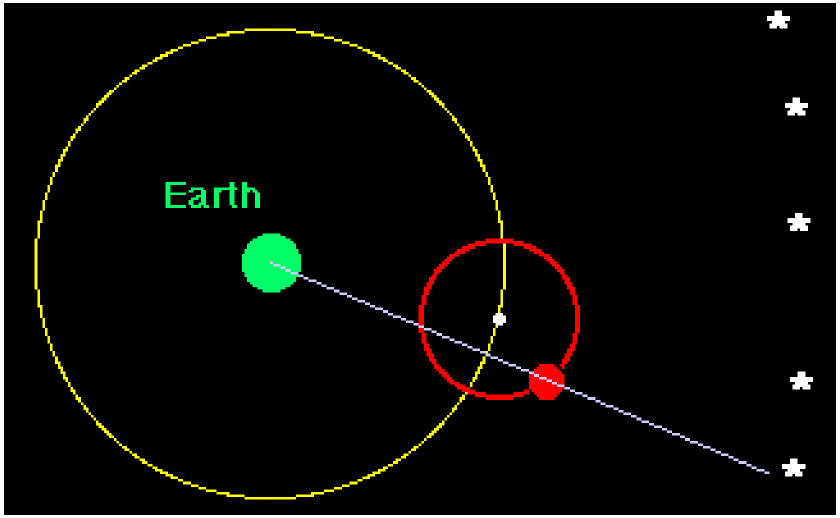
The varying planetary brightness and retrograde motion could not be accommodated !

Retrograde Motion

http://www.scienceu.com/observatory/articles/retro/retro.html







Apparent retrograde motion of Mars in 2003

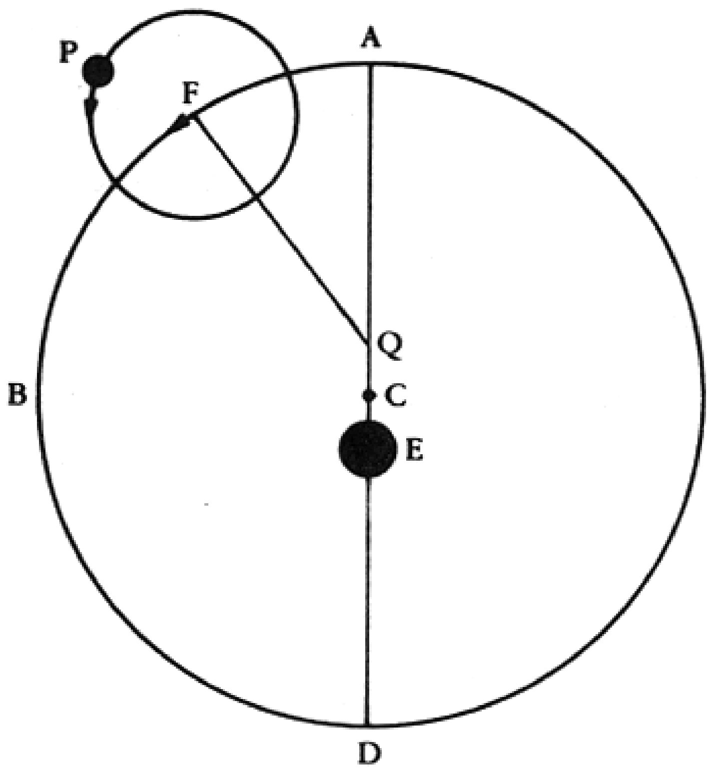
Ptolemaeus (100 AD)

Mathematical constructions that accounted successfully for the motions of heavenly bodies within the standards of observational accuracy of his day.

Varying brightness and retrograde motion explained.

Accepted for over a millennium as the correct model.

Ptolemaic System



E: Earth, P: Planet.

C: Geometric center of the eccentric circle (the Earth is not the center of the cosmos !)

Q: Equant point (imaginary point that "sees" the planet move at a uniform angular speed)

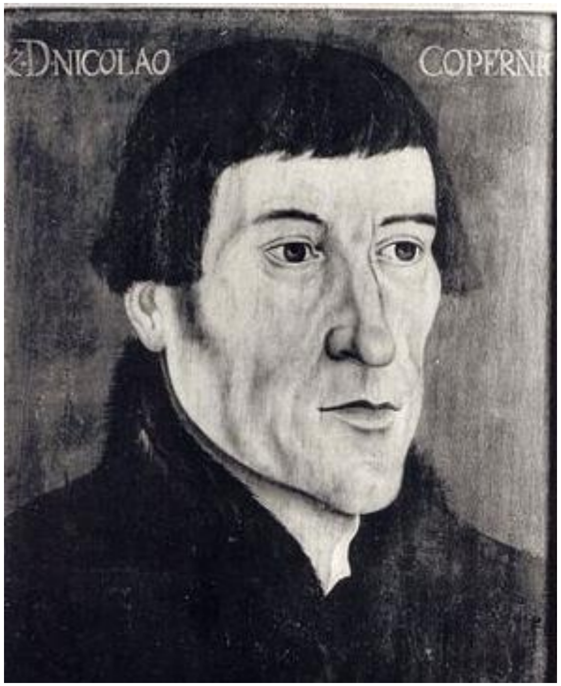
F: Center of the epicycle (to account for the observed retrograde motion of the planets)

Idea: break down the complex observed planetary motion into components with perfect circular motions. **The uniform circular motion is saved !**

http://astro.unl.edu/naap/ssm/animations/ptolemaic.swf

Copernicus (1473-1543, Polish)

First astronomer to formulate a scientifically-based heliocentric cosmology (but other published heliocentric hypotheses centuries before him).



Revolutionibus orbium coelestium (*On the revolutions of the celestial spheres*) is regarded as the starting point of modern astronomy.

All planets on circular orbits around the Sun.

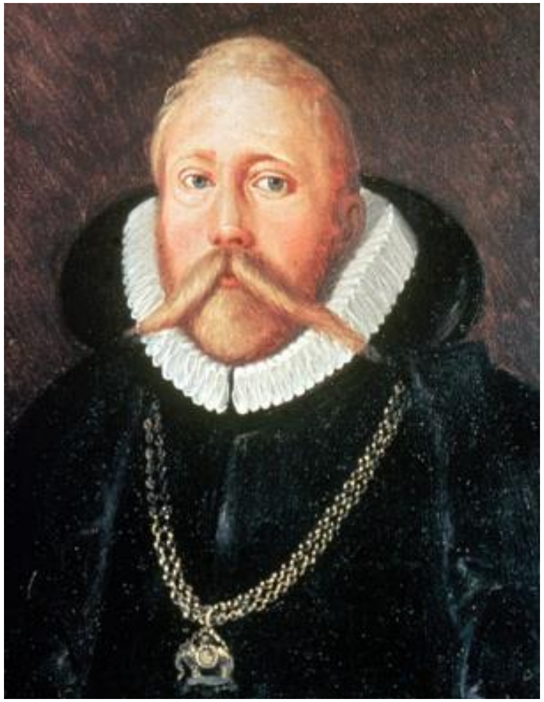
Tycho Brahe (1546-1601, Danish)

Accurate and numerous observations of planetary and star positions in the pretelescope era.

No adequate mathematical tools to exploit these observations.

Earth's axial tilt: 23° 31.5’ (currently 23° 26’).

He believed in geocentrism (the sun orbited the Earth while the other planets orbited the sun).



An experimentalist

Johannes Kepler (1571-1630, German)

Met Tycho Brahe in 1600 and found a mathematical description for his observations. He realized that Brahe's data did not fit a Copernician view of the solar system.

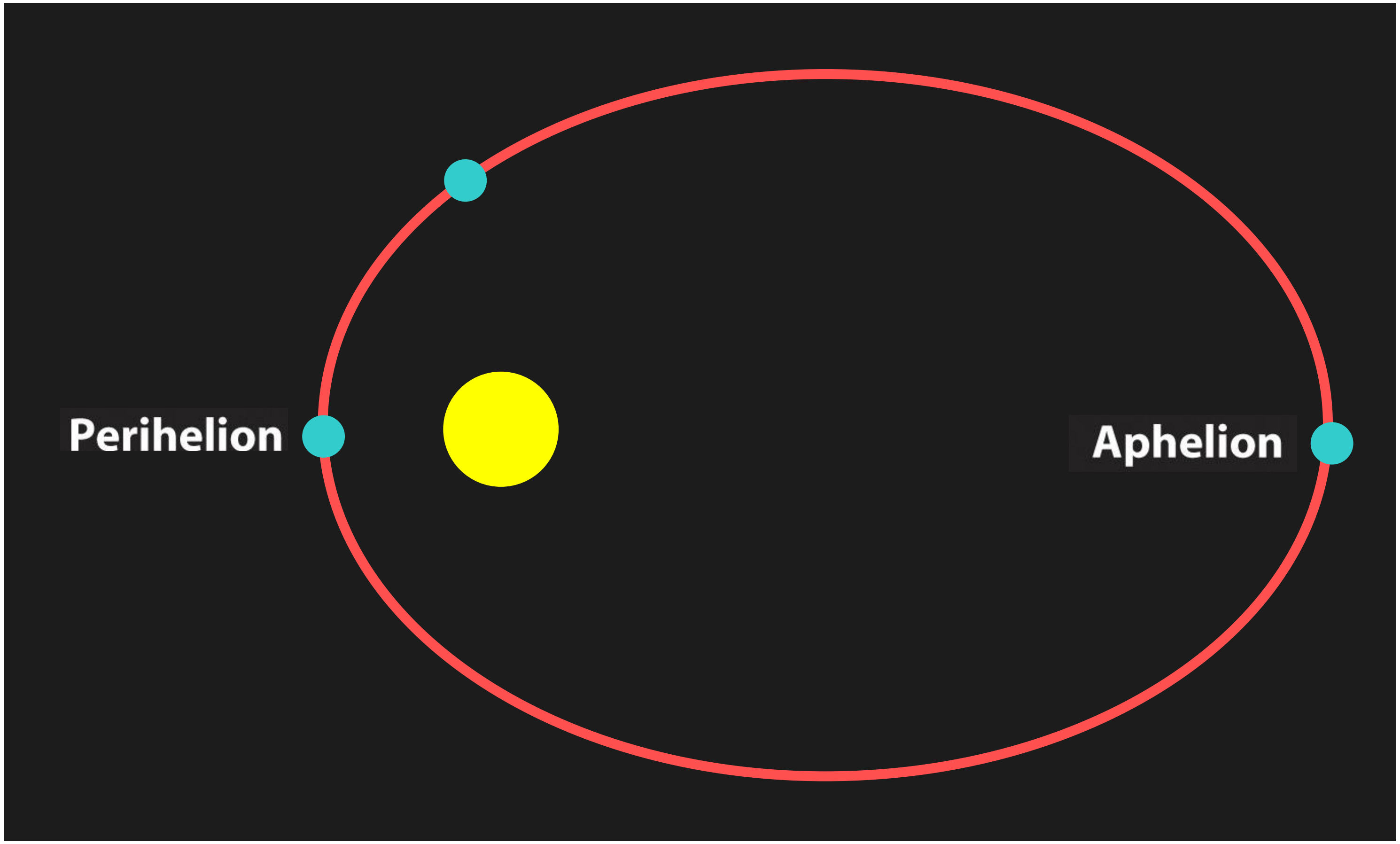
Introduced the idea of elliptic orbits of the planet.

Kepler's primary obligation was to produce horoscopes for the emperor Rudolf II. He considered astrology as a source of income rather than science…

A mathematician

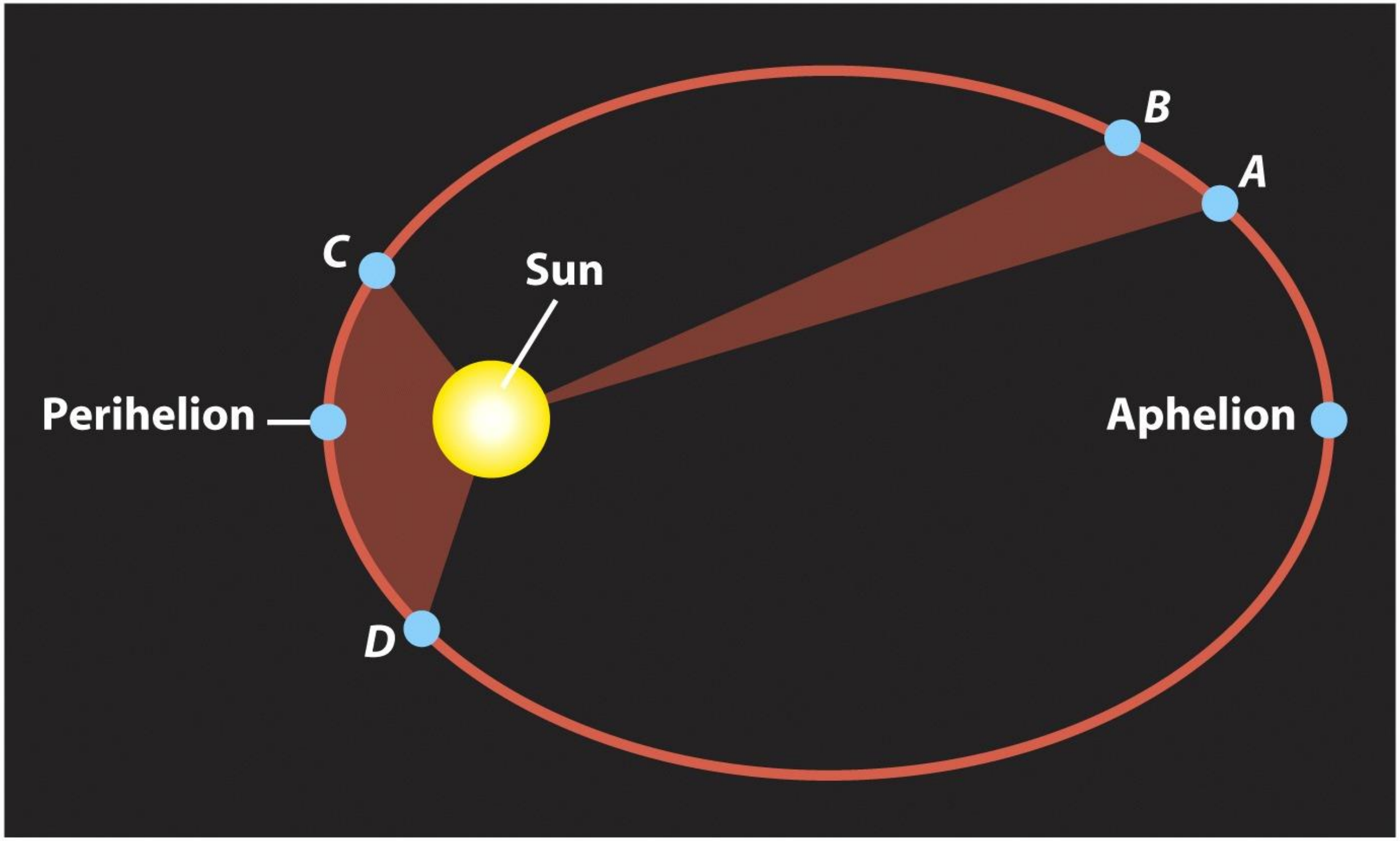
First Kepler's Law (1609)

The orbit of each planet is an ellipse with the sun at one focus.



Second Kepler's Law (1609)

The line from the sun to a planet sweeps out equal areas inside the ellipse in equal lengths of time.



Third Kepler's Law (1619)

The squares of the orbital periods of the planets are proportional to the cubes of their mean distances from the sun.

$$\frac{T_1^2}{T_2^2} = \frac{a_1^3}{a_2^3}$$

T, period

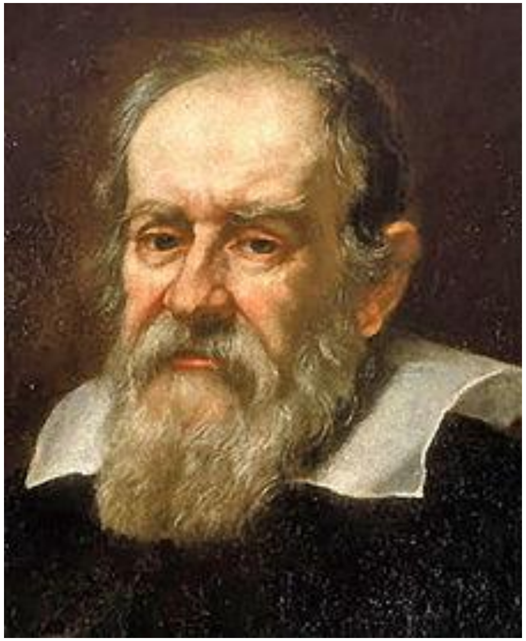
A, semi-major axis

Galileo Galilei (1564-1642)

Did not invent the telescope but greatly improved the design the year following its invention (1609).

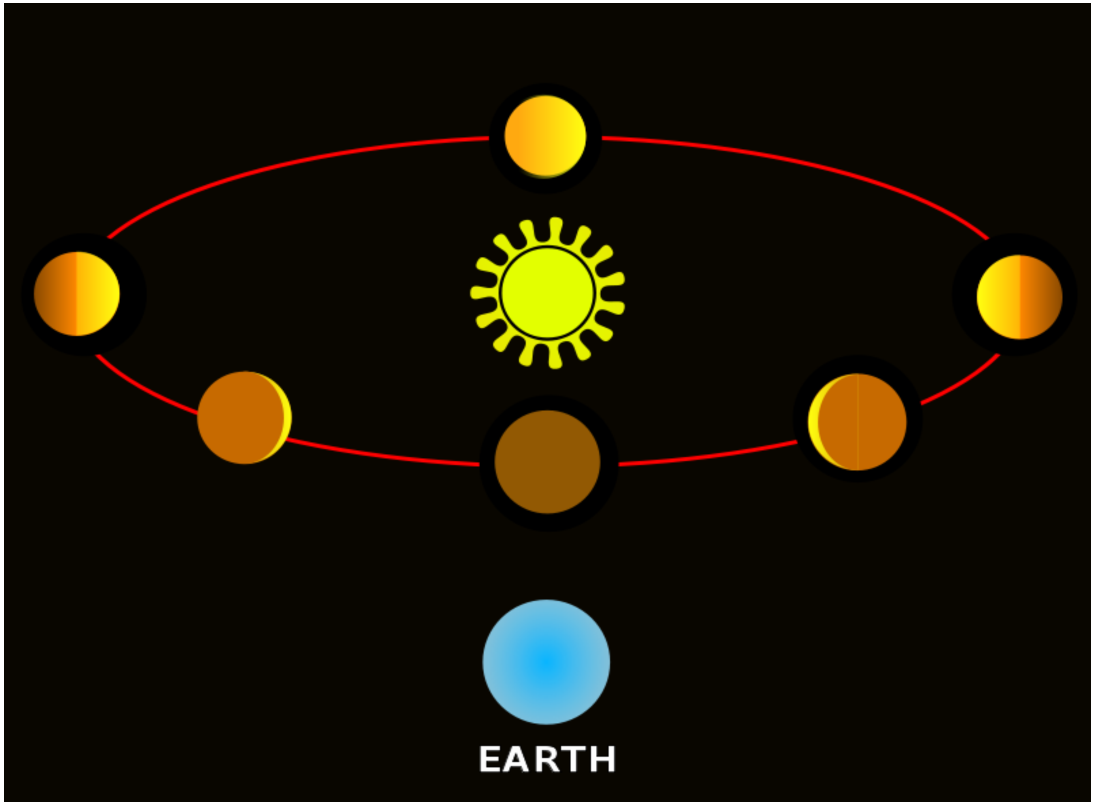
On 7 January 1610 he observed *three fixed stars, totally invisible by their smallness, all within a short distance of Jupiter*.

On 10 January, he noted that one of them had disappeared. Within a few days he concluded that they were orbiting Jupiter. He had discovered Io, Europa and Callisto. He discovered the fourth, Ganymede, on 13 January.



Confirmation of Heliocentric System

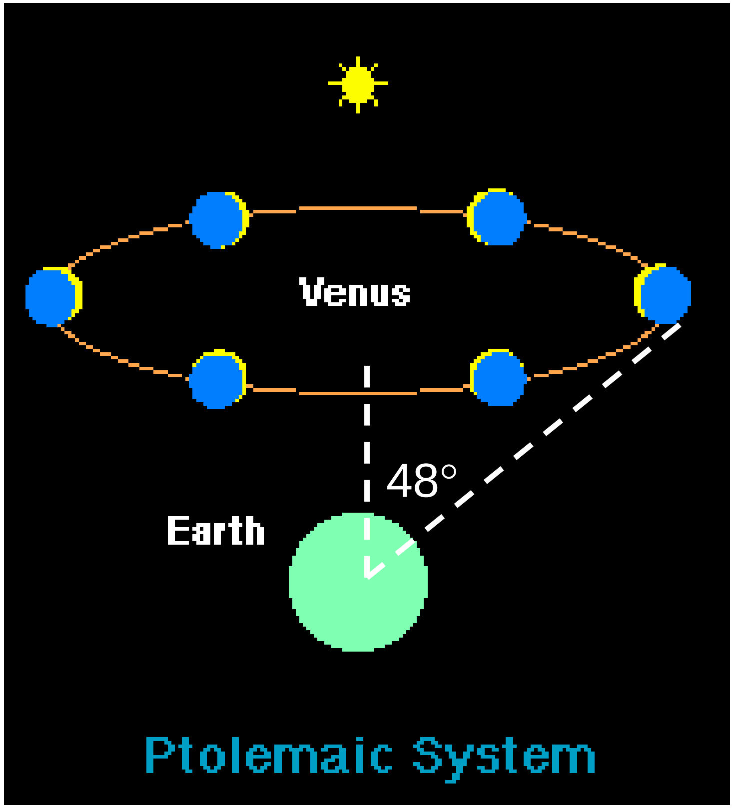
He made the first conclusive observational proof that confirmed the hypothesis of heliocentric system.



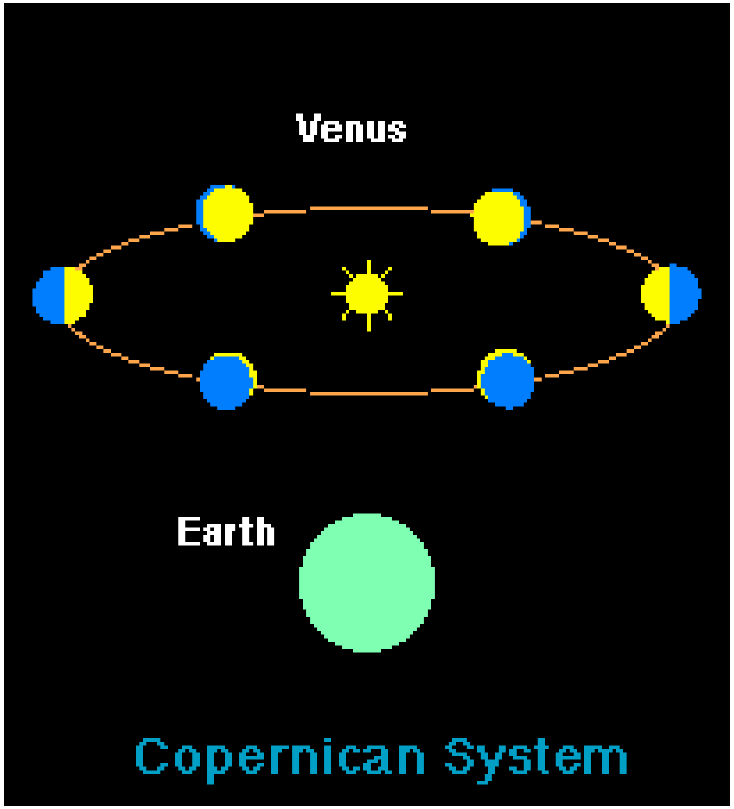
The phases of Venus (1610)

Confirmation of Heliocentric System

Empirical fact: Venus never appeared more than 48°east or west of the sun.



Venus should always be in crescent phase as viewed from the Earth.



Venus should exhibit a complete set of phases over time as viewed from the Earth.

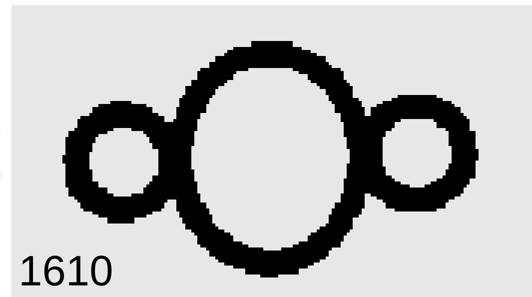
Other Key Discoveries

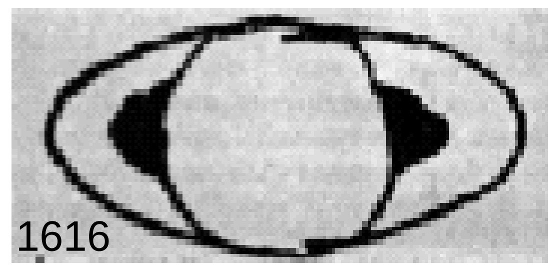
The first to observe Saturn's rings (1610). In 1612, he noted that the rings had “disappeared” ! In 1616, they “reappeared”.

One of the first to observe sunspots in 1612 (the sun rotates !).

Discovered lunar mountains and craters and estimated of the mountains’ heights.

Observed Neptune (1612) but did not realize it was a planet.





Galileo’s sketches of Saturn

Controversy

Among other things, Galileo openly questioned the veracity of the Book of Joshua (10:13) wherein the sun and moon were said to have remained unmoved for three days to allow a victory to the Israelites.

He was found vehemently suspect of heresy (Roman Inquisition).

He was eventually forced to recant his heliocentrism and spent the last years of his life under house arrest.

Kinematics vs. Dynamics of Motion

Kepler developed, using Tycho Brahe's observations, the first kinematic description of orbits.

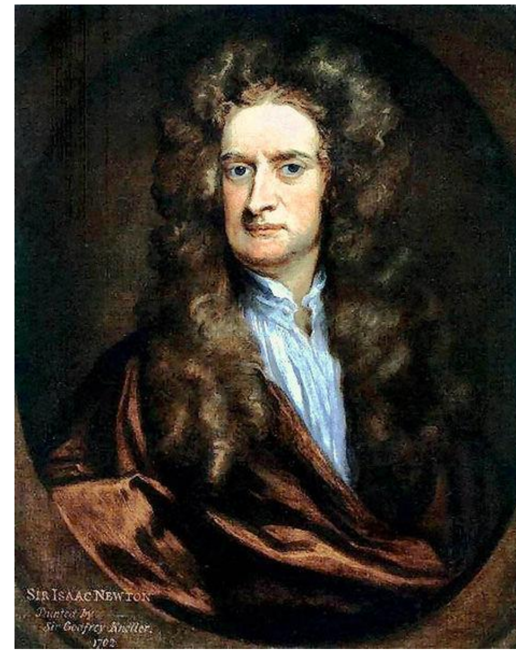
But a dynamic description that involves the underlying influence (gravity) was missing.

Isaac Newton (1642-1727, English)

Introduced the three laws of motion.

Introduced the inverse square law of gravitational force.

$$\vec{F} = G\frac{Mm}{\|\vec{r}\|^3}\vec{r}$$



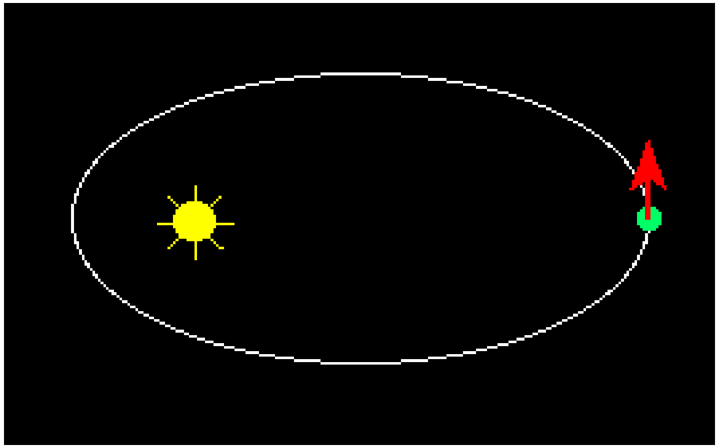
A physicist/engineer

Philosophiae Naturalis Principia Mathematica (1687) is considered to be the most influential book in the history of science.

Developed the first "practical" reflecting telescope.

Kepler's Laws and Gravitation

Demonstrated the consistency between Kepler's laws and his theory of gravitation, removing the last doubts about heliocentrism.



Kepler's first and third laws are a natural consequence of the inverse-square gravitational force field of the sun.

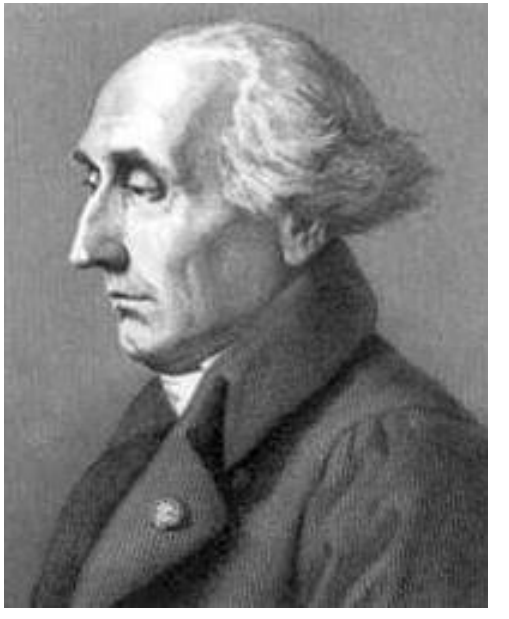
Kepler's second law is a consequence of the conservation of angular momentum.

Lagrange (1736-1813, Italian)

Worked on the restricted three-body problem and found in 1772 five fixed points where the third body experiences zero net force.

These points were named Lagrange points or libration points (concept of Halo orbits widely used: SOHO,JWST).

It took over a hundred years before his mathematical theory was observed with the discovery of the Trojan asteroids in the 1900s at the Lagrange points of the Sun–Jupiter system.



1500-1800: The Golden Age

By 1800, the physics laws which govern astrodynamics were known. These same principles are used today for orbit prediction, orbit determination and mission design

Poincaré (1854-1912, French)

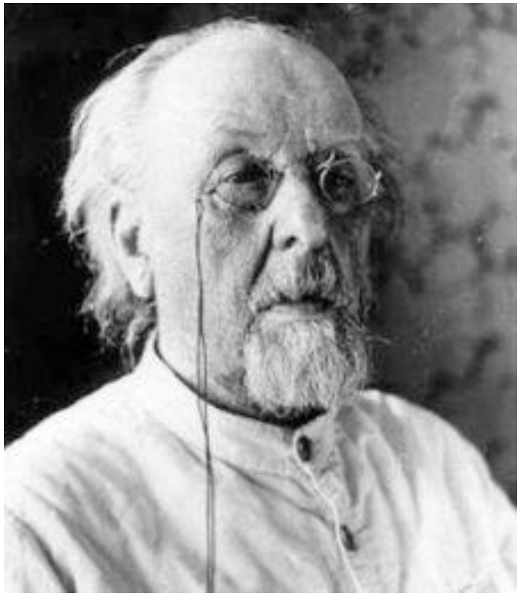
Established the concept of non-integrable dynamical system.

In his research on the three-body problem, he became the first person to discover a chaotic deterministic system which laid the foundations of modern chaos theory.

Tsiolkovsky (1857-1935, Russian)

Published calculations in 1898 and 1903 that described in depth the use of rockets for launching orbital space ships. The first academic treatise on rocketry.

Never built any practical models.



$$\Delta v = v_e \ln \frac{m_0}{m_1}$$

v_e, exhaust velocity
m_0 initial mass
m_1 final mass

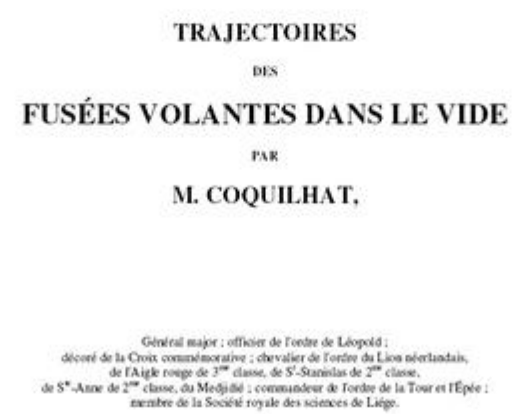
Rocket equation

But… Coquilhat (1811-1890, Belgian)

Established the rocket equation in 1873 !

Trajectoires des fusées volantes dans le vide, Mémoires de la Société Royale des Sciences de Liège.

Recent “discovery”.



TRAJECTOIRES

DES

FUSÉES VOLANTES DANS LE VIDE

PAR

M. COQUILHAT,

Général major ; officier de l'ordre de Léopold ;
décoré de la Croix commémorative ; chevalier de l'ordre du Lion néerlandais,
de l'Aigle rouge de 3^{me} classe, de S^{t}-Stanislas de 2^{me} classe,
de S^{te}-Anne de 2^{me} classe, du Medjidié ; commandeur de l'ordre de la Tour et l'Épée ;
membre de la Société royale des sciences de Liége.

Goddard (1882-1945, American)

Launched the world's first modern rocket in March 1926 (liquid-fueled).

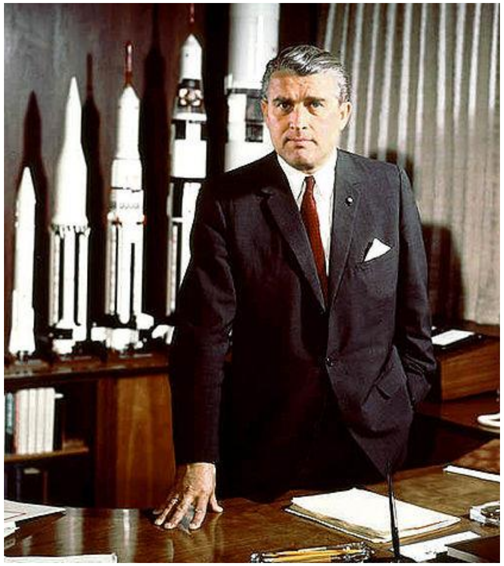
Von Braun (1912-1977, German)

One of the most important rocket developers (1930s-1970s).

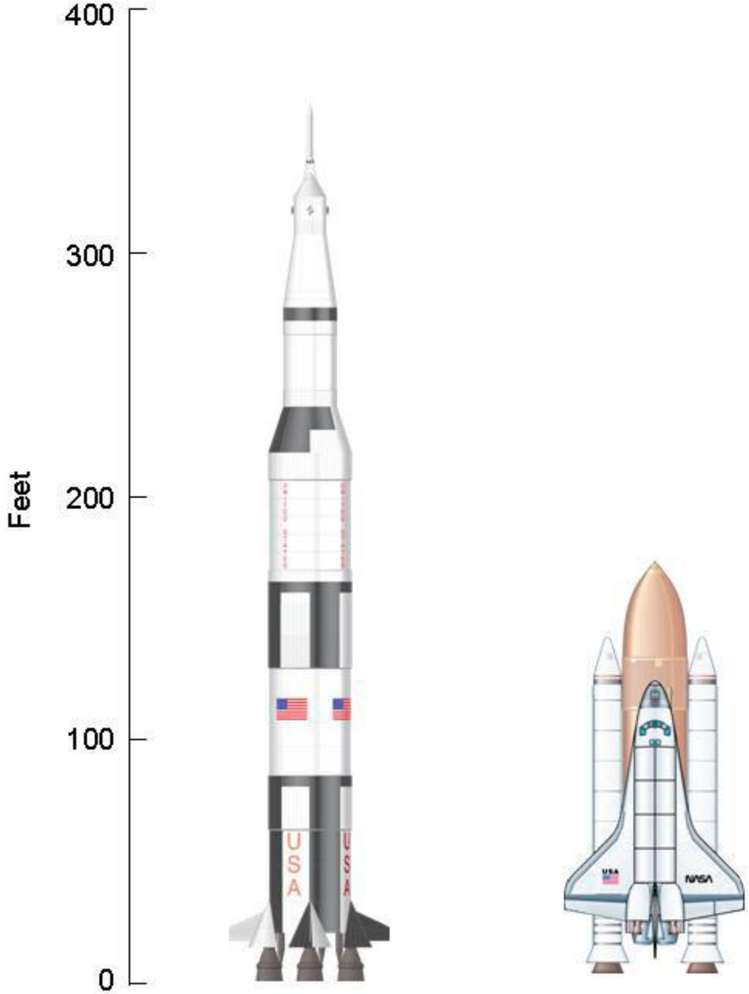
Leader of the "rocket team" which developed the V-2 ballistic missile for the Nazis during World War II.

After World War II, he worked with the USA. He built the Jupiter ballistic missile, used to launch Explorer I.

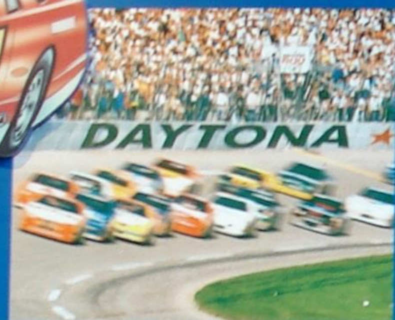
Chief architect of the Saturn V launch vehicle.



Saturn V



MORE POWERFUL THAN...



EIGHT THOUSAND DAYTONA 500 STARTING FIELDS

The Saturn V's first stage alone generated approximately 160,000,000 horsepower. That makes it over eight thousand times more powerful than all of the race cars in this year's Daytona 500 combined.

ELECTRICITY TO NYC FOR 1-1/4 HOURS

The Saturn V's first two stages together generated enough energy to have supplied electricity to New York City for over one hour and fifteen minutes.

POWER

OVER TWO HUNDRED F-18 JET FIGHTERS

The five F-1 engines in the rocket's first stage together generated over 7.5 million pounds of thrust, a force larger than the thrust produced by two hundred thirteen F-18 jet fighters.

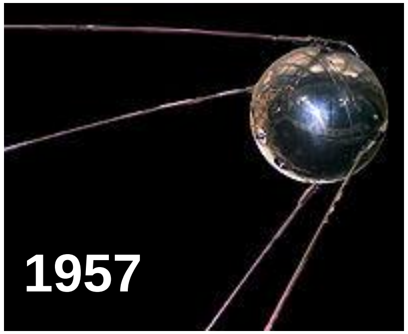
Korolev (1907-1966, Russian)

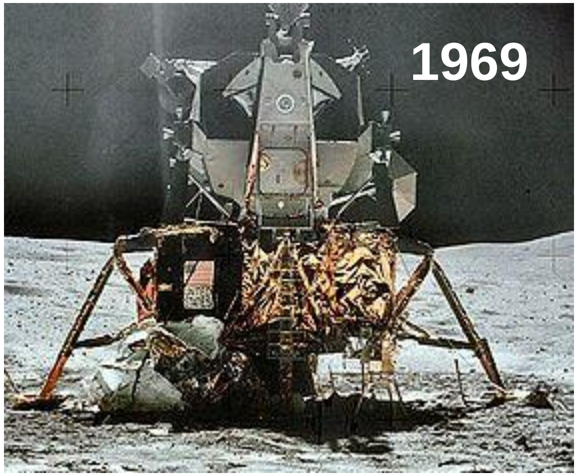
Flew to Germany to recover the technology of the V-2 rocket and produced a working replica of the rocket, R-1.

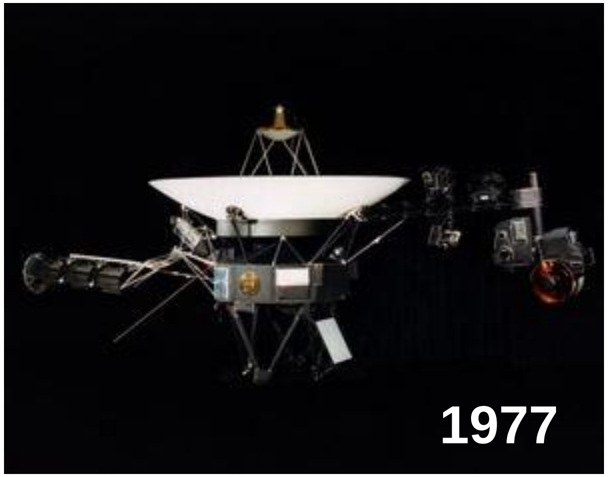
Produced the first intercontinental ballistic missile, the R-7 Semiorka which could carry the Soviet's nuclear bombover a distance of 7000 km.

In modified form, the R-7 launched Sputnik in October 1957, the first artificial satellite, into orbit, and became the basis for the Soyuz space launcher.

The Satellite Era





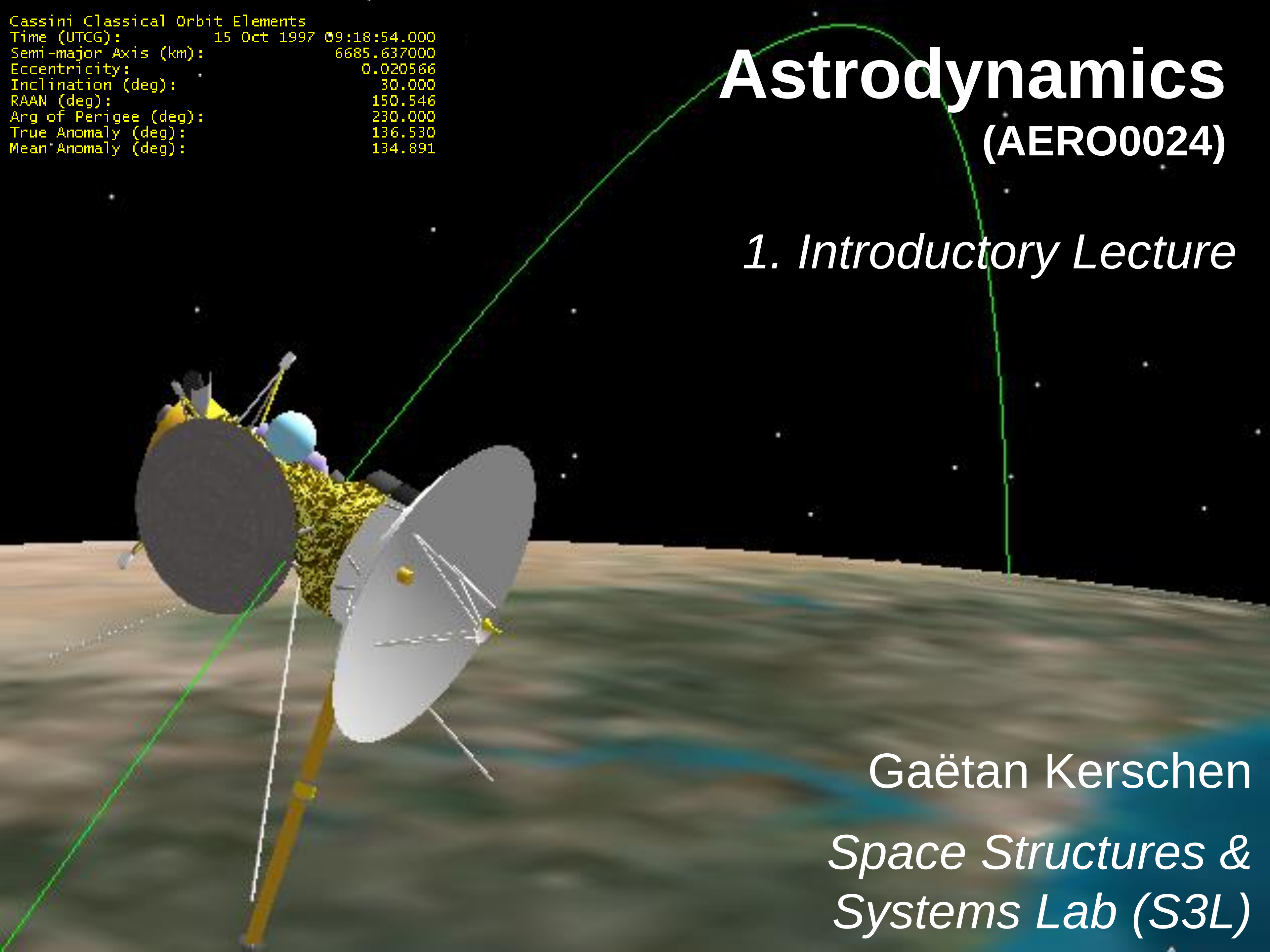


1975

The Satellite Era

The Satellite Era

The Satellite Era



Astrodynamics
(AERO0024)

1. Introductory Lecture

Gaëtan Kerschen

Space Structures & Systems Lab (S3L)