SOLAR-C Plan-A Mission

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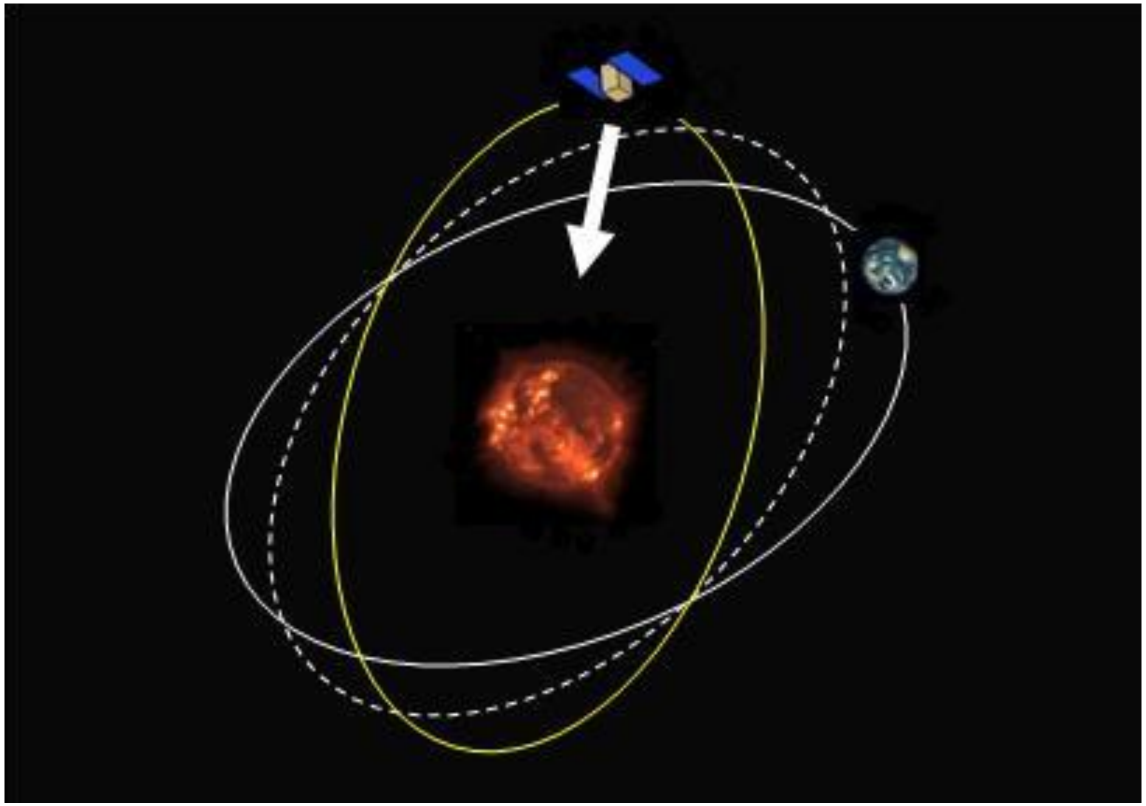
SOLAR-C WG
2008 Nov 18

Outline

- Science
- Scientific payload
- Orbit   (presentation by Dr. Kawakatsu)
- A spacecraft system
- Output from this meeting
  - Target orbit inclination to achieve science goal
- Summary

Mission Description

- Exploration of the Sun (and heliosphere) with spacecraft in an out-of-ecliptic interplanetary orbit from 1AU distance



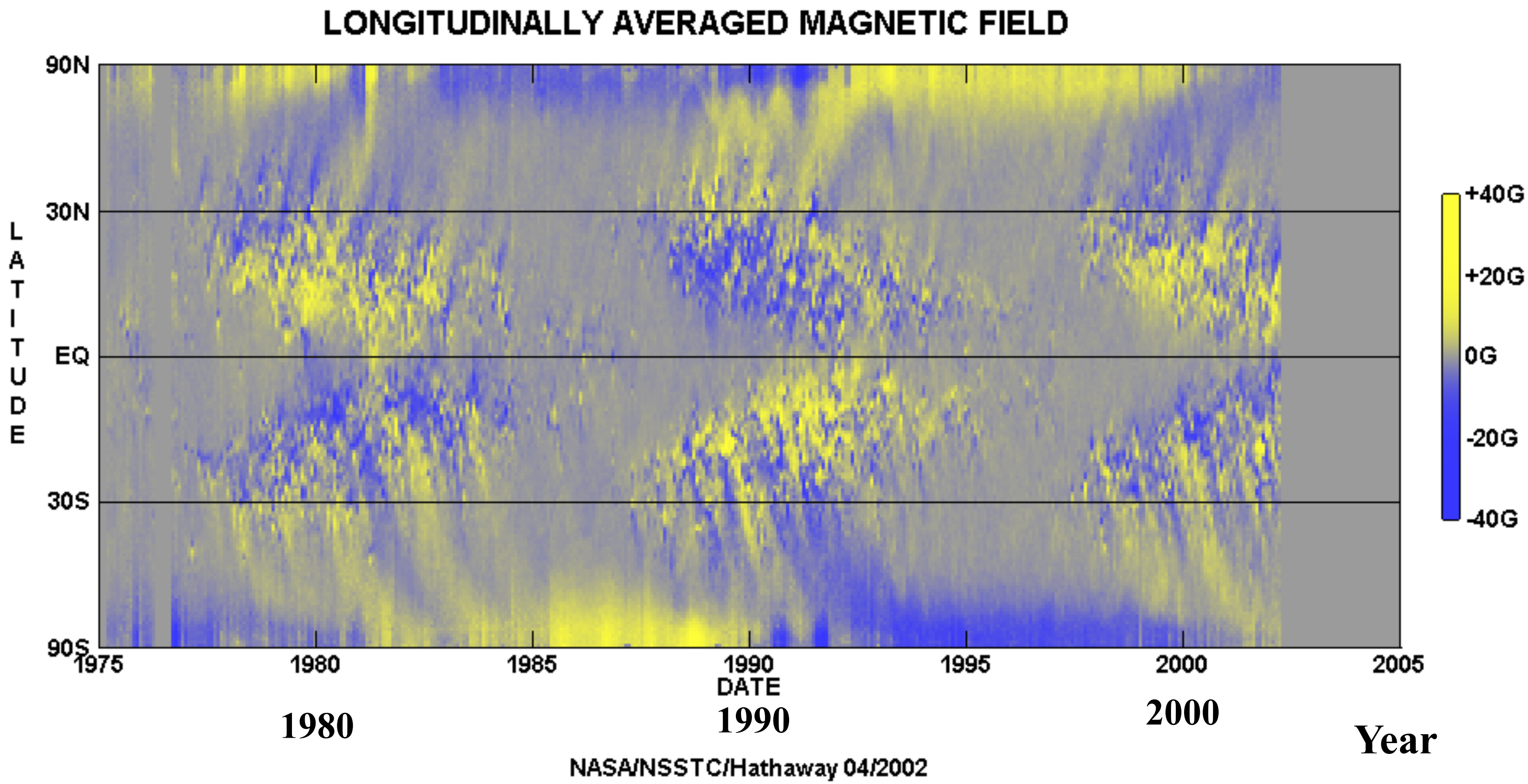
Scientific Objectives

- How are magnetic fields created in the sun?
  - Obtain missing information on angular rotation speed and meridional flows in high-latitude and polar regions
  - Can we discover a difference of a large-scale convective motion between the equator and poles?
  - Explore the magnetic flux tube at the tachocline
- Understand how polar fields are reversed
- Understand what causes the high coronal activity in polar regions
- Understand how the fast solar wind is accelerated
- Measure the solar irradiance variation as a function of latitude to understand the variability of sun-like stars
- Study influence of the sun to heliosphere

Dr. Yokoyama presents his view on the Science Objectives of SOLAR-C plan-A, mainly on the solar dynamo.

Solar Magnetic Activity Cycle

- How are magnetic fields created in the sun? (Dynamo)

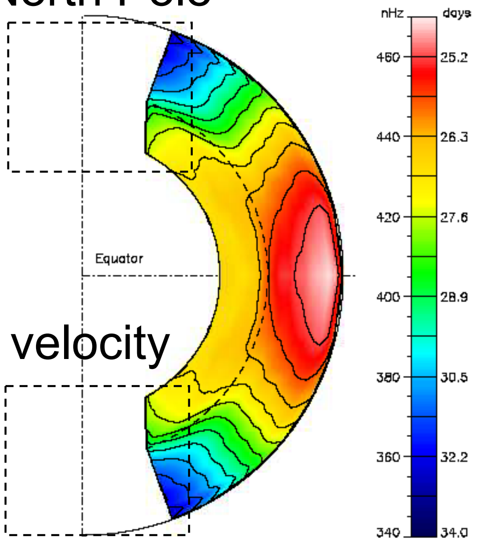


Dr. Rempel provides a presentation on the solar dynamo.

Rotation and Meridional Flows

- Basic quantities to understand the solar dynamo
- cannot be determined from observations in ecliptic plane for high-latitude and polar regions
- Need out-of-ecliptic helioseismic observations to fill up for all latitude regions

North Pole

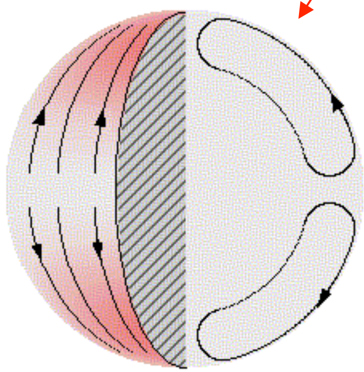


Angular velocity

South Pole

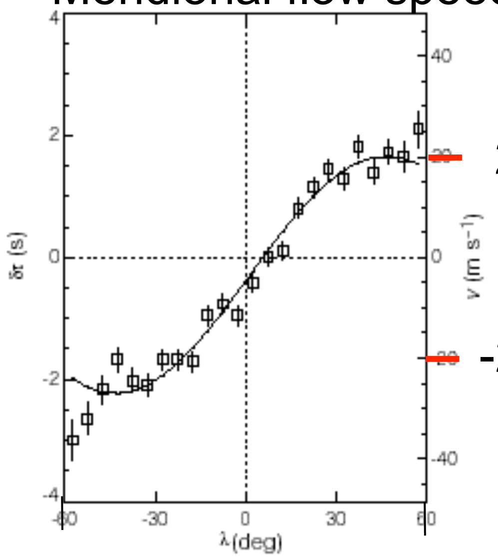
Submergence of magnetic field？

Surface magnetic field transport



Meridional flow

Meridional flow speed



20m/s

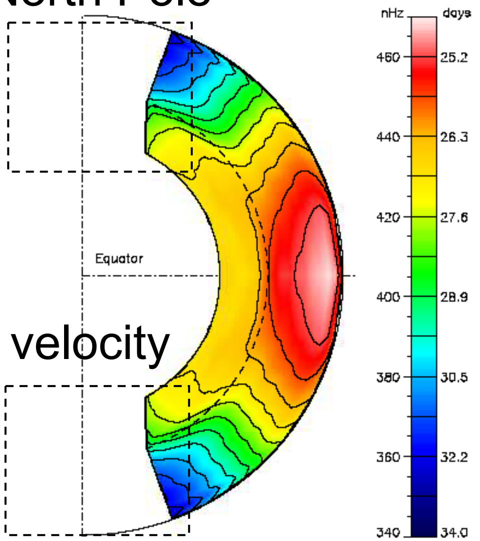
-20m/s

-60 deg Latitude 60 deg

Rotation and Meridional Flows

- Basic quantities to understand the solar dynamo
- Dr. Kosovichev and Dr. Gizon show the science topic of helioseismology and helioseismic technique for Plan-A mission.
- fill up for all latitude regions

North Pole

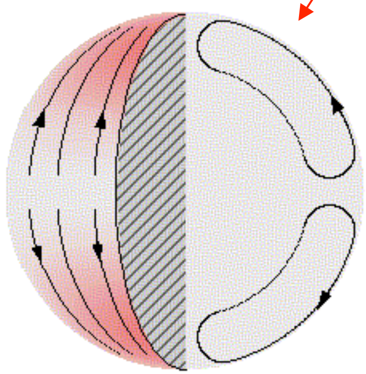


Angular velocity

South Pole

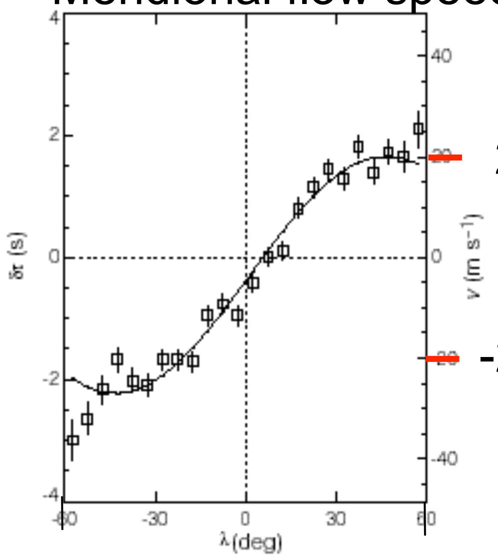
Submergence of magnetic field？

Surface magnetic field transport



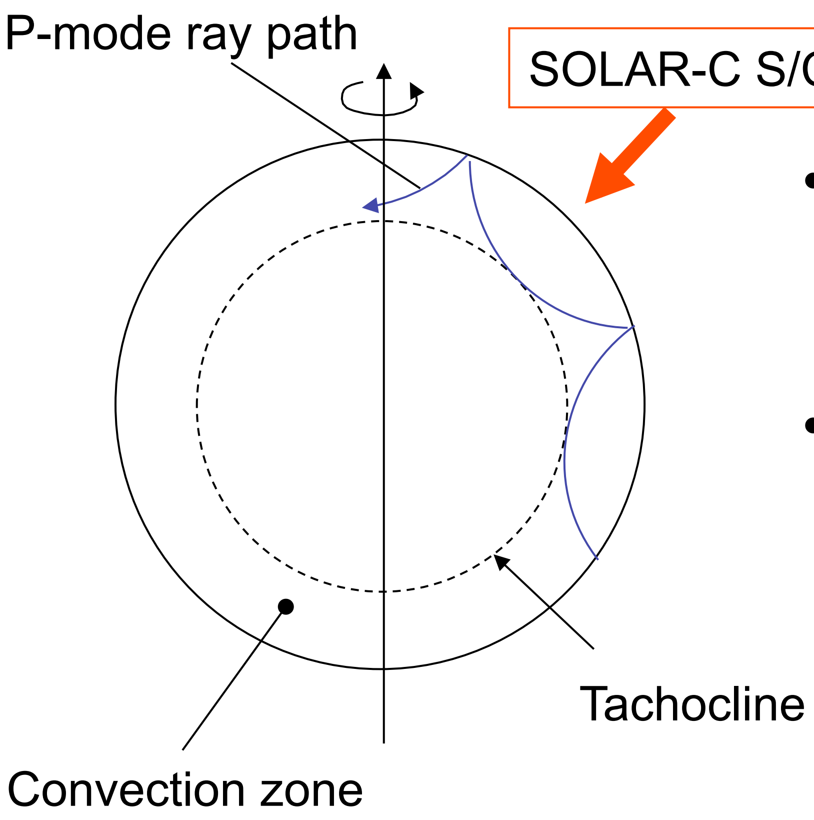
Meridional flow

Meridional flow speed



-60 deg Latitude 60 deg

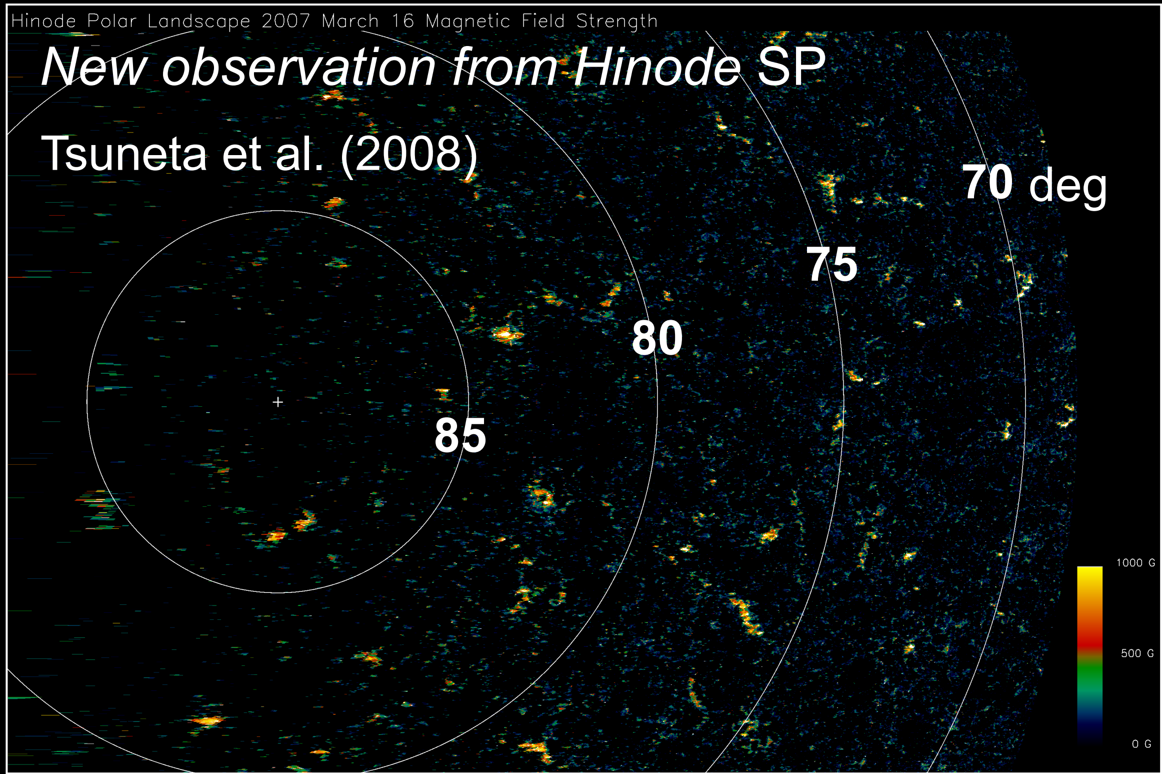
Flux tube search at depth of tachocline



- Intense magnetic flux tube is thought to be created at the tachocline.
- Search of magnetic flux tube near tachocline may be possible by a large skip angle method of local helioseismology.

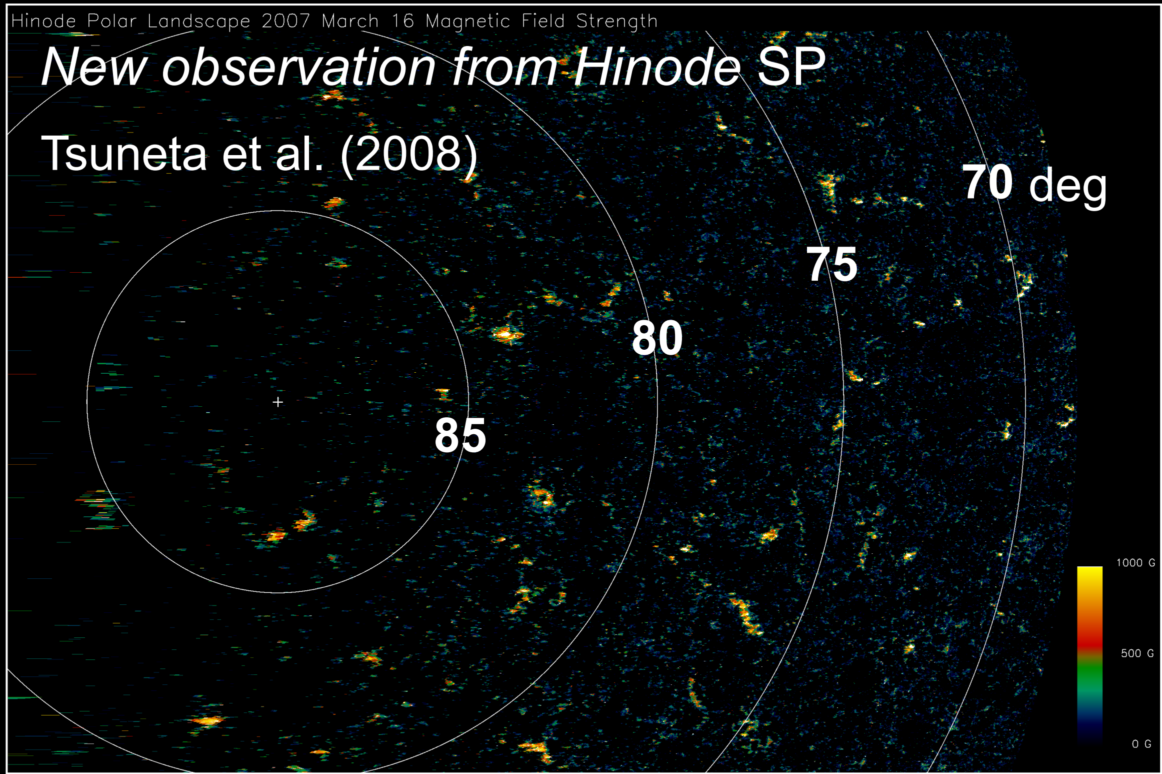
Dr. Sekii presents his estimate on
whether the signature of magnetic flux is detected at tachocline.

Polar Magnetic Fields



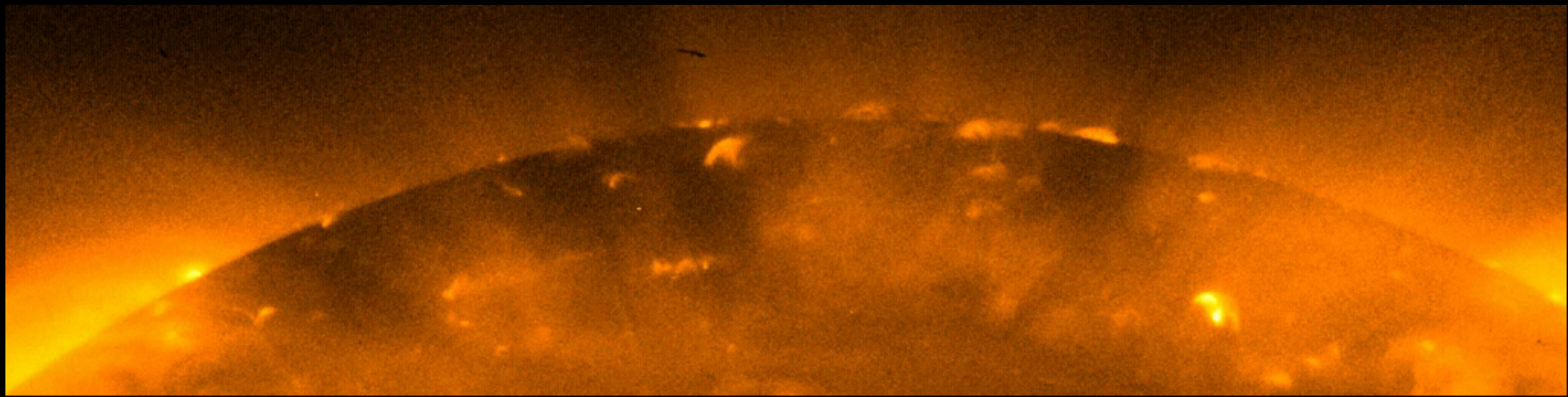
- What is the shape of global polar fields?
- How are polar fields reversed near solar maximum?
- What is the source of ubiquitous horizontal fields?

Polar Magnetic Fields



- Knowledge from recent Hinode observations and science topic of SOLAR-C plan-A by Dr. Tsuneta
- Comments on polar fields from SOLIS obs. by Dr. Harvey
- Polar magnetic flux budget and dynamo by Dr. Schrijver

Polar Coronal Activity

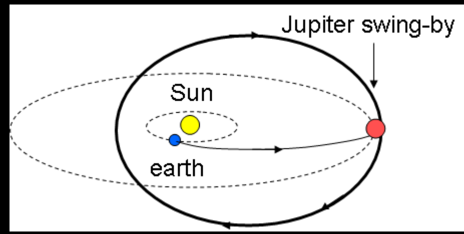


Hinode XRT

- Dynamic polar regions of the sun
- Highly transient jets
- More stable plumes in EUV images
- Source of high-speed solar wind

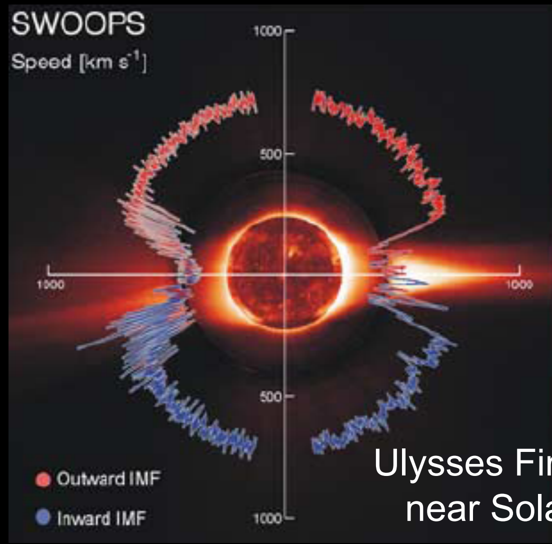
Dr. Cirtain shows a presentation on the science topic of coronal activity from out-of-ecliptic orbit.

Solar Wind

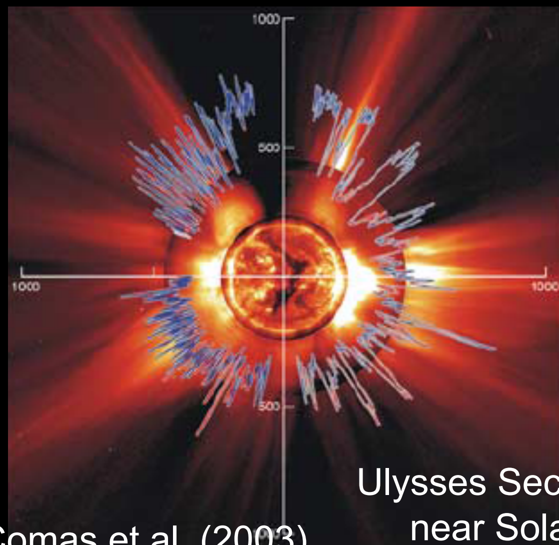


- How is the high-speed solar wind from polar coronal holes accelerated?
- Measurement of global magnetic fields in polar coronal holes, flows in transition region and low corona, and the wind speed may provide the linkage between sun and inner heliosphere.

Dr. Sakurai and Dr. Imada show their views on the acceleration of solar winds and what should be done by SOLAR-C



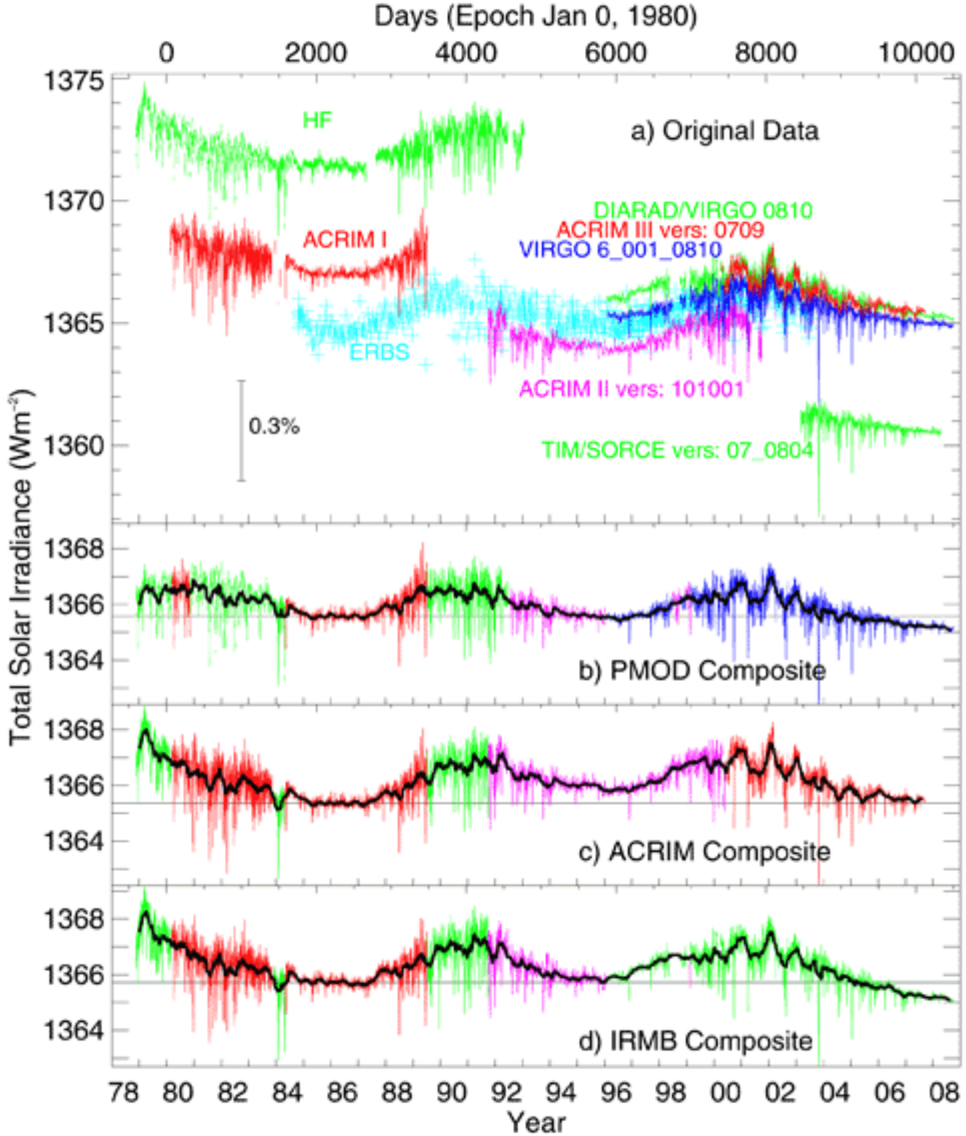
Ulysses First Orbit near Solar Min



Ulysses Second Orbit near Solar Max

McComas et al. (2003)

Total Solar Irradiance (TSI) from out-of-ecliptic plane



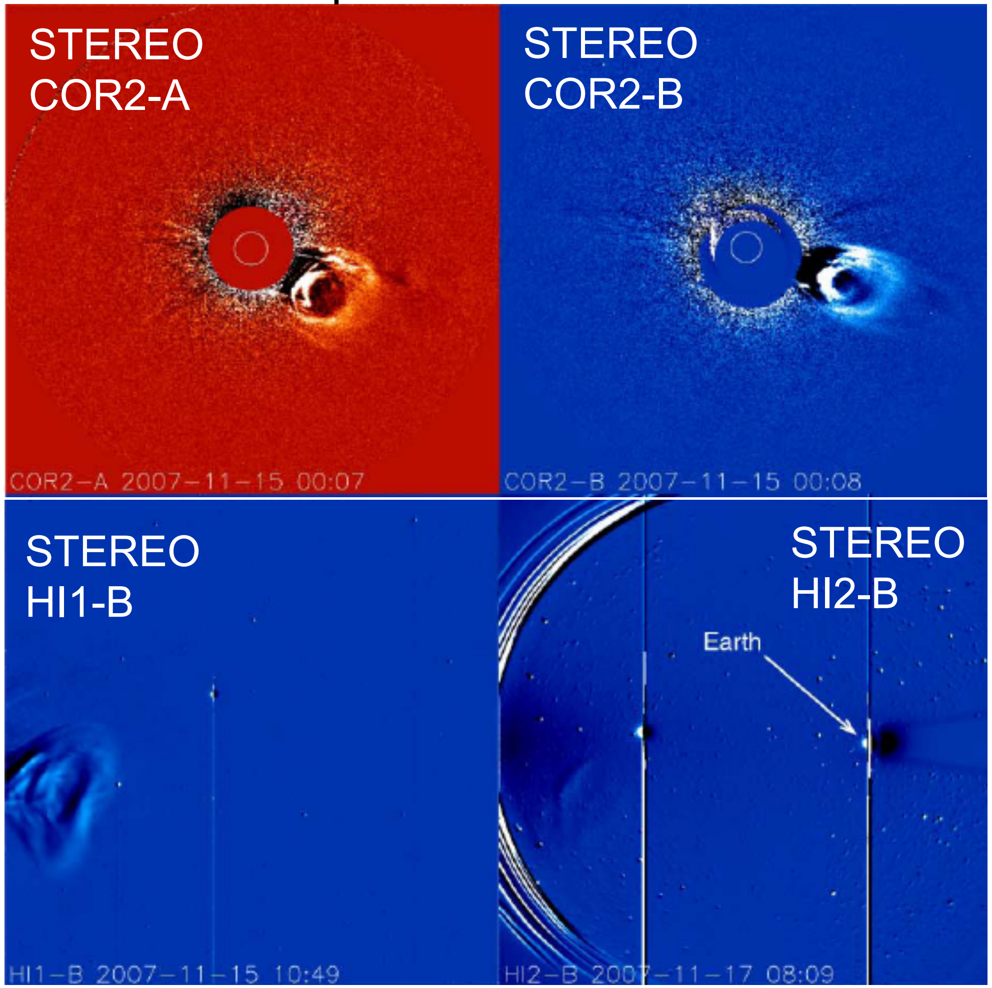
- Understand the sun as a star
- Solar irradiance TSI cycle variation ~0.1%
- Larger amplitude of variation for other sun-like stars
- Interesting to measure TSI from an orbit inclination >40 deg

Dr. Schmutz shows presentation on TSI instrument and its science.

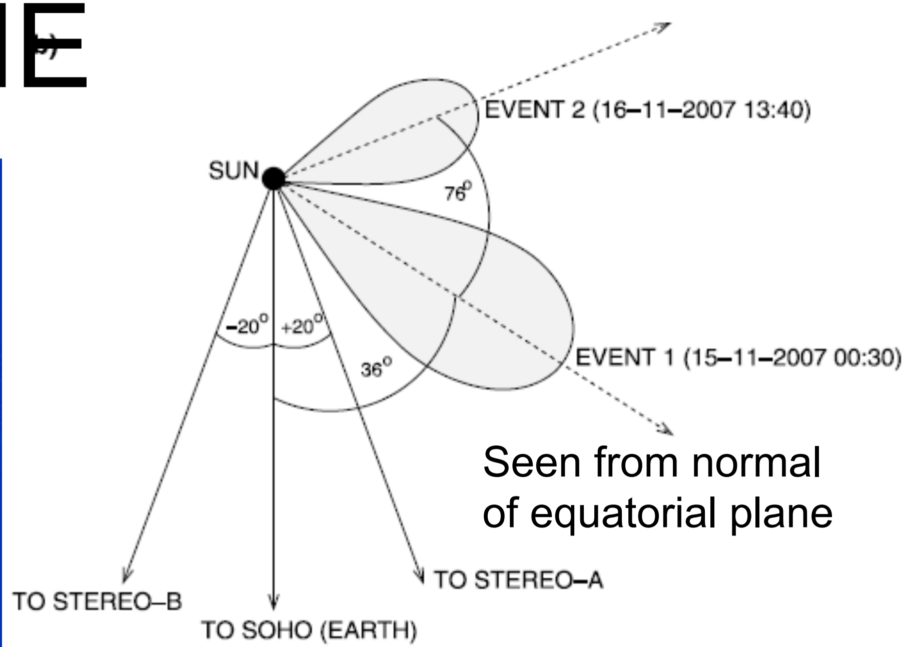
Figure from PMOD WRC homepage

CME

Stereoscopic view from STEREO

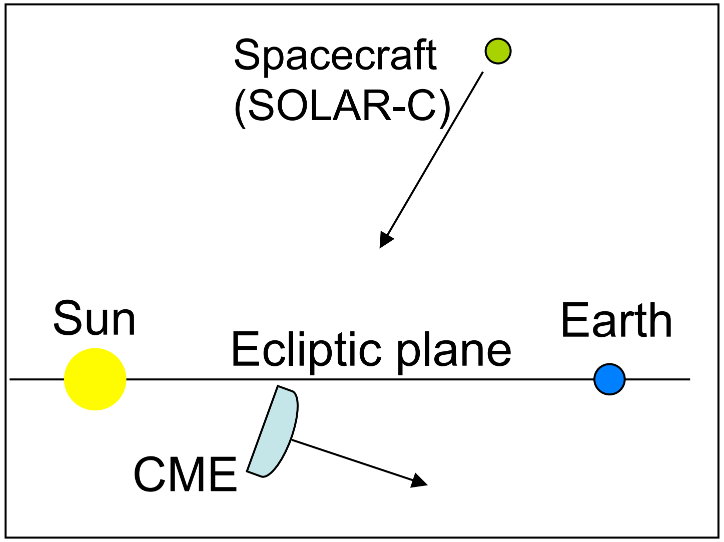


Howard & Tappin (2008)



Seen from normal of equatorial plane

Can we see a signature of Parker-spiral structures by an imaging observation?



Dr. Culhane mentions on the sun-earth connection by SOLAR-C

Model Payload

- **Visible-light Imager**
  - Photospheric Doppler velocity and magnetic field
  - Need a wide range tunable filter to first observe features in polar regions in various wavelengths. ↔ different from MDI and HMI
- **Coronal Imager**
- **High-throughput EUV Imaging spectrometer**
  - High-throughput and smaller (lighter) than Hinode EIS will be possible.
- Optional (as treated in the SOLAR-C WG proposal, 2007)
  - **Total irradiance monitor**
  - **Heliospheric imager**
  - **In-Situ instruments**(not discussed with interplanetary physics group)

- Total weight ~100 kg
- Total data recording rate ~100 kbps ave. (not easy)

Presentation on Payload suitable for SOLAR-C Plan-A

- **Visible-light Imager** by Dr. Apporchaux
  - Photospheric Doppler velocity and magnetic field
  - Need a wide range tunable filter to first observe features in polar regions in various wavelengths. ↔ different from MDI and HMI
- **Coronal Imager** by Dr. Auchere
- High-throughput EUV Imaging spectrometer by Dr. Davila
  - High-throughput and smaller (lighter) than Hinode EIS will be possible.
- Optional (in the SOLAR-C WG proposal, 2007)
  - **Total irradiance monitor** by Dr. Schmuts
  - **Heliospheric imager** by Dr. Vourlidas
  - **In-Situ instruments** (not discussed with interplanetary physics group) Probably something mentioned by Dr. Sakurai and Dr. Culhane
- Total weight ~100 kg
- Data recording rate ~ 100 kbps ave.

Candidate Orbit (1)

- Methodology to achieve an out-of-ecliptic orbit
  - ➢ Planet-gravity assisted Swing-by like Ulysses
  - ➢ Interplanetary cruise by ion engine like ISAS HAYABUSA, NASA DAWN,…

  } Heritage in previous missions

  - ➢ Solar sail, not discussed in this talk

    POLARIS/SPI is introduced by Dr. Appourchaux and Dr. Alexander

For the feasibility of Mission (spacecraft and payload), Sun-spacecraft distance ↔ thermal design and Earth-spacecraft distance ↔ telemetry condition need to be considered in selecting the Plan-A orbit.

Candidate Orbit (2)

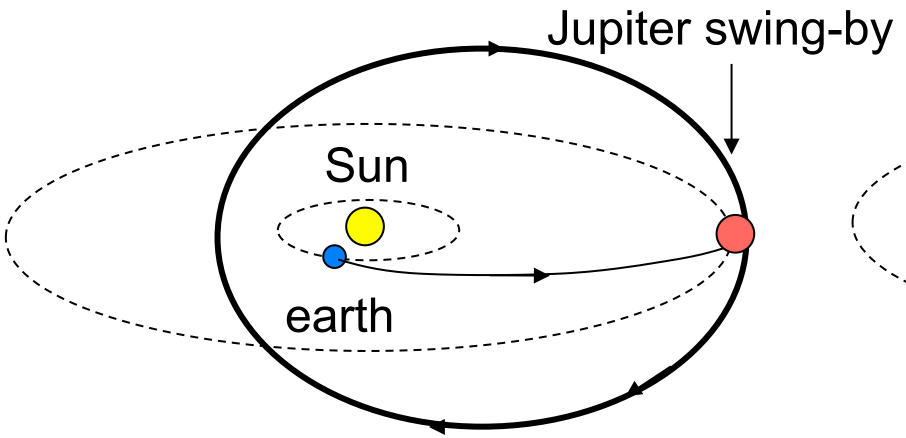
Except for No.2 case, the distance between the spacecraft and the sun is generally long.

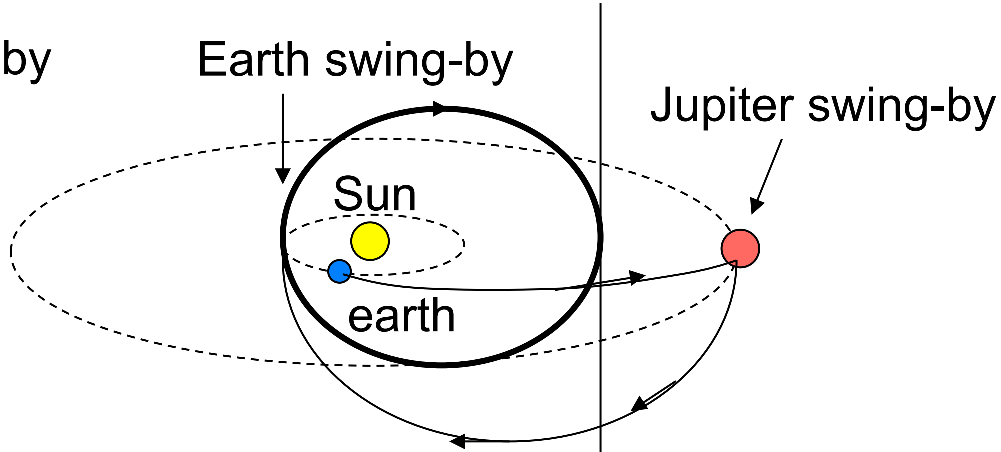
No.	Method	Property
1	Jupiter swing-by	Used in **Ulysses** mission: long orbital period > ~6 years
2	Earth and Venus swing-by	Planned for **Solar Orbiter**: Concern in huge heat load near the sun ~25 times solar radiation at 0.2 AU
3	Jupiter swing-by and earth swing-by	Reduction of orbital period by earth swing-by **Investigated in SOLAR-C WG**
4	Jupiter swing-by and powered earth swing-by	Reduction of orbital period by earth swing-by **Investigated in SOLAR-C WG**

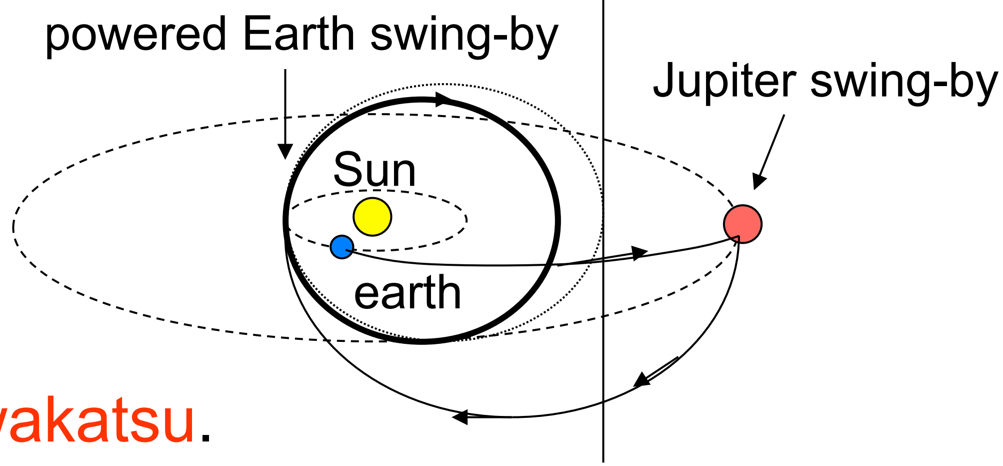
Candidate Orbit (3)

No.	Method	Property
5	Use of ion engine for orbit of 1AU distance from the Sun	- Stable heat load - Low spacecraft weight for high inclination orbit **Investigated in SOLAR-C WG**
6	Use of ion engine and Earth swing-by for ellipsoidal orbit of 0.7-1.3 AU distance from the Sun	- Double heat load at ~0.7 AU compared to 1AU condition. **Investigated by SOLAR-C WG**
7	Use of ion engine and Earth & Venus swing-by for ellipsoidal orbit of 0.7-1.3 AU distance from the Sun	- Double heat load at ~0.7 AU compared to 1AU condition. - Limited launch window **may be Investigated by SOLAR-C WG**
8	Between case 5 and 6	

Various types of orbit control







Details are shown by Dr. Kawakatsu.

Current status for JGA orbit study

Advantage:

- High-inclination orbit i > 60 deg is possible.
- There is a possibility of larger payload weight than orbit design by use of ion engine

Disadvantage for solar observations:

- 4 years after launch or orbit points far from the sun: probably no solar observations
- Distance between Sun and spacecraft > 1 AU

  poor spatial sampling for 2D solar imaging

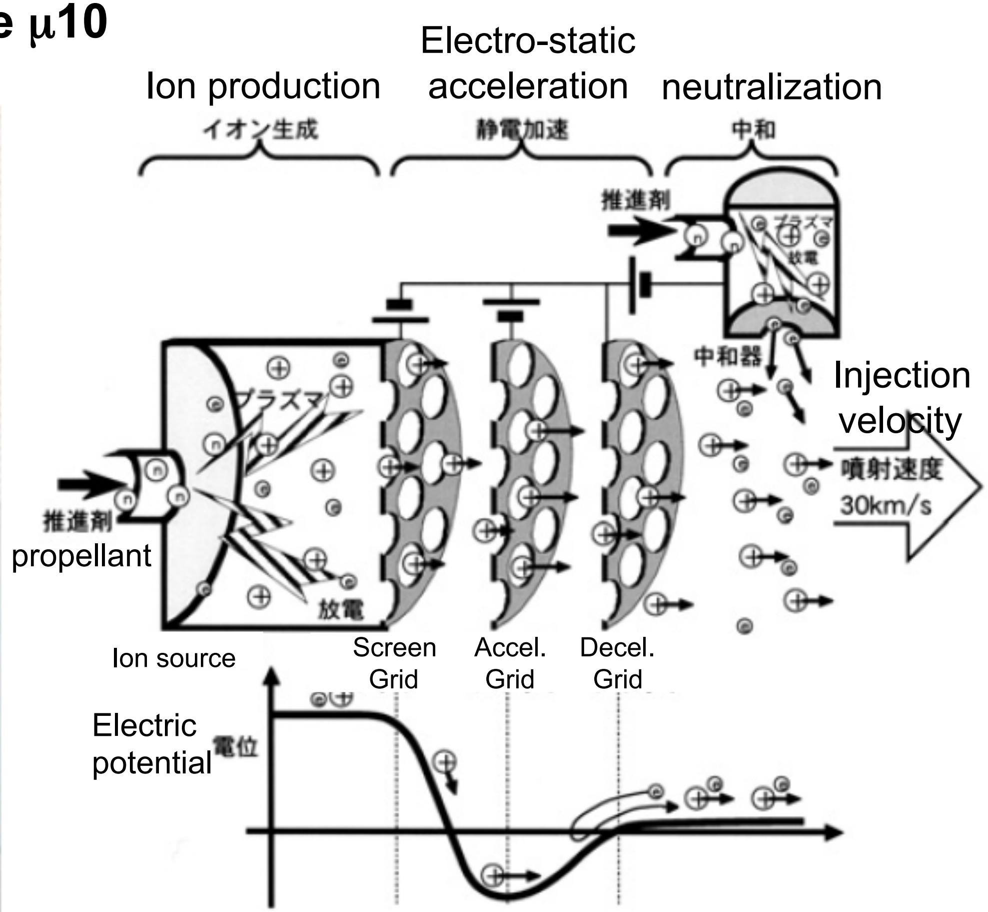
- SOLAR-C WG has not done the feasibility study of spacecraft for the JGA orbit cases.

Ion Engine

Asteroid ‘Itokawa’

Ion Engine μ10

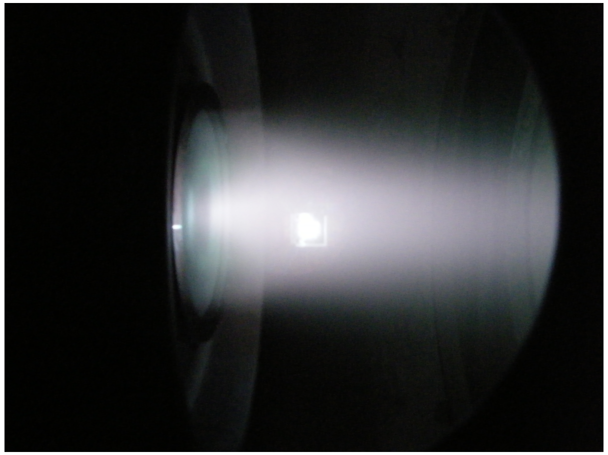
HAYABUSA



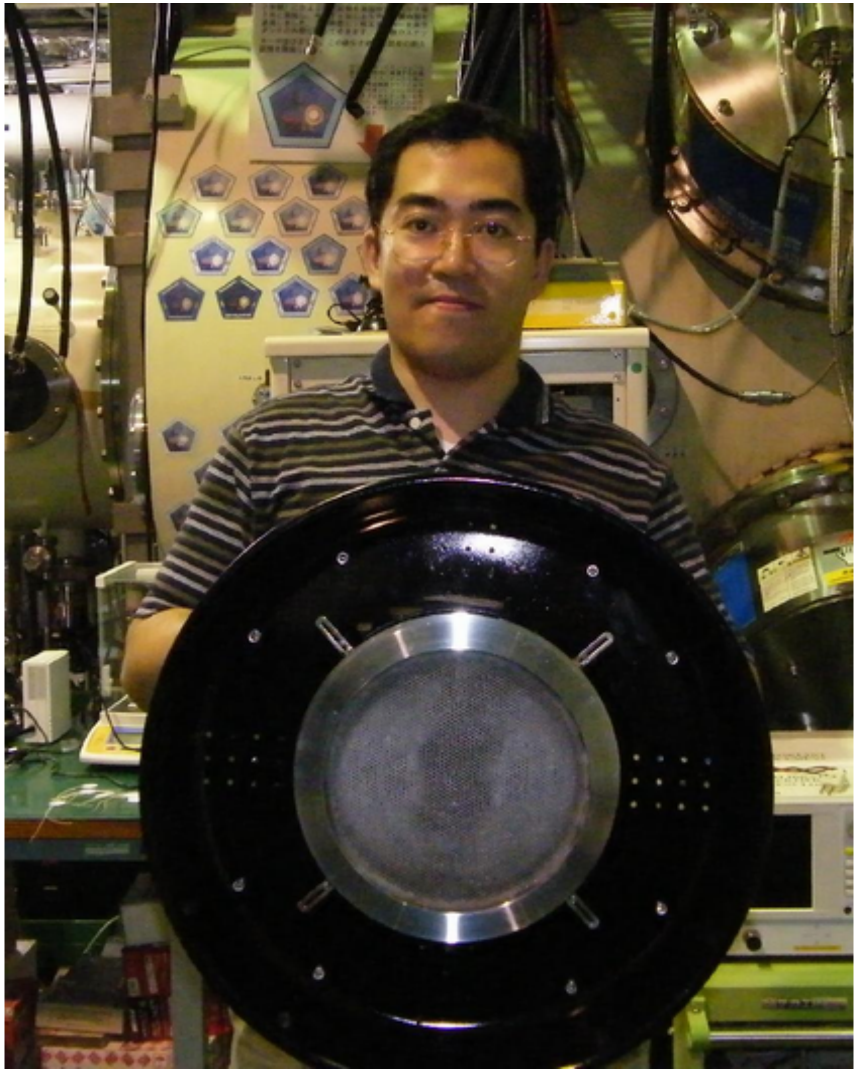
Note: Permanent magnets are used in ion engines.

Ion Engine μ20

- Beam diameter 200mm
- Specific impulse 2800 s
- Thrust 28mN
- Microwave Power 100W
- System Power 1050 W
- Simultaneous use of 4 sets of this engine is currently assumed in Plan-A.



Endurance test under way



μ20 and Dr. Nishiyama

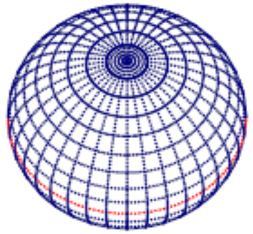
Two Practical Cases

- Dr. Kawakatsu show two orbit cases using ion engines.
- Leverage 7.25 deg tilt of solar rotation axis by selecting launch window

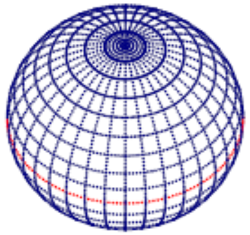
- (1) Spacecraft can see the sun at 45 deg view angle from the solar equatorial plane.
  - Earth swing-by is used.
  - 0.7-1.3AU Sun-S/C distance in the early phase
  - 1AU Sun-S/C distance at the final orbit.
- (2) An orbit keeping 1AU distance.
  - Spacecraft can reach a moderate inclination orbit in a short spacecraft life
  - A possibility to go to higher inclination slowly if a long spacecraft life is allowed.

How is appearance of solar poles as a function of inclination?

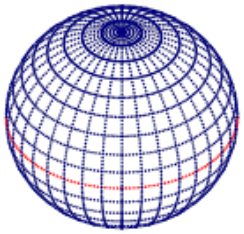
i: inclination angle between solar equatorial plane



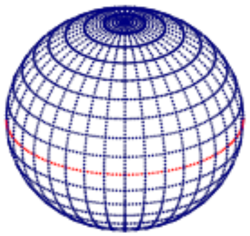
i = 60 deg



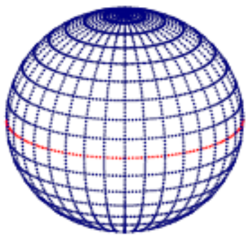
i = 50 deg



i = 40 deg

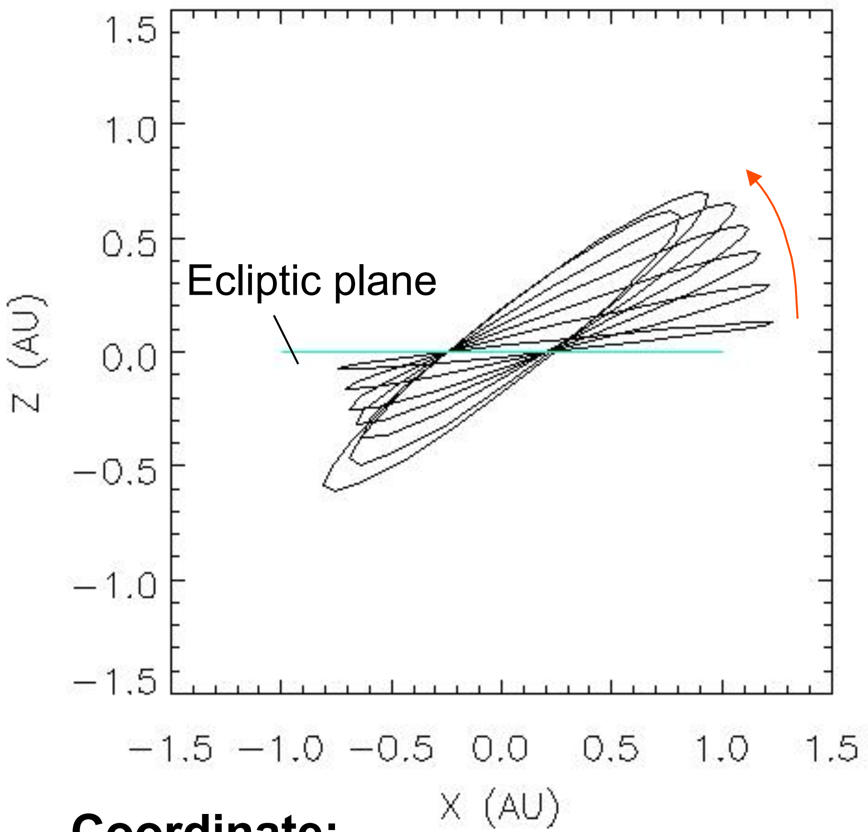


i = 30 deg



i = 20 deg

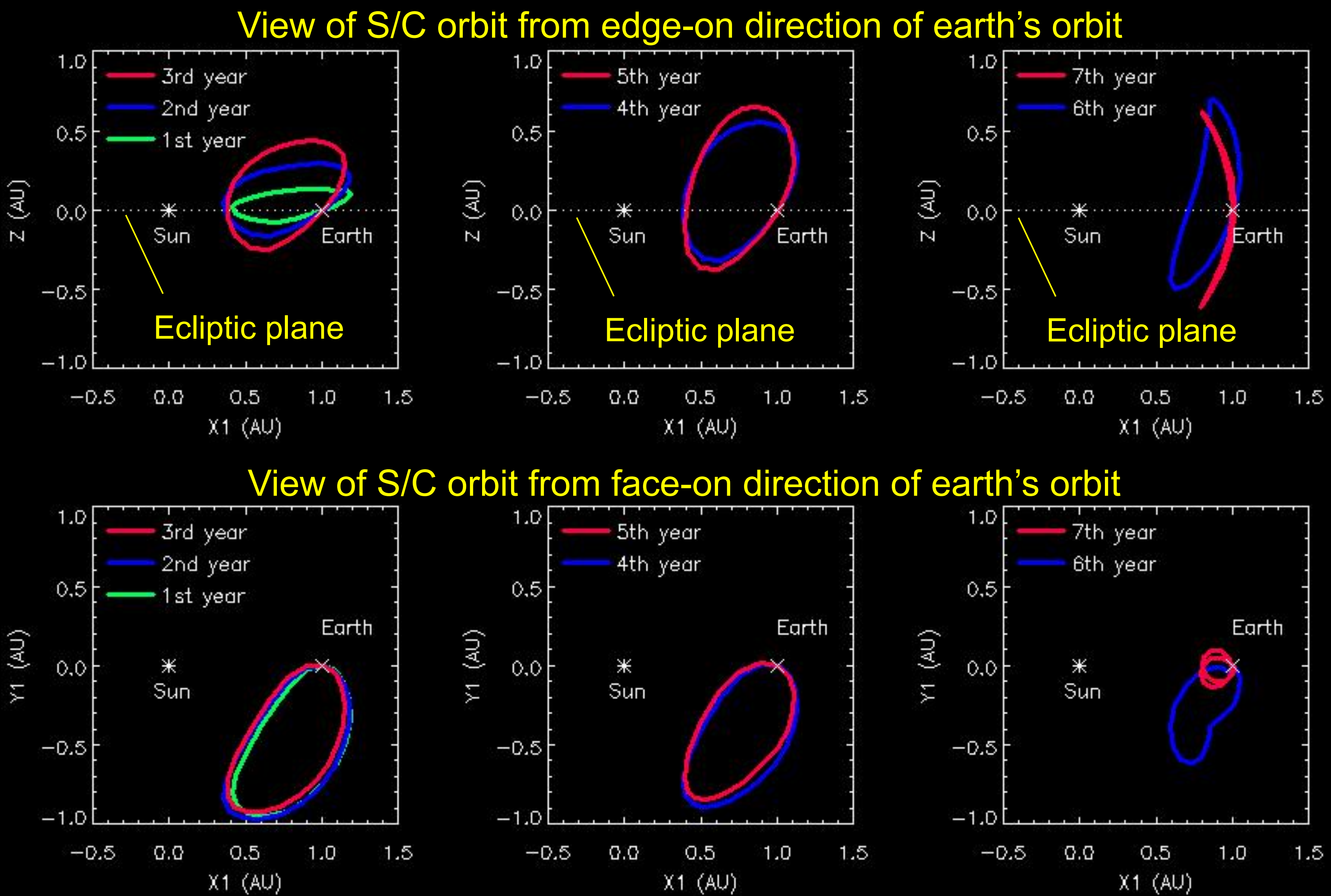
A Candidate Orbit with Earth Swing-by



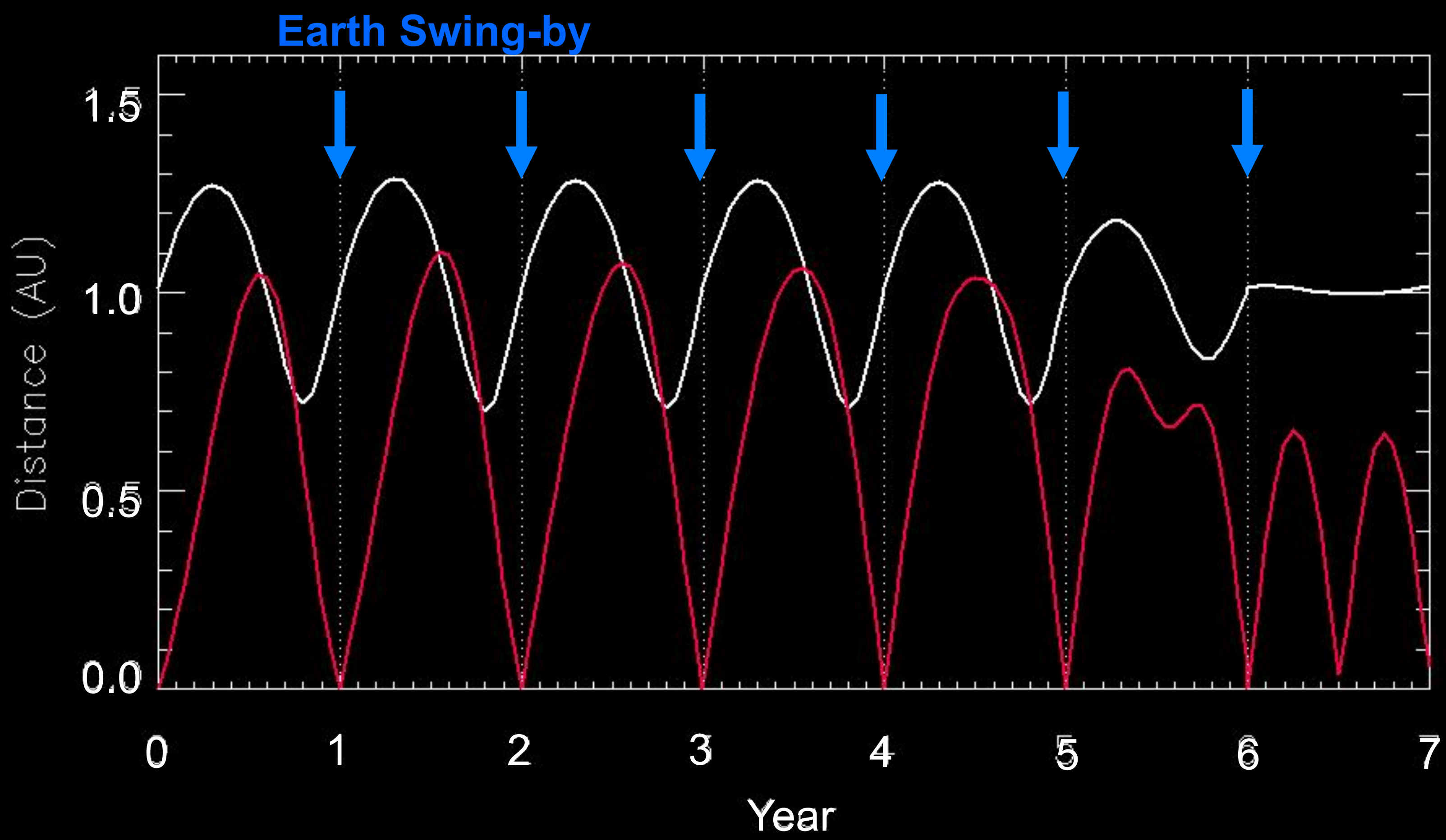
Coordinate:
Orbital plane of Earth is in X-Y plane.

- Use of ion engine
  - 3000 s specific impulse
  - Simultaneous use of 4 engines, each having 30mN max thrust
- H2A + KM-V2 kick motor
- 1200 kg initial wet S/C mass
- Accelerated in orbit plane by ion engine
- Step-like change of the orbit inclination by the earth gravity assist (swing-by)
- Eccentricity = 0.3 for early phase and 0.0 for the final.

A Candidate Orbit with Earth Swing-by



Sun-S/C & Earth-S/C Distance

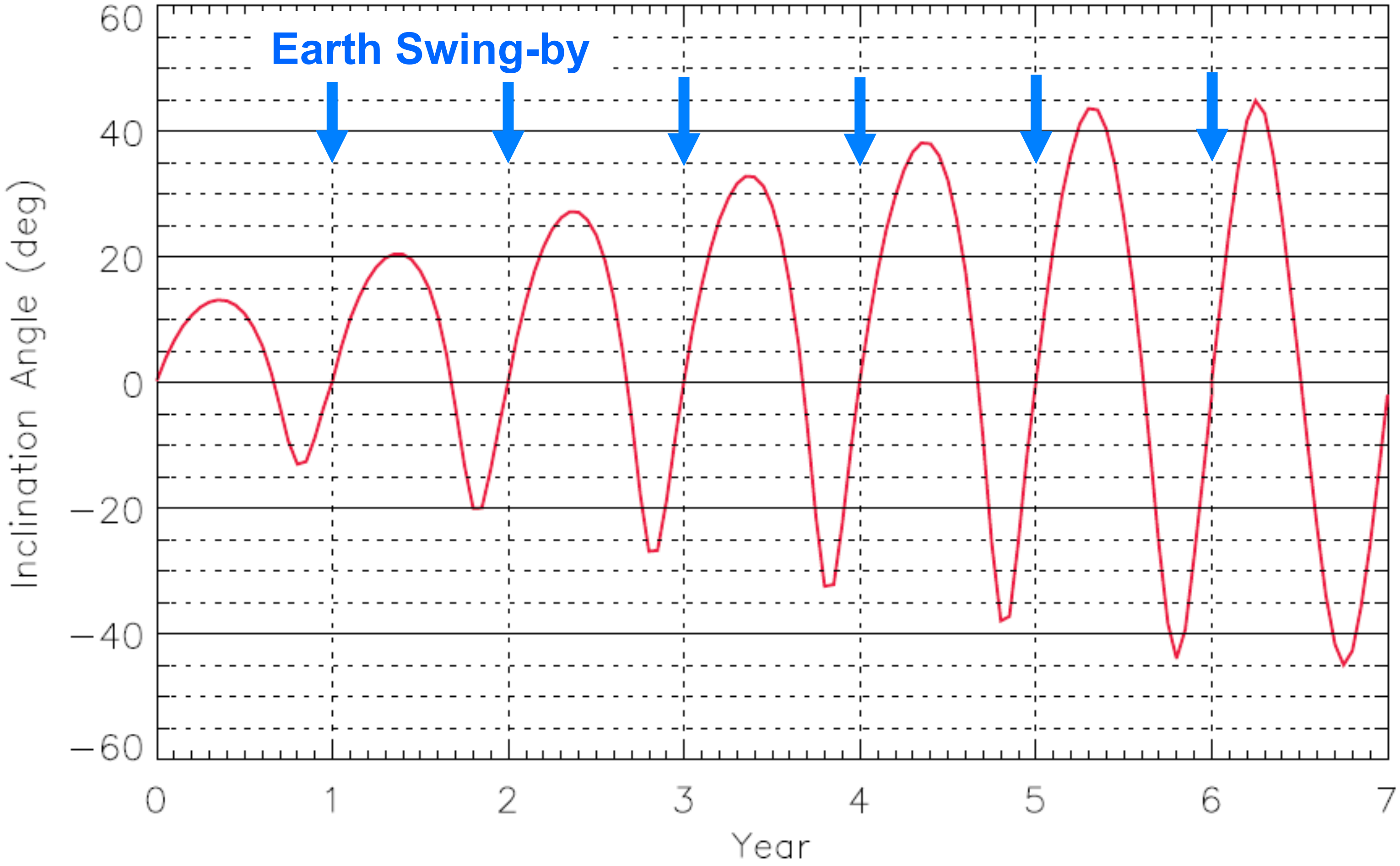


Sun-S/C distance ⟷ Thermal design

Earth-S/C distance ⟷ Telemetry rate

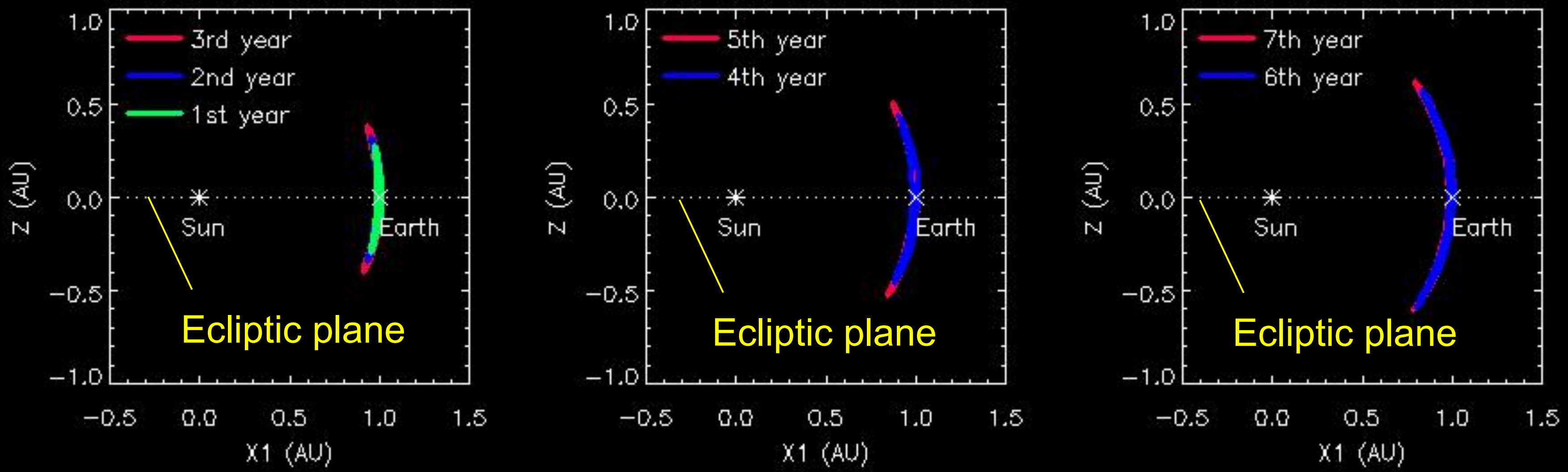
Inclination angle from Solar equatorial plane

Ion engine duty (%)	69	71	71	64	62	0	0
Spacecraft Weight (kg)	1200	1127	1052	975	902	831	831

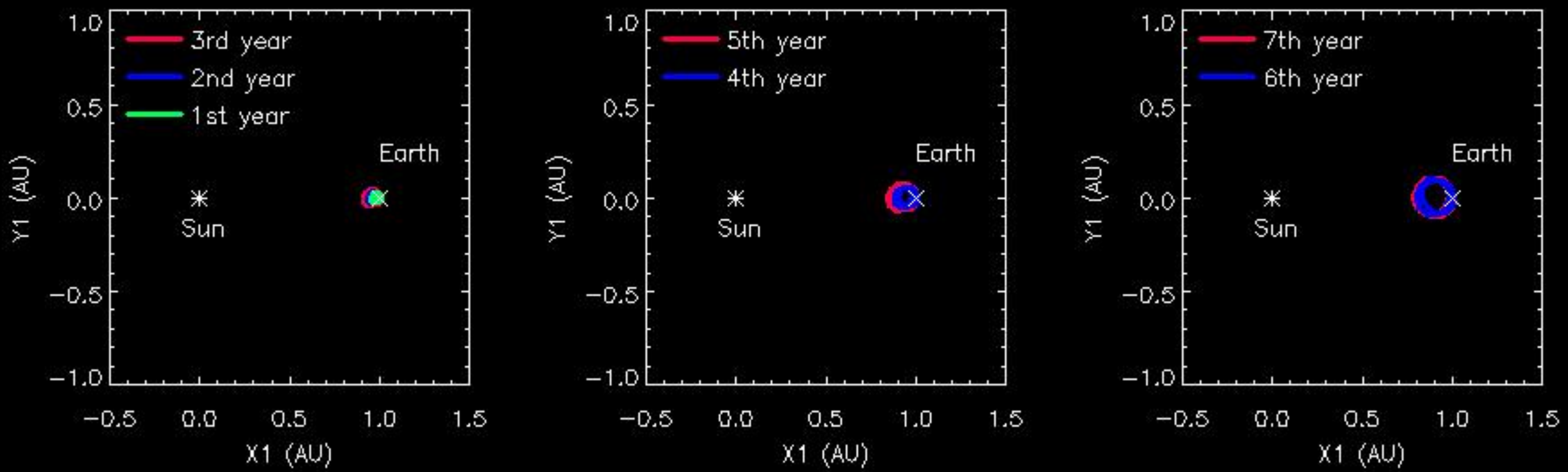


A Simplified Orbit

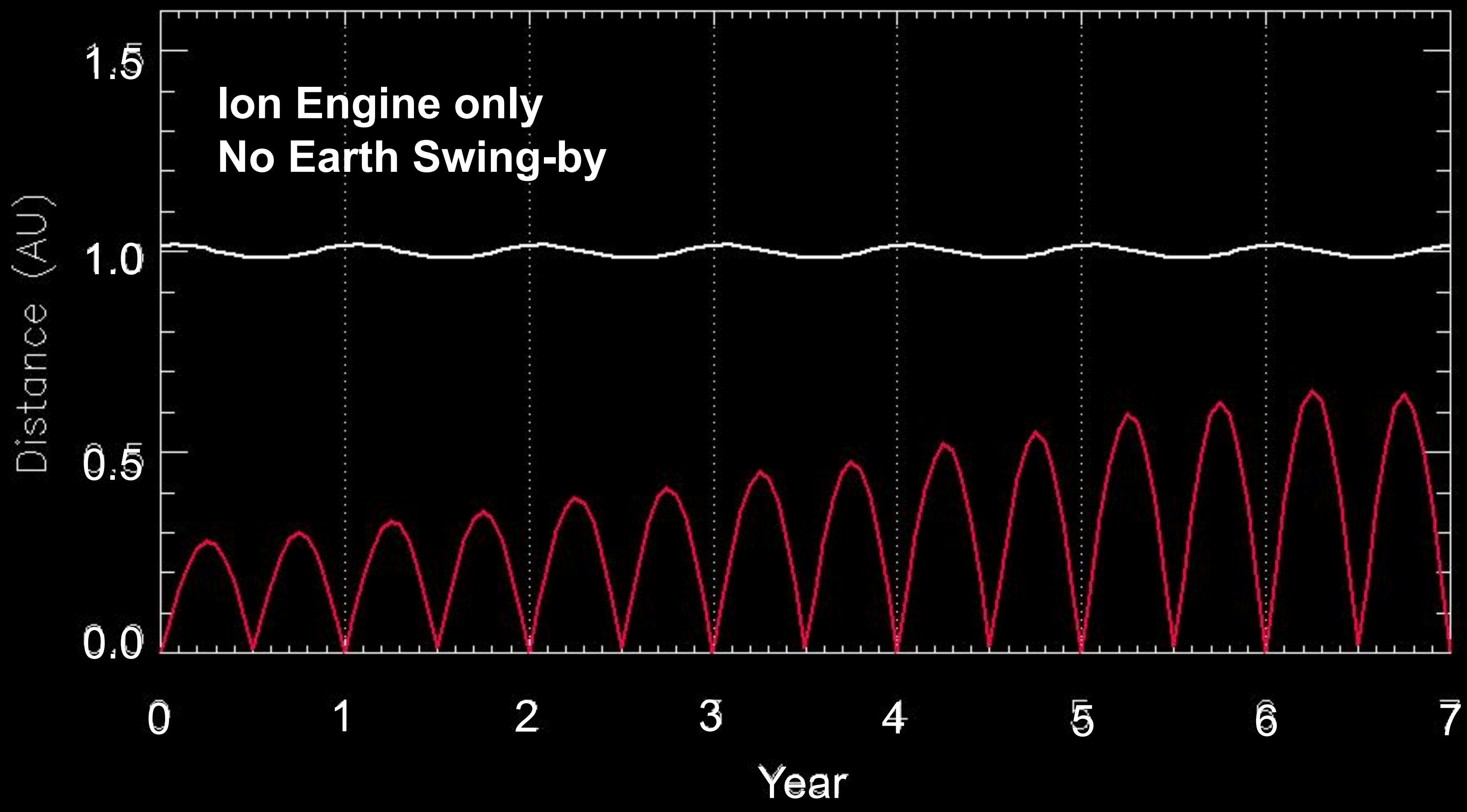
View of S/C orbit from edge-on direction of earth's orbit



View of S/C orbit from face-on direction of earth's orbit



Sun-S/C & Earth-S/C Distance

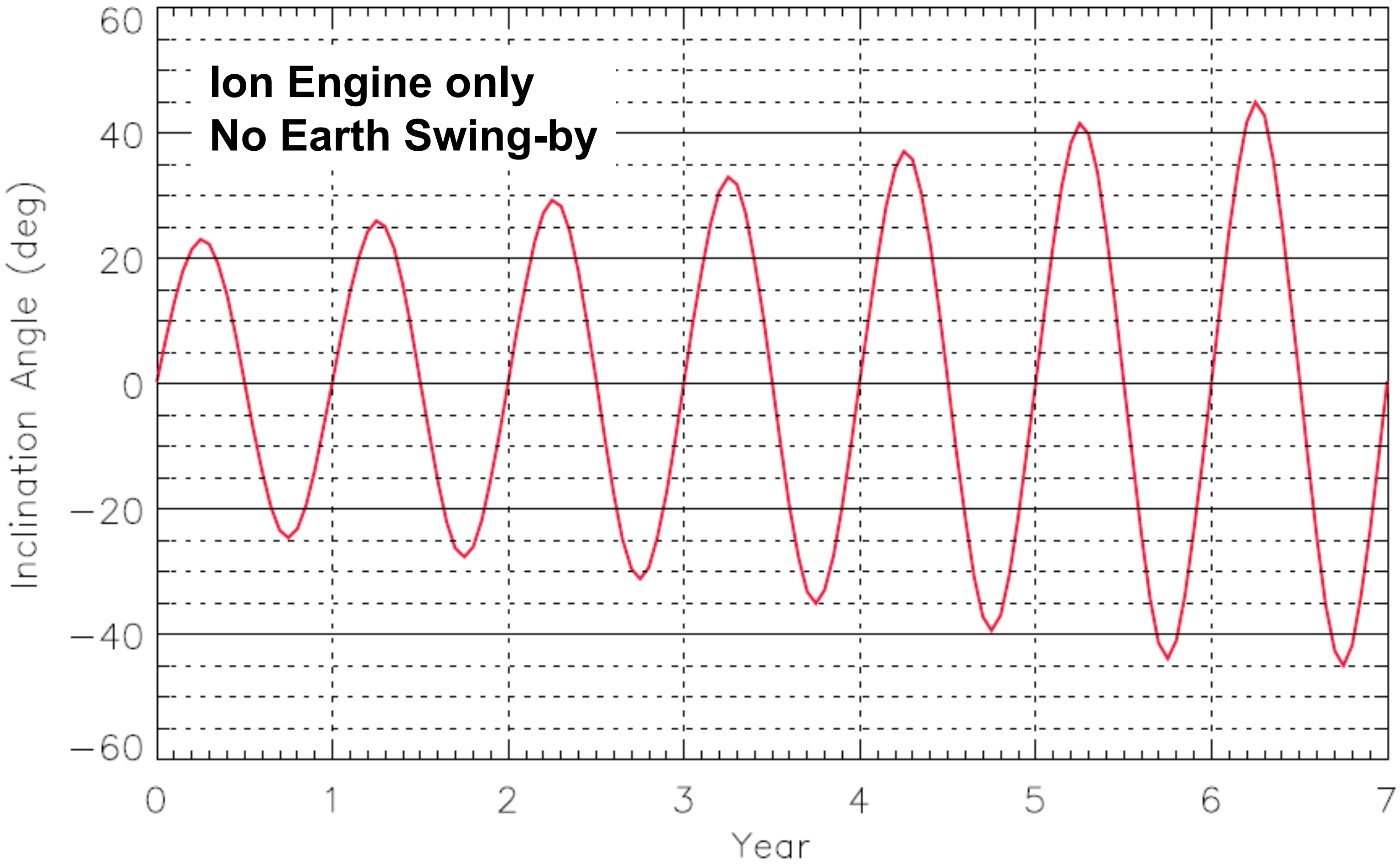


Sun-S/C distance ⟷ Thermal design

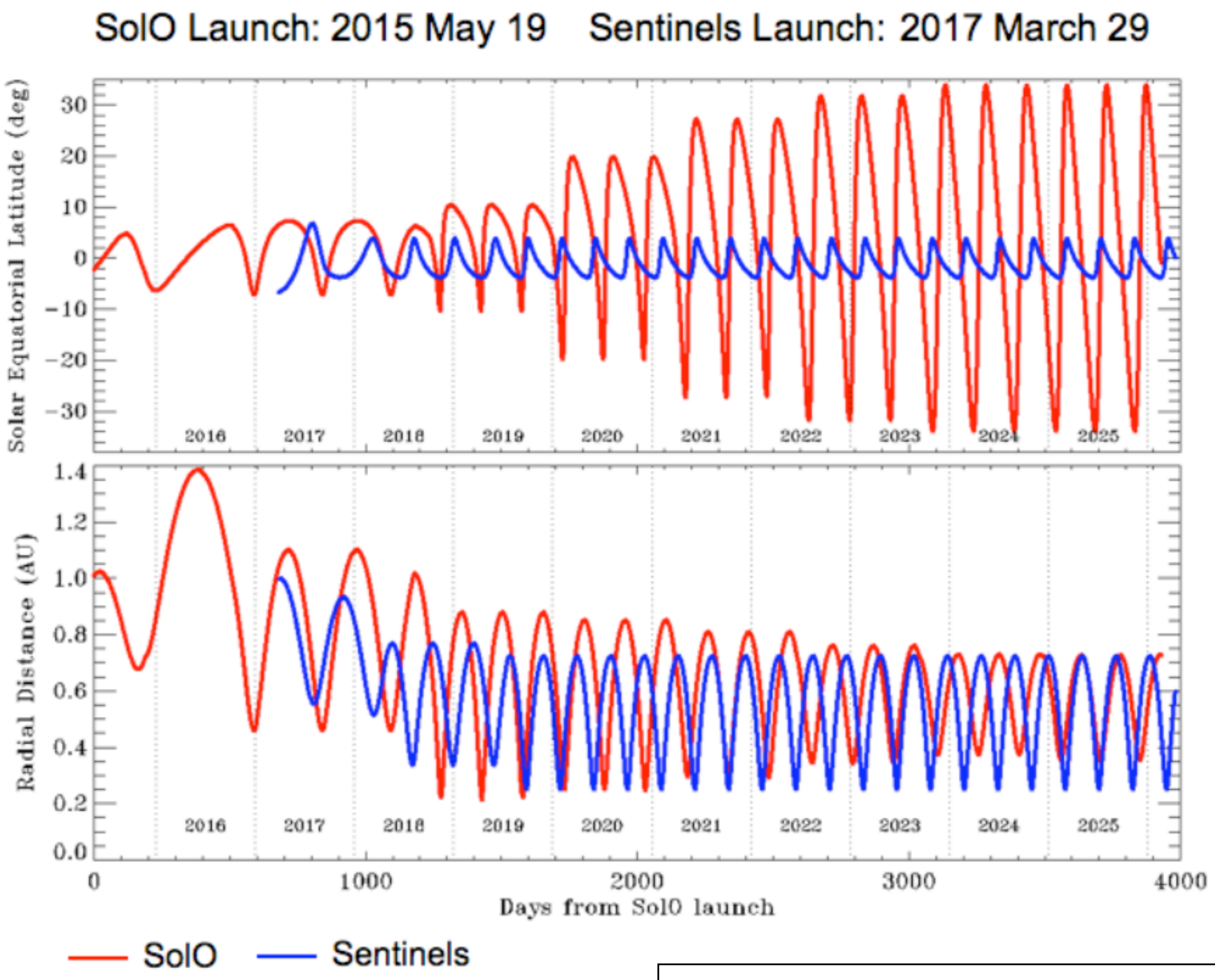
Earth-S/C distance ⟷ Telemetry rate

Inclination angle from Solar equatorial plane

Ion engine duty (%)		61	61	67	70	71	60	0
Spacecraft Weight (kg)	1200	1123	1046	963	876	789	713	

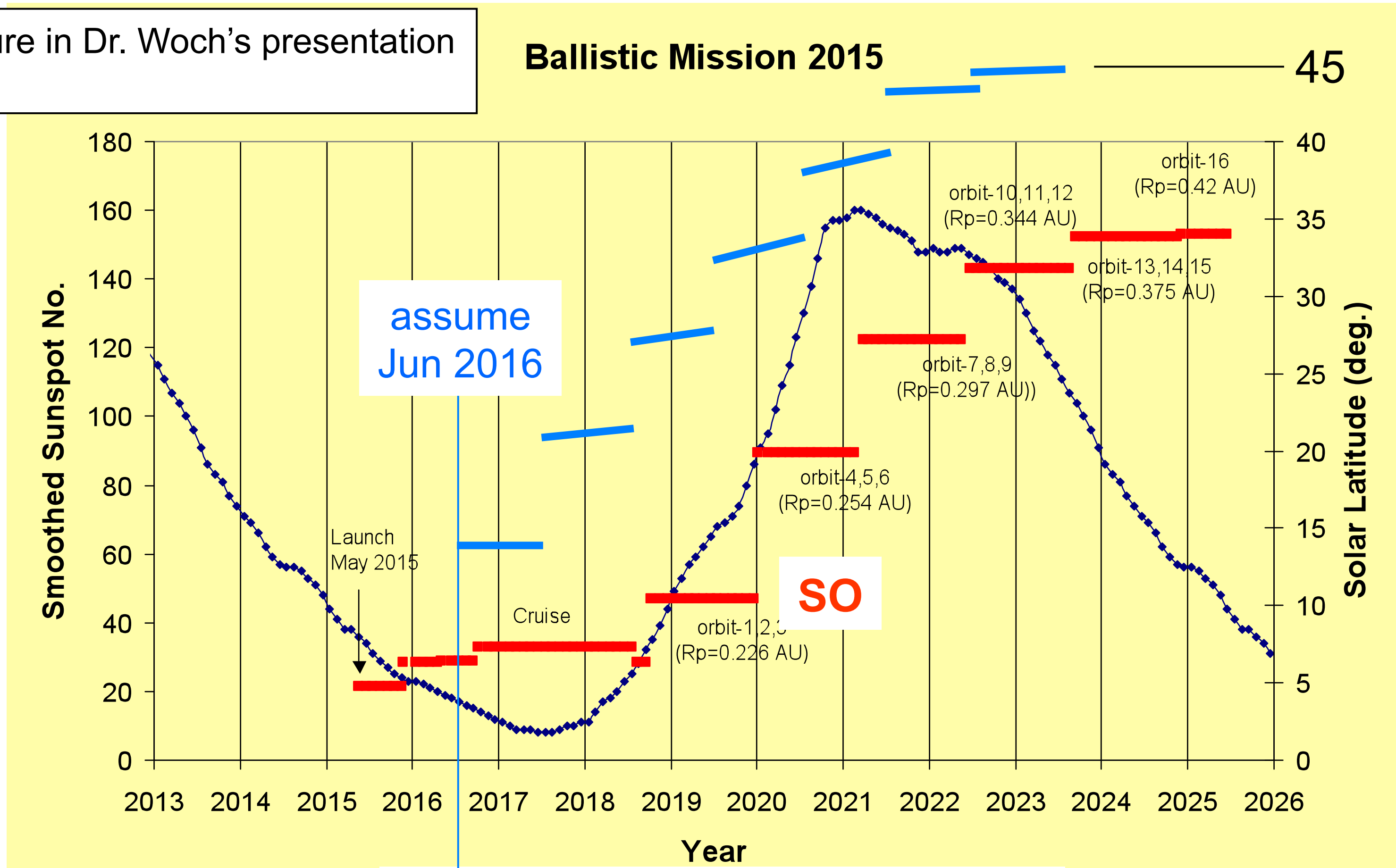


Solar Orbiter

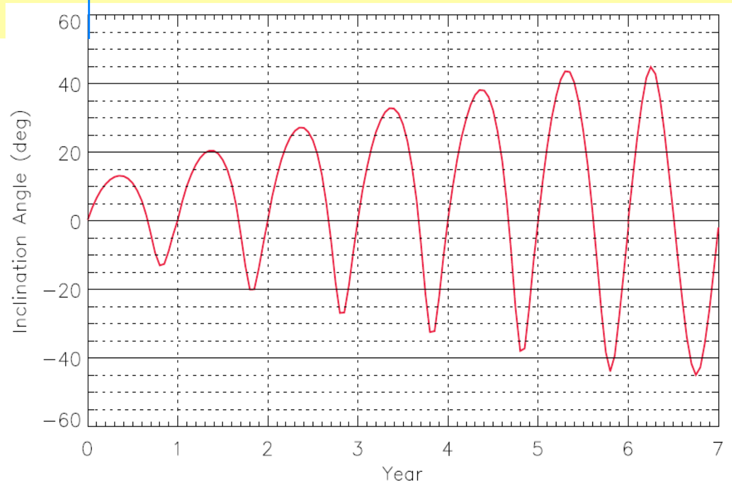


From a figure in Dr. Woch's presentation at MPS

From a figure in Dr. Woch's presentation at MPS



SOLAR-C:
Earth Swing-by case

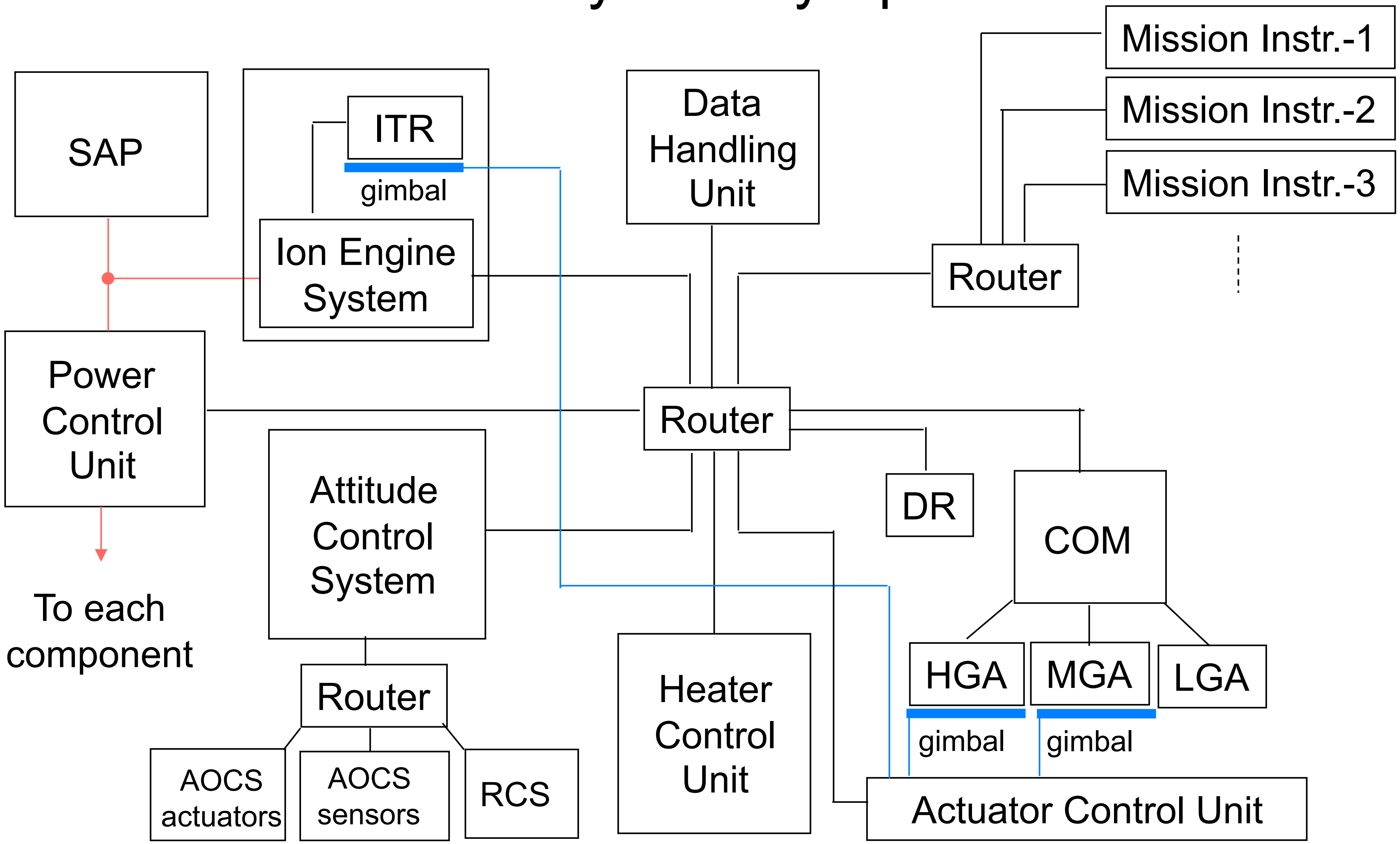


Mass budget (very preliminary)

Subsystem	Weight (kg)	Fuel	Weight (kg)
Communication	50	Chemical (N_2H_4)	40
Data handling	12	Ion engine (Xe)	400
Attitude control	72	**Total (Fuel)**	440
Electrical harness	15		
Structure	100	**Dry S/C+ Fuel**	1139
Thermal control	20		
Electrical power	160	**Total with margin**	1200
RCS	30		
Ion Engine System	140		
Mission payload	100		
Dry spacecraft mass	699		

SOLAR-C Plan-A System

a network system by Spacewire



Communication System (1)

- Low-weight High Gain Antenna (HGA) needed.
- Ground support antenna required at both northern and southern hemisphere
- ~100 kbps (TBD) data recording rate needs 400 kbps (800 kbps) telemetry speed for 6 (3) hour downlink time per day
- For the science data transfer X-band is better than Ka-band for a weather (rainy) condition, and Ka-band is better for the HGA antenna on S/C to be small.

Communication System (2)

- X-band, **1.5mϕ** HGA, **50W** transmission power, JAXA Usuda 64mϕ ground station, **0.7AU** distance:

  ~200 kbps telemetry rate possible

  = 50 kbps ave. recording rate for 6 hours downlink duration per day

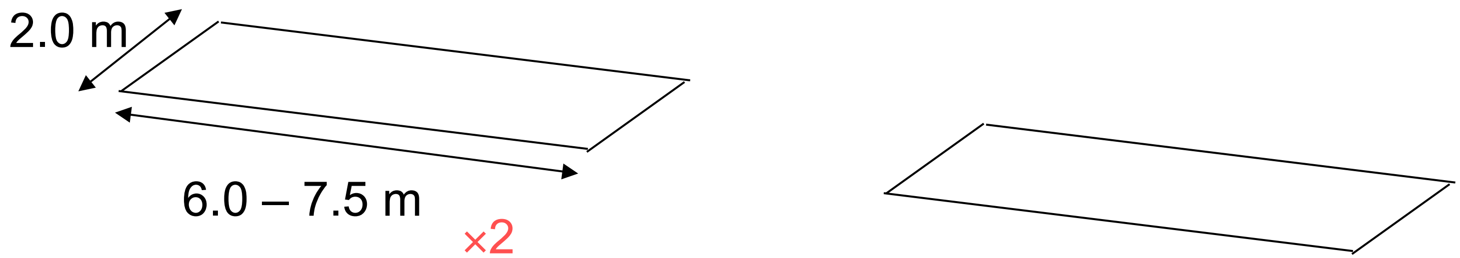
  → will need higher telemetry rate for helioseismic observations (a question to helio-seismologists)

- cf. 750 kbps telemetry rate for STEREO at 0.5 AU:
  - X-band, 1.2 ϕ HGA, 60W transmission power
  - DSN ground stations

Electrical Power System

- Distance between the sun and S/C = 0.7-1.3AU
  → Switching regulator system

- Solar Array Panel (SAP)
  GaAs triple junction solar cell arrays assumed.
  5 – 6 kW power required → 24 – 30 m^2 area



- BAT: Li-ion battery 23AH

Impact in Thermal Design

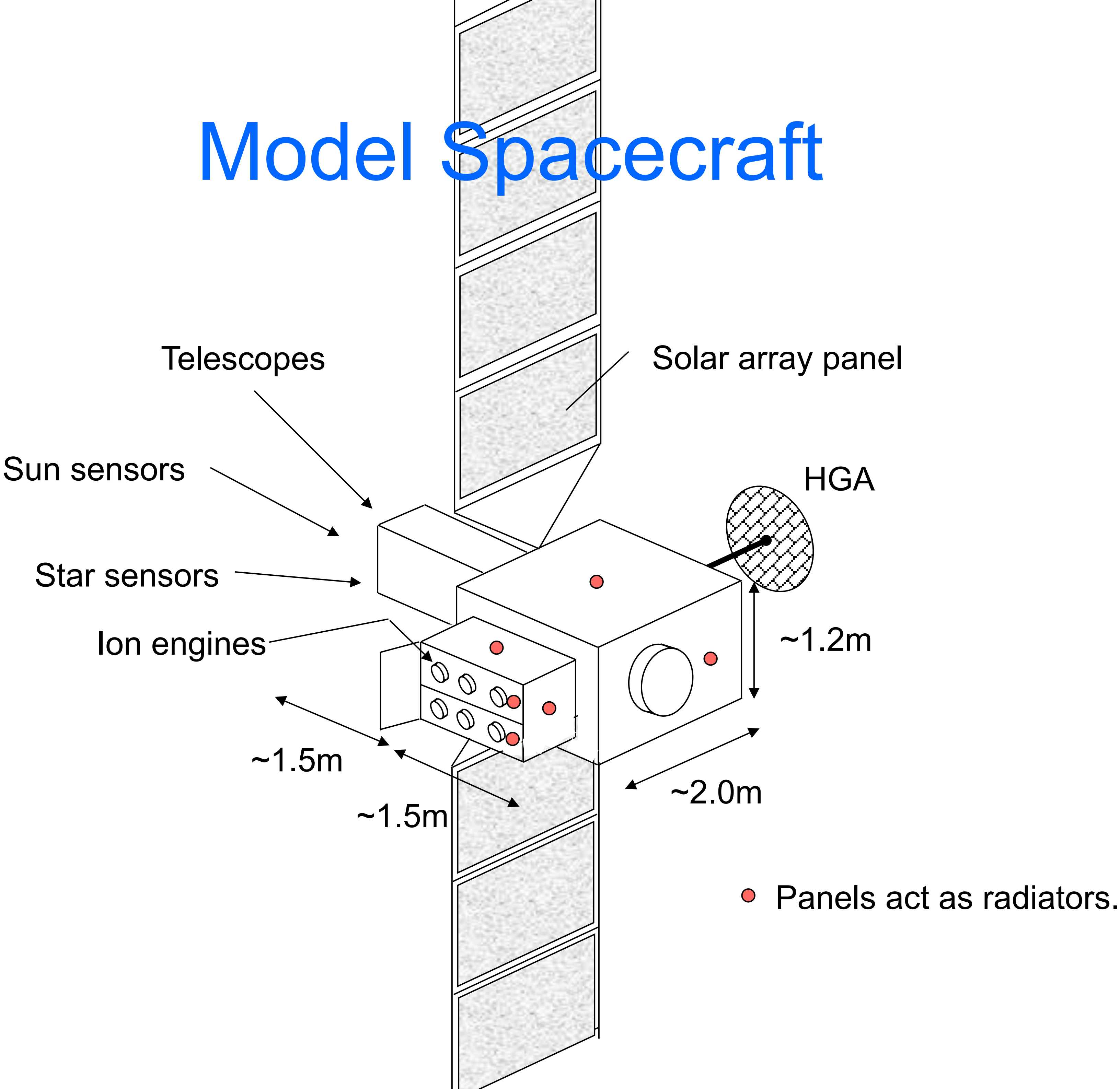
- Thermal environmental condition is much better than SO, but Plan-A S/C needs a treatment for huge internal heat dissipation.
- There are three major heat sources:
  - High-speed communication system
    - 50 – 100 W: high-density heat source
  - Ion engine
    - ~500 W dissipation near ion engine thruster
    - ~500 W dissipation near microwave power supply
    - ~400 W dissipation near DC power supply
    - Use of heat pipe is mandatory.
    - Thermal design is feasible when no direct solar illumination at radiators. Feasibility study in a selected orbit condition is necessary.
  - Others (spacecraft bus components)

Attitude Control

- Three axis stabilized
- No external disturbance in the interplanetary space except for disturbance due to photon pressure and internal disturbance in the spacecraft.
- The accumulated torque is released by thruster impulse that will probably happen once per day. This will become a noise in the helioseismic observations.
  Periodic unloading every day should be prohibited.

- There will not be a problem in S/C pointing stability because the requirement is less severe than that in Hinode.

Model Spacecraft



Output after this meeting

Target Orbit Inclination to the solar equatorial plane

The following table needs to be filled during this meeting.

Science Target	Target Inc. (deg)	Note
Magnetic field measurements at high latitudes (Lat. > 50°)	##	
Rotation profile at high latitudes (Lat. > 50°)	##	
Meridional flow at high latitudes (Lat. > 50°)	##	
Super granulation pattern at high latitudes	##	
High-speed solar wind	##	
Total solar irradiance variation with inclination	##	
In-situ measurements	##	
Imaging of Helioshphere	##	

Summary

- SOLAR-C plan-A is a mission to look at the sun from a high-inclination out-of-ecliptic orbit.
- We will observe features all over the latitudes on the sun and a wide rage of latitude in heliosphere at ~1AU:

  Magnetic fields, convection, internal rotation, meridional flows from direct or helioseismic observations, activity of upper atmosphere, source region of solar wind, and interplanetary in-situ measurements.
- There is a practical solution for a spacecraft to enter a high-inclination orbit using ion engine.
- Higher inclination is better, but the target inclination needs to be clearly defined from science objectives.
- Effort to increase the total weight of payload has been continued. Better estimate in weight is required for ion engine system, power supply system, and communication system which are coupled with the selection of orbit.

Jupiter Gravity Assist

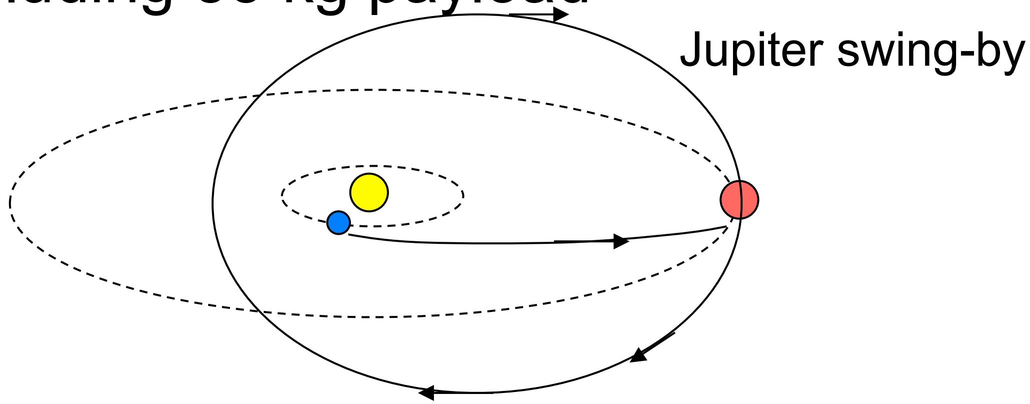
- Orbital period of a final orbit >~6 years
- High inclination (i >60 deg) is possible.
- Not good for long-period observations of the sun
- Need a large solar array paddle ~27 times larger than near-earth spacecraft
- RTG was used in Ulysses as electrical power supply

RTG (Radioisotope Thermoelectric Generators):

power through the natural radioactive decay of plutonium

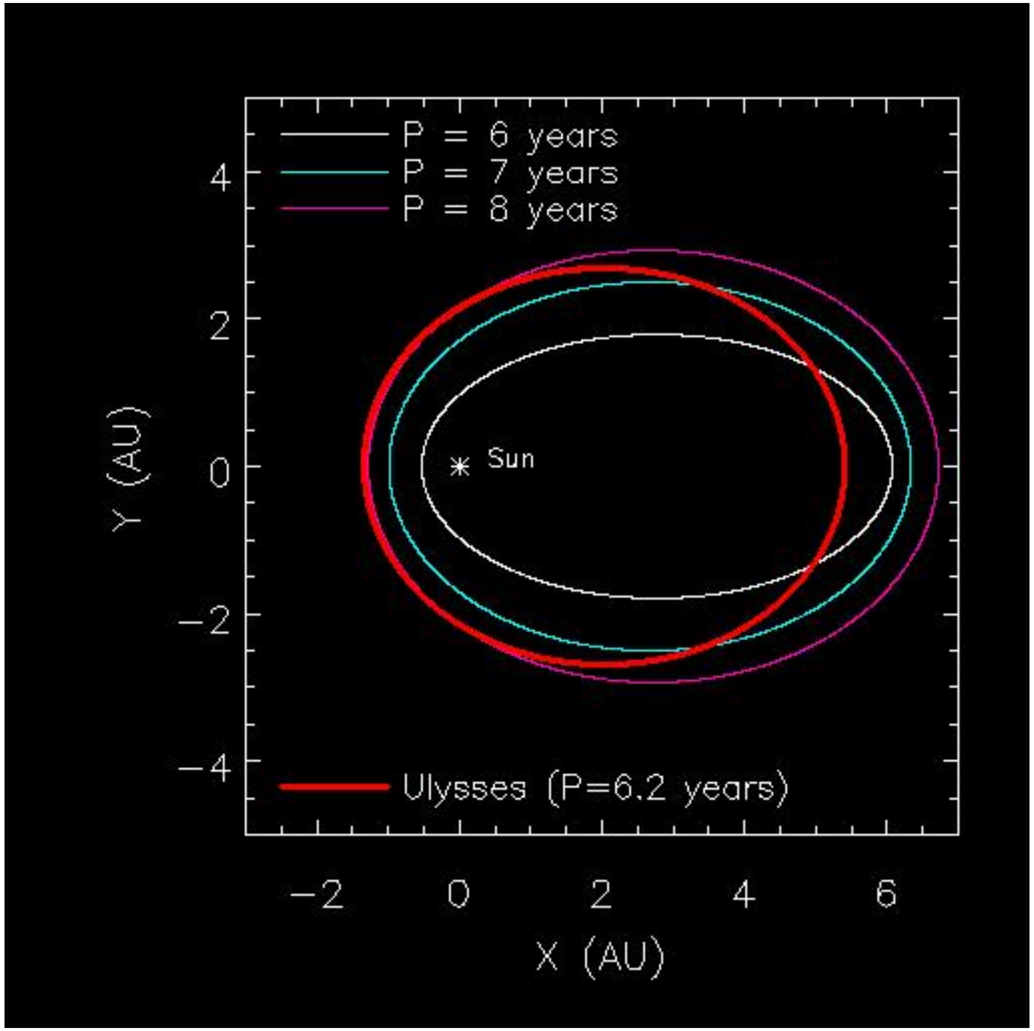
- Ulysses: a = 3.37 AU, i = 79.1 deg, P=6.2 years

weight: 367 kg including 55 kg payload



Jupiter Gravity Assist (JGA)

- H2A202
  +KM_V2 (kick-motor)
- Solar observations starts at ~4 years after launch.
- Sleep mode in the S/C cold condition required.
- Feasible S/C plan will be in an orbit of Sun-spacecraft distance > 1AU

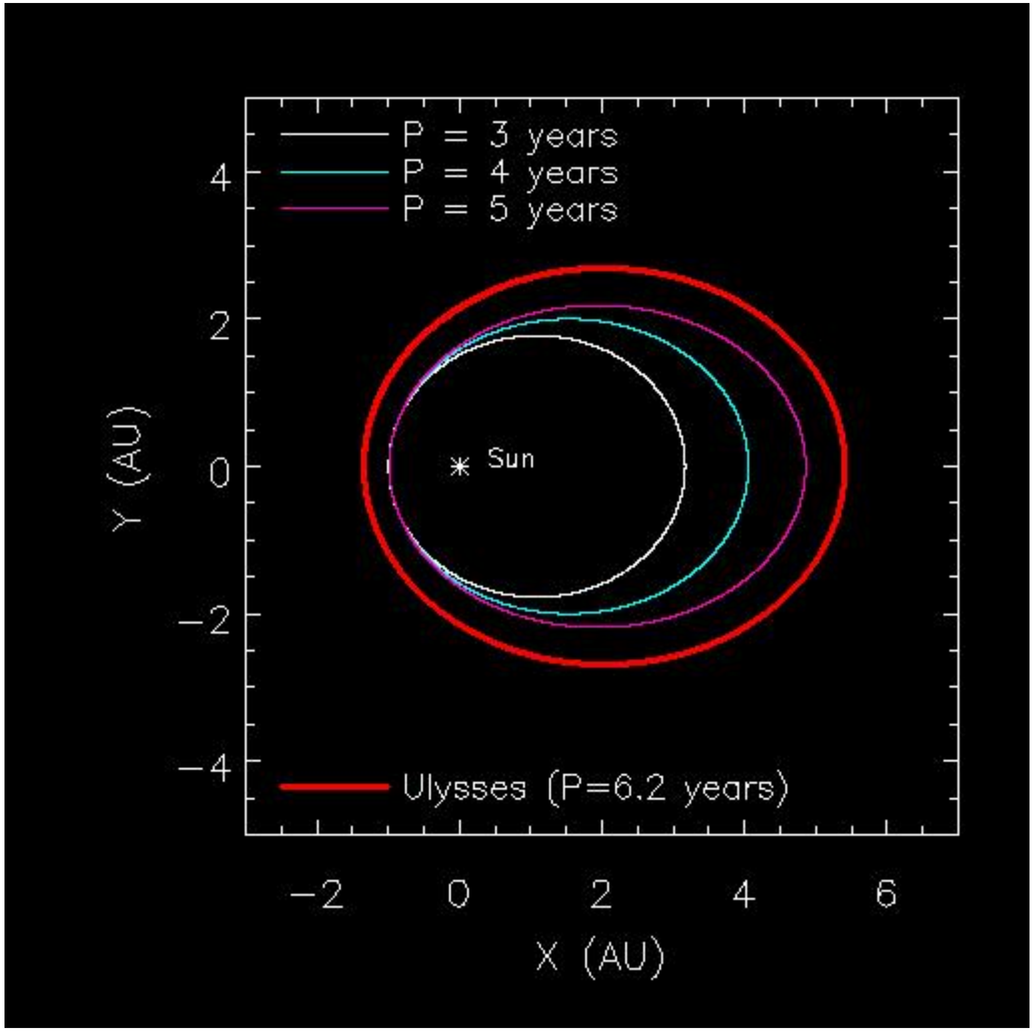


Looking at the final orbit
from the normal to the orbital plane.

JGA + Earth Gravity Assist

- H2A202
  +KM_V2 (kick-motor)
- Orbital period of the final orbit becomes shorter.
- The final weight of spacecraft is almost the same as the cases of JGA only.

Looking at the final orbit
from the normal to the orbital plane.



JGA + Powered EGA

- H2A202+KM_V2 (kick-motor) + additional engine for powered earth swing-by
- Orbital period of the final orbit becomes shorter than the cases of JGA+EGA, but we could not find a solution to have a circular orbit of 1AU distance from the sun.
- Reduction of payload weight due to the additional engine and its fuel cannot be ignored.