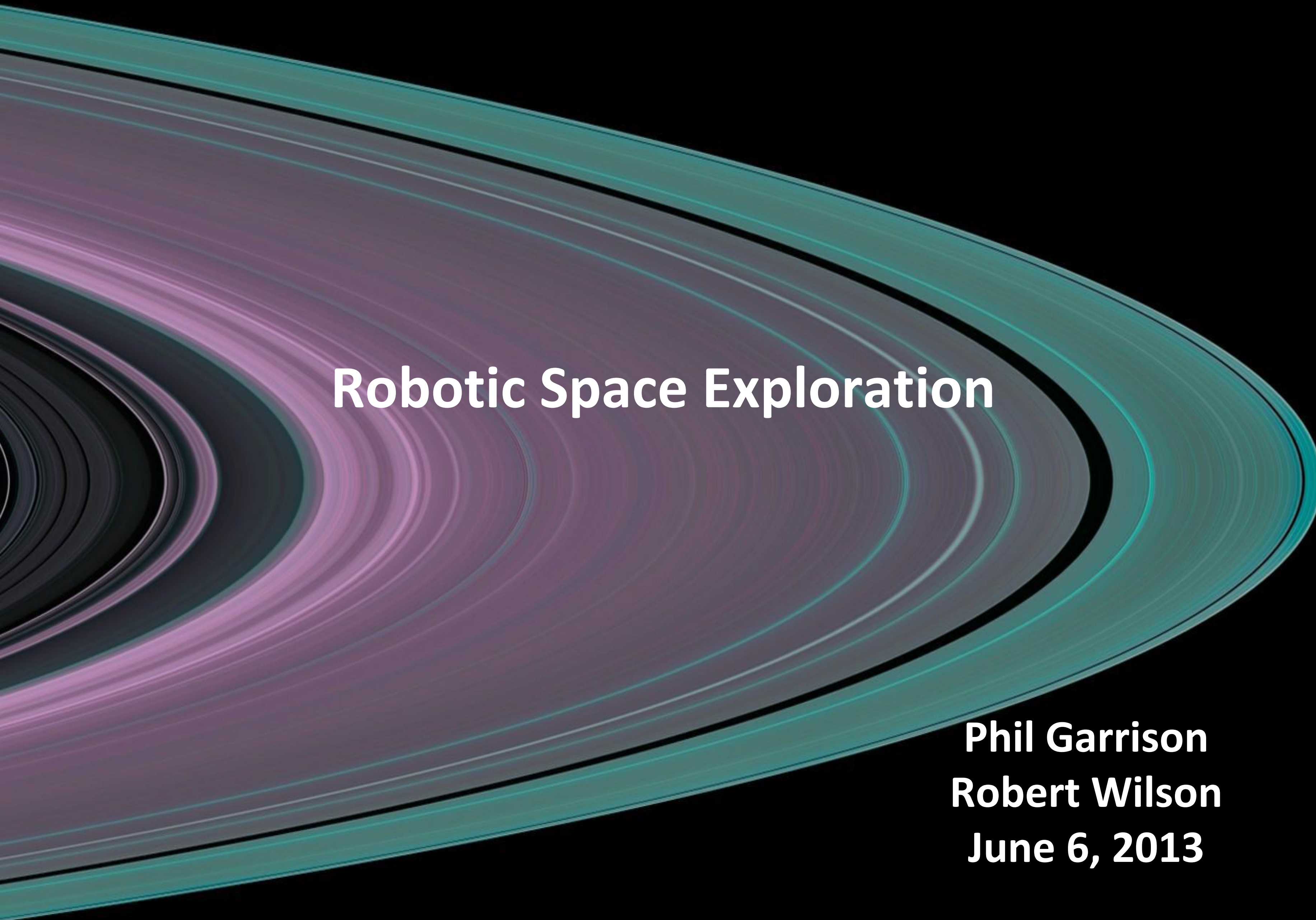
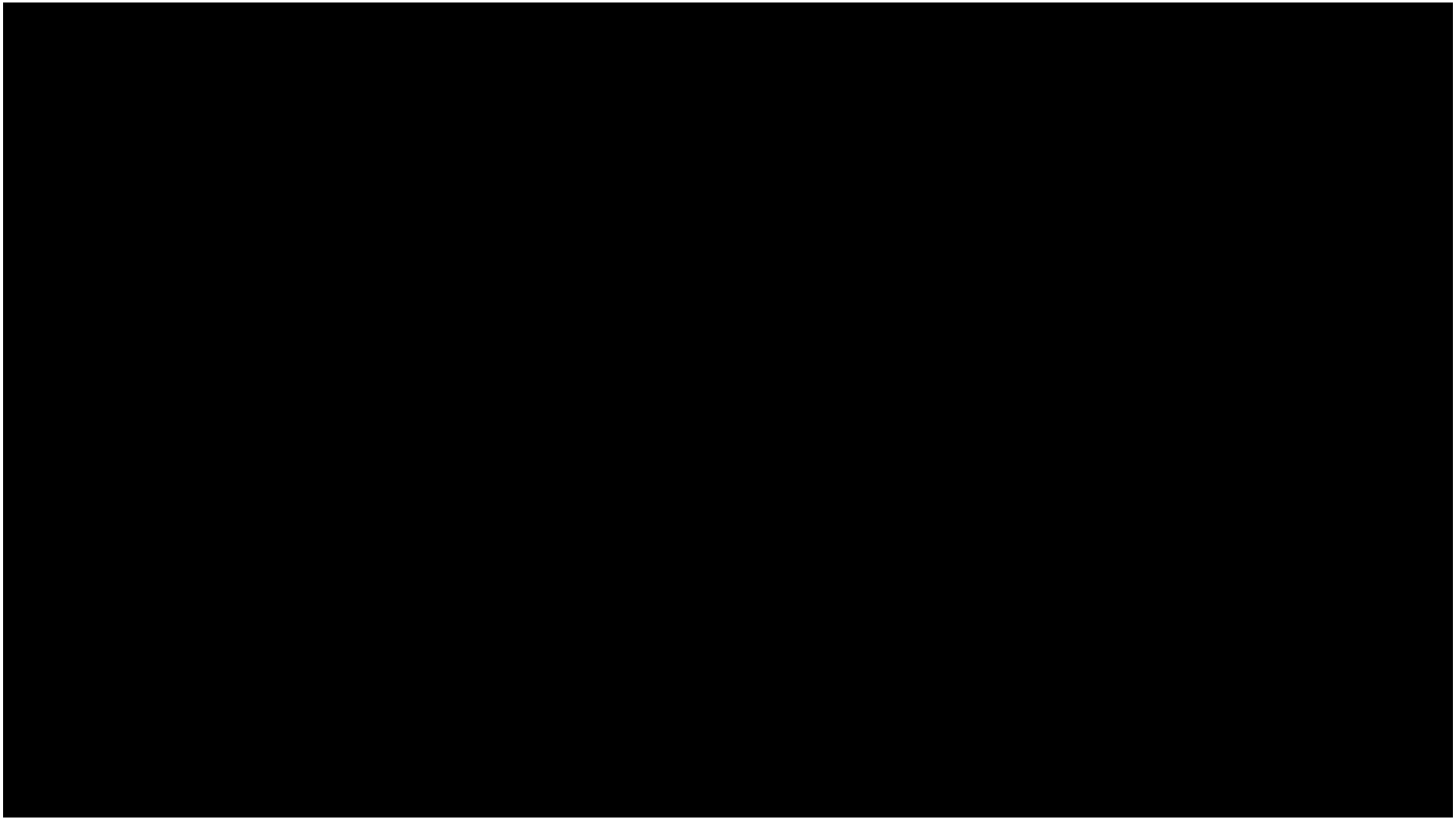


Robotic Space Exploration

Phil Garrison
Robert Wilson
June 6, 2013



Course Outline

- Day 1
  - Program and Mission Development (1)
    - Program
    - Mission Design
    - System Design
  - Earth Science and Planetary Missions
- Day 2
  - Program and Mission Development (2)
    - Subsystem Development
    - Integration and Test
    - Mission Operations
  - Astrophysics and Heliophysics Missions

Programmatic Overview

- Why Explore?/Open Questions
- Who Are the Players?
- What is the Investment?
- How Are Missions Selected?

Big Questions for NASA Science

(http://science.nasa.gov/big-questions/)

Earth

How is the global earth system changing?

How will the Earth system change in the future?

Heliophysics

What causes the sun to vary?

How do the Earth and Heliosphere respond?

What are the impacts on humanity?

Planets

How did the sun's family of planets and minor bodies originate?

How did the solar system evolve to its current diverse state?

How did life begin and evolve on Earth, and has it evolved elsewhere in the Solar System?

What are the characteristics of the Solar System that lead to the origins of life?

Astrophysics

How do matter, energy, space, and time behave under the extraordinarily diverse conditions of the cosmos?

How did the universe originate and evolve to produce the galaxies, stars, and planets we see today?

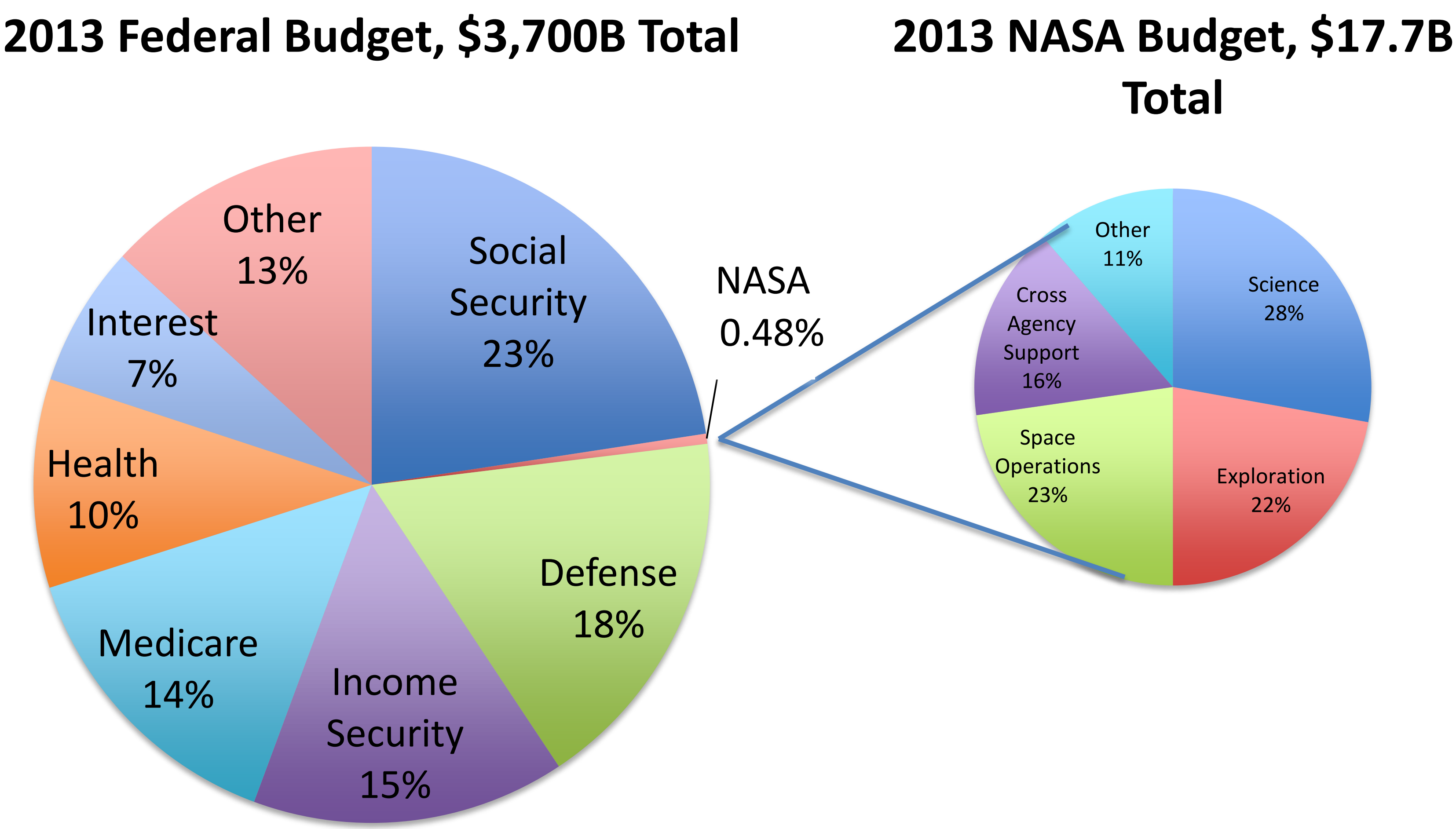
What are the characteristics of planetary systems orbiting other stars, and do they harbor life?

NASA Science Planning

(http://science.nasa.gov/media/medialibrary/2010/03/31/Science_Plan_07.pdf)

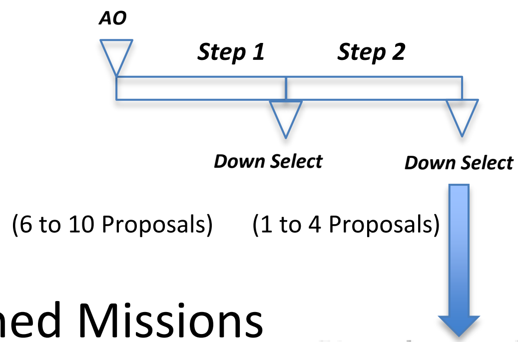
- NRC (NAS) Decadal Surveys Establish Science Priorities
- Science Community and NASA Develop Roadmaps to Plan Implementation and Missions
- Assigned and Competed Missions

U.S. Federal Spending – Fiscal Year 2013

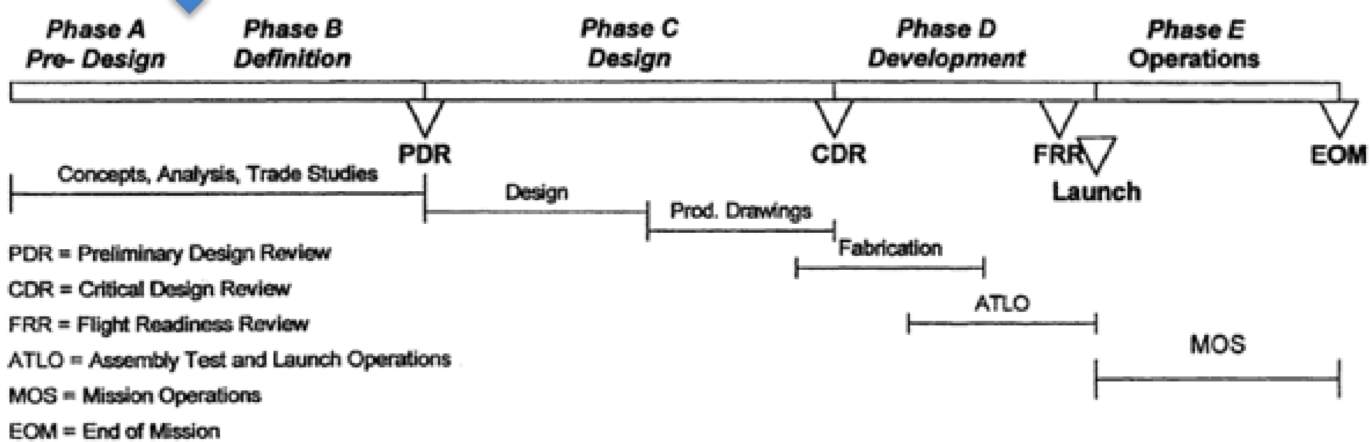


Project Life Cycle

Competed Missions



Assigned Missions

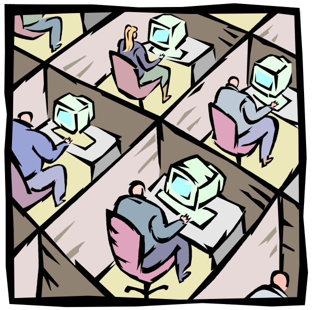


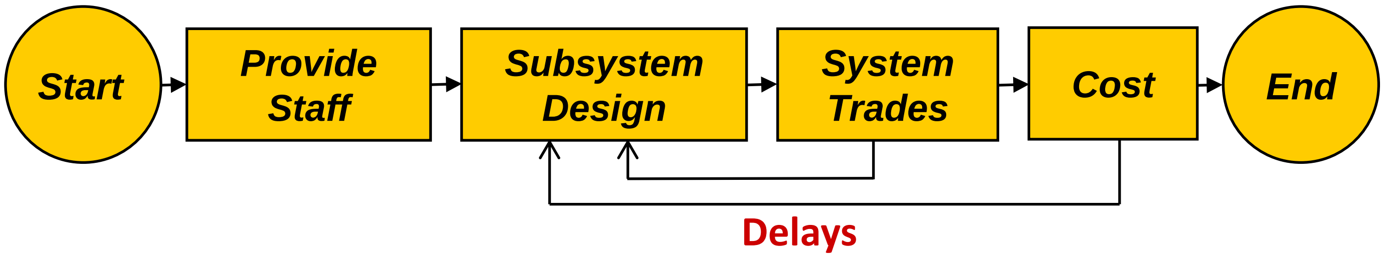
Mission Design

- Science and Engineering Team Collaboration
  - Science Teams Establish Science Requirements
  - Engineering Teams Develop Mission Options
- Team X Provides Environment for Rapidly Exploring Option Space

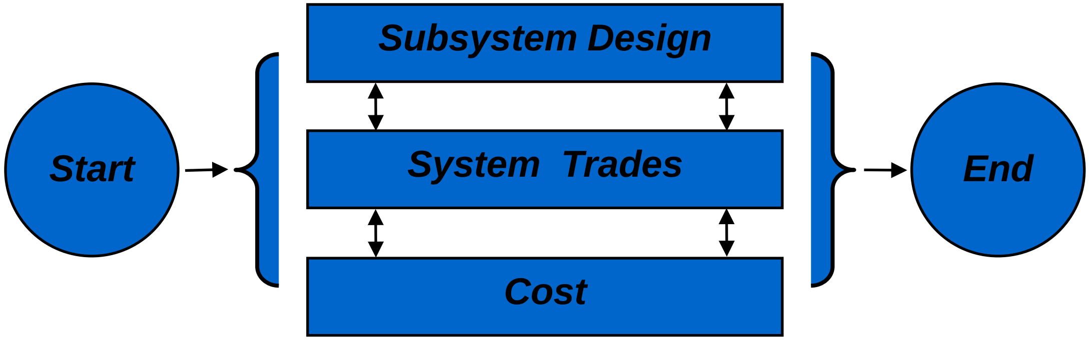
Concurrent Engineering – What is it?

- Traditional Method – Serial





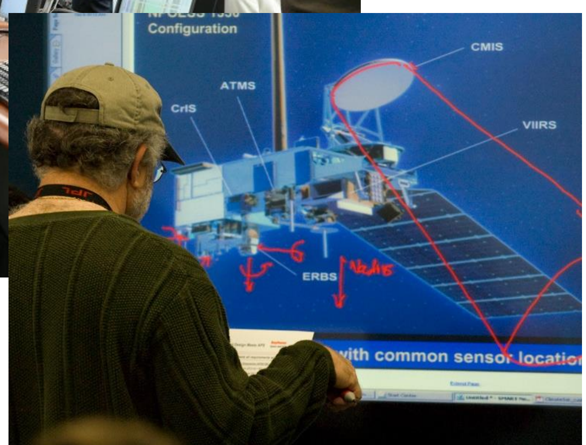
- Concurrent Engineering – Parallel
  - Diverse specialists working in real time, in the same place, with shared data, to yield an integrated design



Team X

JPL's concurrent engineering team for rapid design and analysis of space mission concepts

- Developed in 1995 to reduce study time and cost
- More than 1100 studies completed

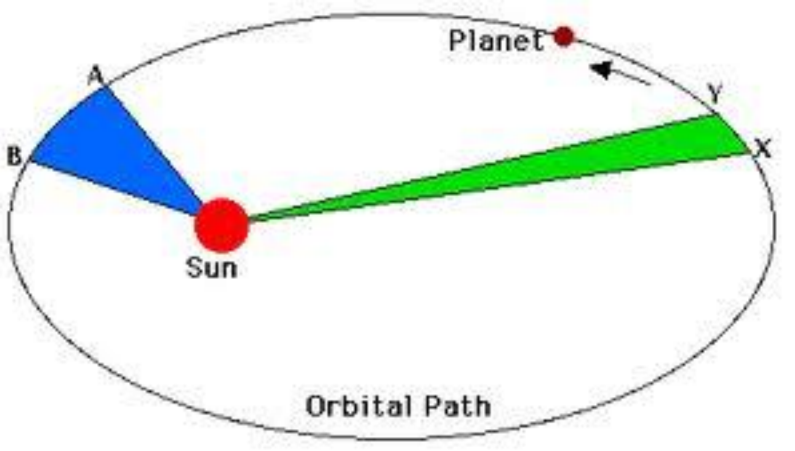


Multidisciplinary Team

- Science
- System Engineering
- Configuration
- Attitude Control
- C&DH/Software
- Power
- Propulsion
- Structures
- Thermal
- Telecom
- Ground Systems
- Reliability
- Cost

Orbital Mechanics 101
Kepler's Laws

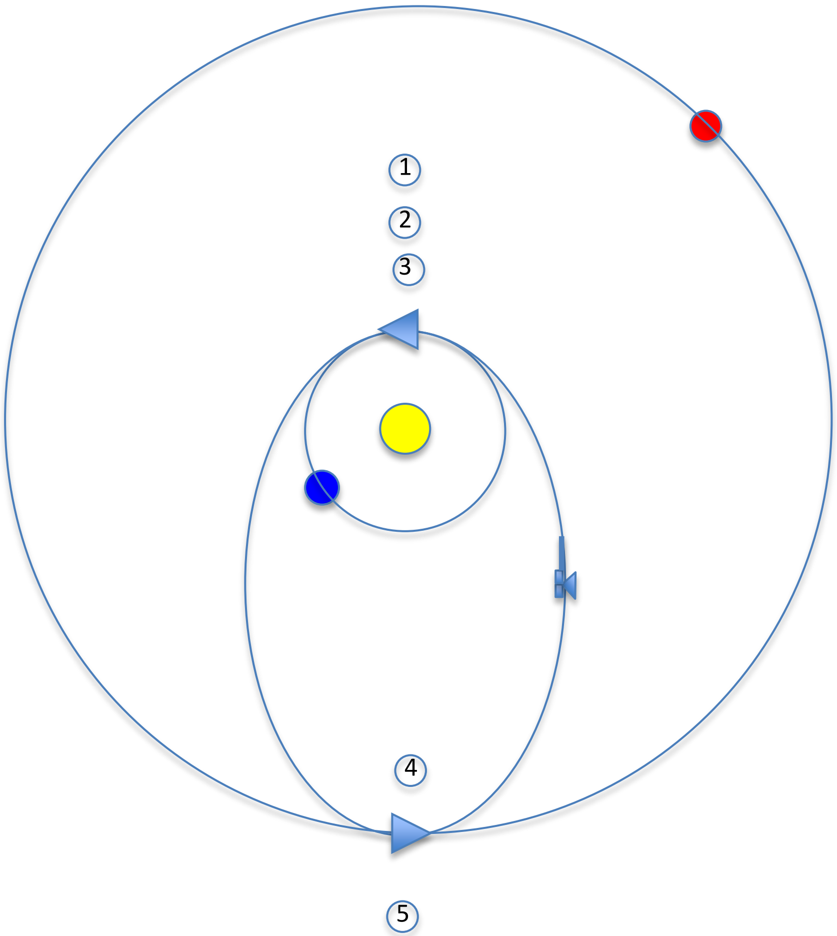
Johannes Kepler
1571-1630

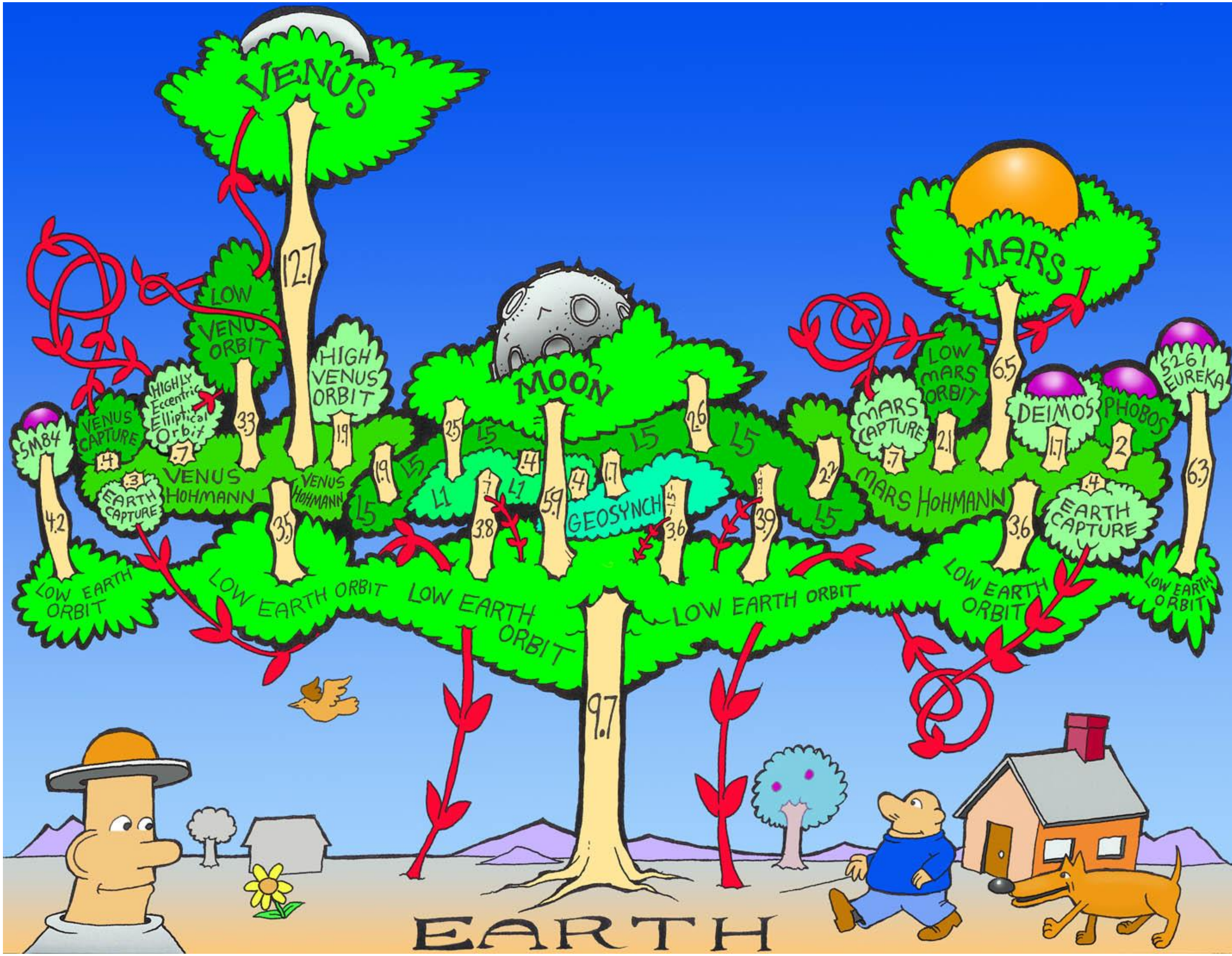


1. Planets move around the Sun in **ellipses**, with the Sun at one focus
2. The line connecting the Sun to a planet sweeps **equal areas in equal times.**
3. The **square** of the orbital period of a planet is proportional to the **cube** (3rd power) of the mean distance from the Sun

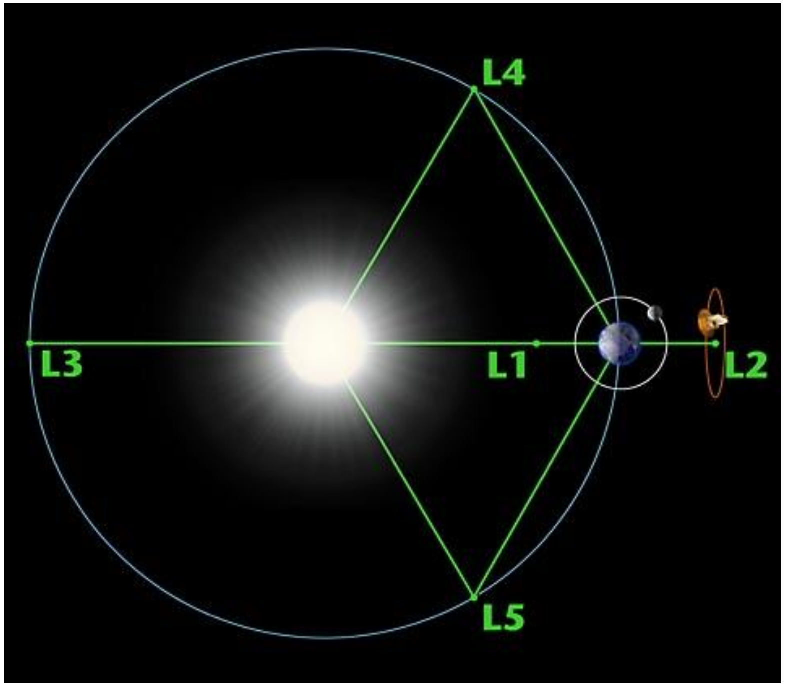
Hohmann Transfer Earth to Mars

		V (km/s)	D V (km/s)
1	E_{∞}	11	
	$E_{Rotation}$	1.5	9.5
2	E_{Sun}	30	
3	MTO_E	33	3.0
4	MTO_M	21.6	
5	M_{Sun}	24.3	2.7
	Total		15.2




VENUS
12.7
LOW VENUS ORBIT
HIGH VENUS ORBIT
HIGHLY Eccentric Elliptical Orbit
VENUS CAPTURE
5M84
VENUS HOHMANN
EARTH CAPTURE
3.3
1.9
4.2
3.5
MOON
L1
L5
GEOSYNCH
5.9
9.7
MARS
6.5
LOW MARS ORBIT
MARS CAPTURE
DEIMOS
PHOBOS
5261 EUREKA
6.3
MARS HOHMANN
EARTH CAPTURE
LOW EARTH ORBIT
EARTH

Lagrangian (Libration) Points – Sun Earth System



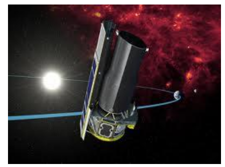
Point	Distance from Earth, 10^6 km
L_1	1.5
L_2	1.5

Mission	Point
ACE	L_1
SOHO	L_1
ISEE-3	L_1
Herschel Planck	L_2
WMAP	L_2
JWST	L_2

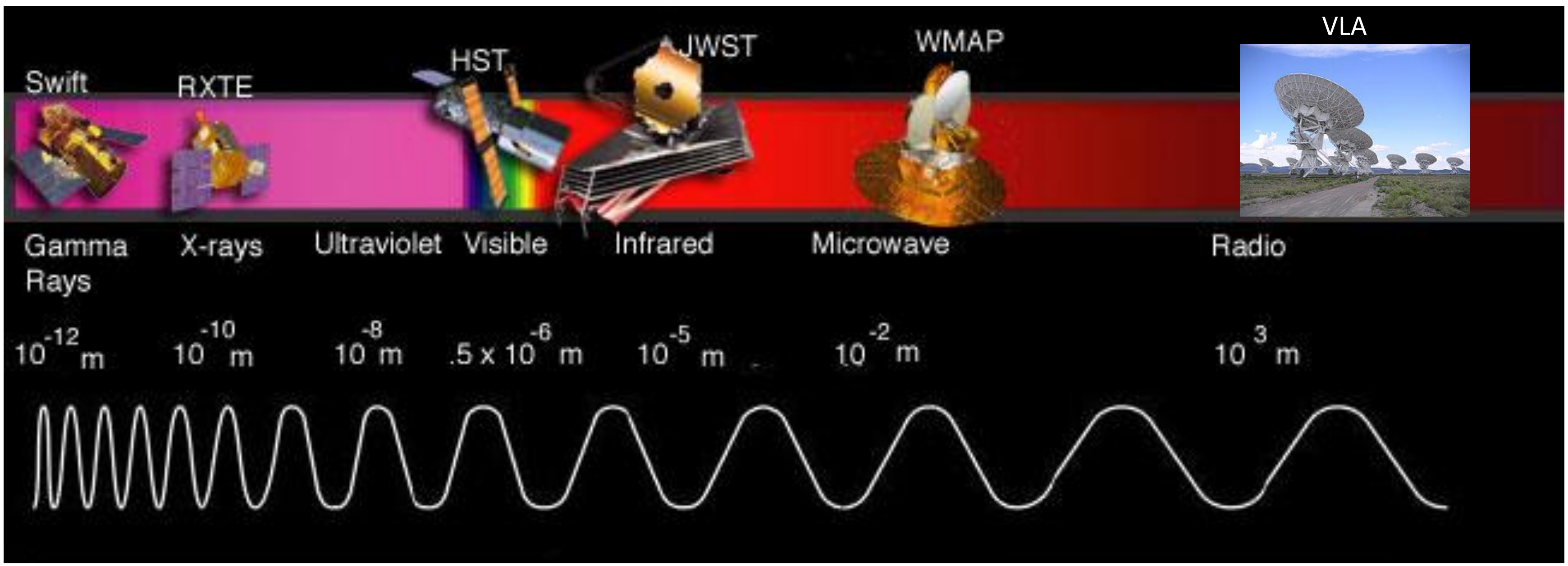
Science Instruments

- Remote sensing
  - Used on an orbiting platform to make observation of planetary body or its atmosphere
- In Situ
  - Used on a landed spacecraft to make some form of “contact” measurement

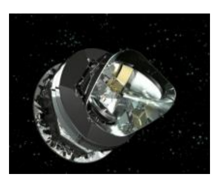
Instruments Span the Electromagnetic Spectrum



Spitzer



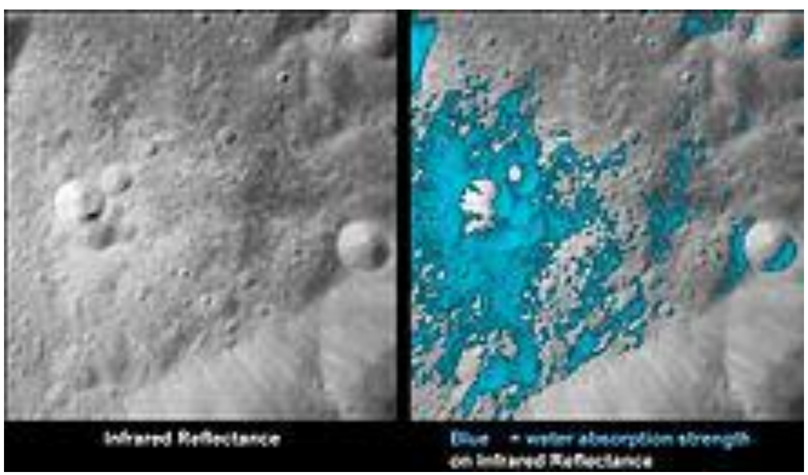
Chandra



Herschel Planck

Moon Mineralogy Mapper on Chandrayaan-1

Moon Mineralogy Mapper (M3)
- 10 kg
- 10 W

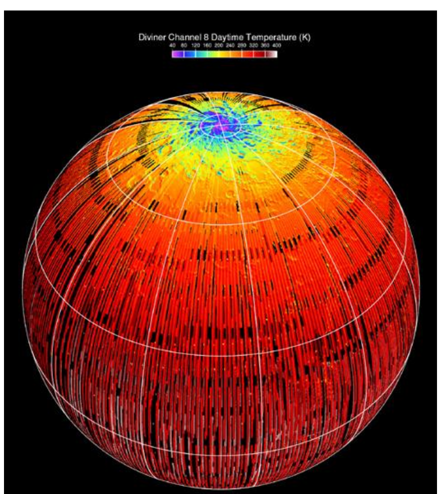


Water Detected in lunar craters

Diviner on Lunar Reconnaissance Orbiter

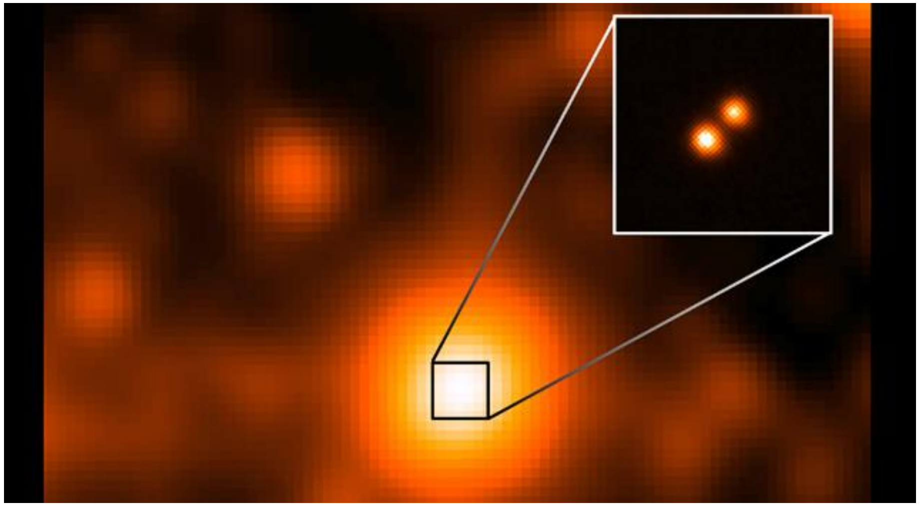
9 channel infrared filter radiometer

- 9 kg
- 11 W



First global temperature map of the moon

Wide-field Infrared Survey Explorer (WISE) Instrument



Closest Star System Found in a Century

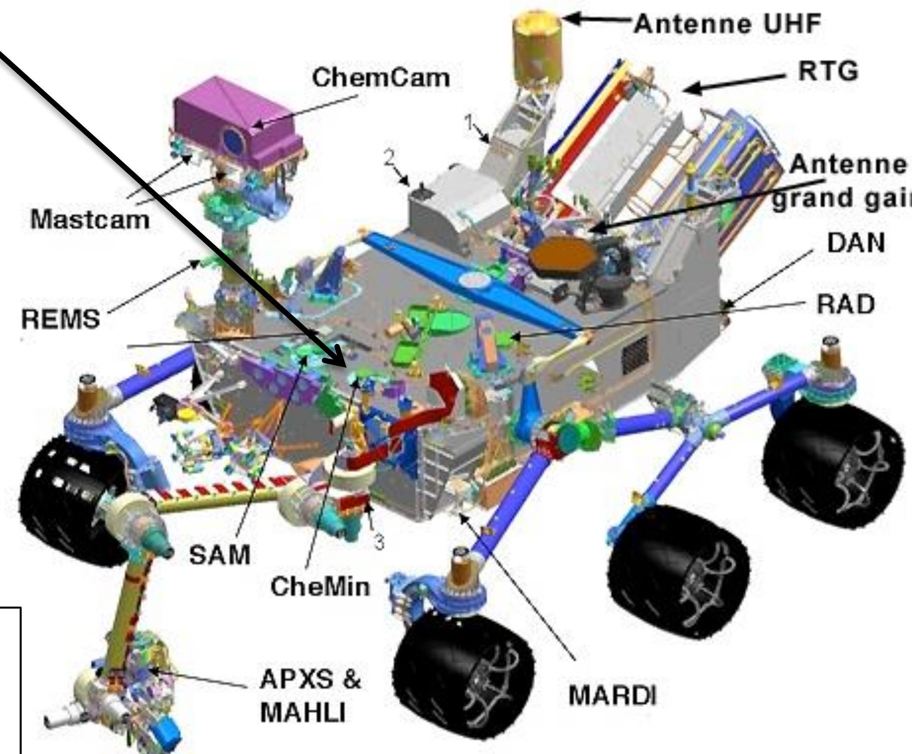
- **Brown Dwarfs**
- **6.5 ly**

WISE IR instrument

- 363 kg (includes telescope)
- 115 W
- Telescope temperature = 20K (-423^{o}F)
- Focal plane temperature =7K (-447^{o}F)

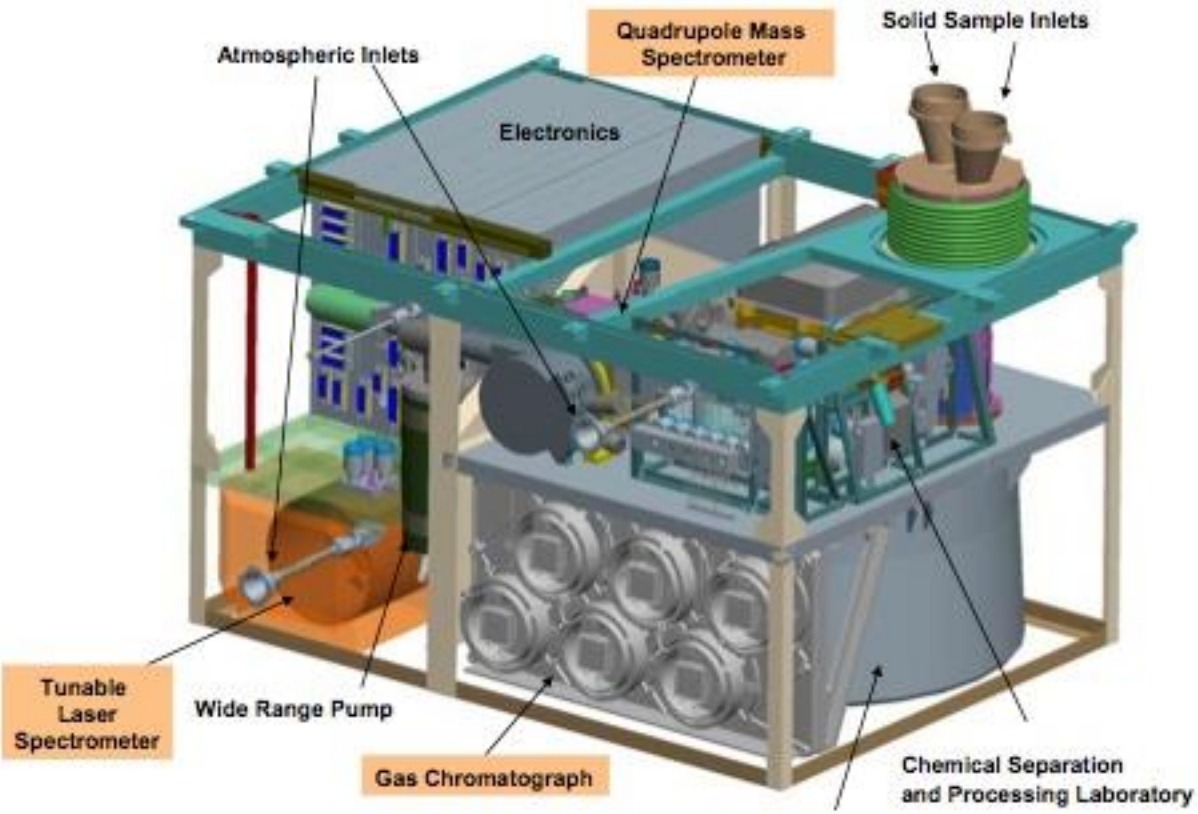
Chemistry and Mineralogy (CheMin) on Curiosity Rover

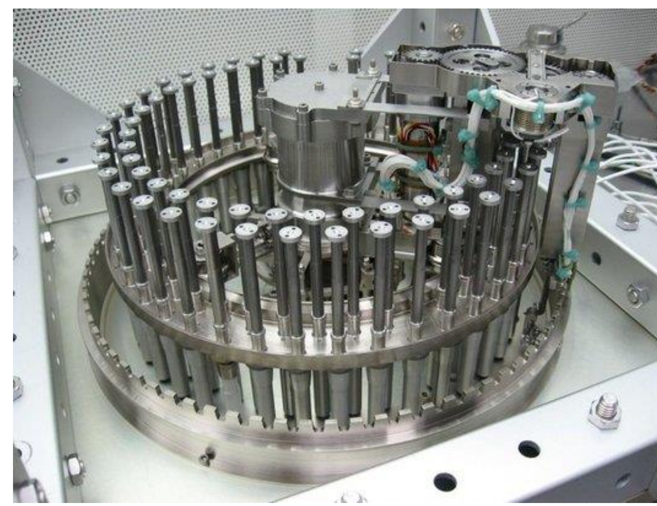
CheMin
- X-ray powder diffraction and fluorescence instrument
- 10 kg
- 40 W



First X-ray diffraction analysis revealed presence of feldspar, pyroxenes and olivine similar to the "weathered basaltic soils" of Hawaiian volcanoes

Sample Analysis at Mars (SAM) on Curiosity



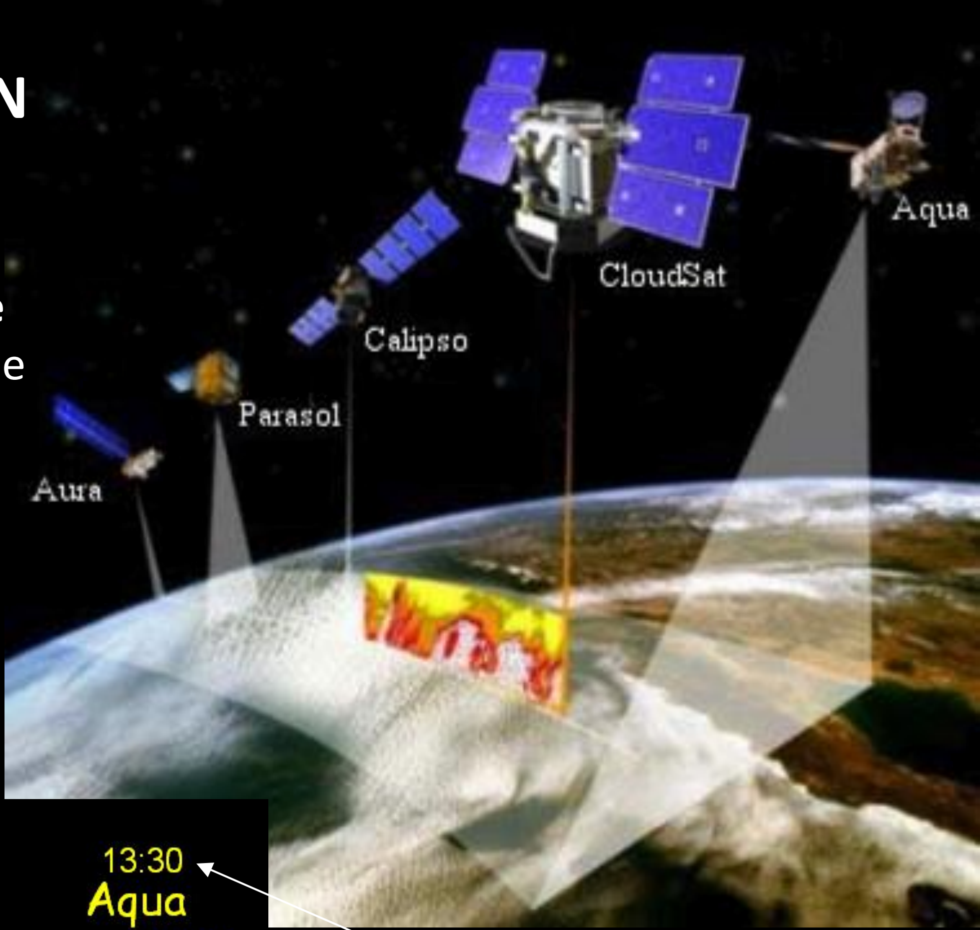


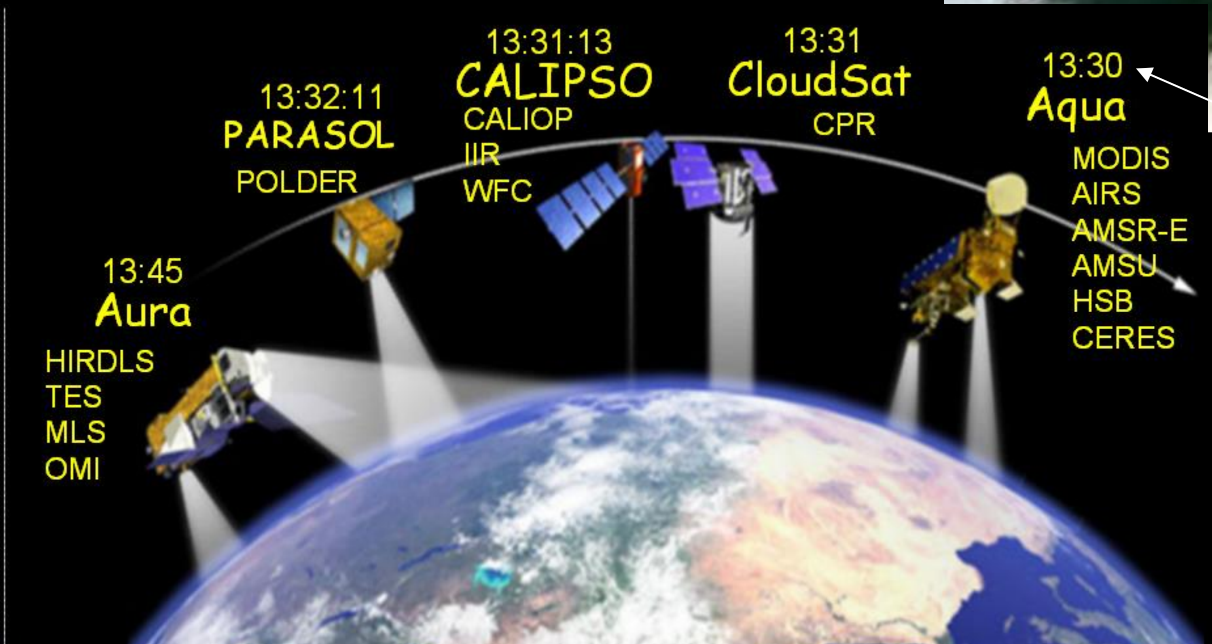
Mass = 40 kg
Power = 25 – 200 W

Earth Science Missions

A-TRAIN CONSTELLATION

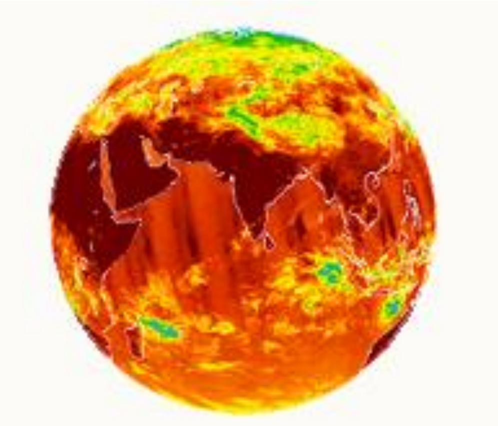
- **5 Satellites**
- **Altitude = 690 km; Inclination = 98.14 deg**
- **Oblatness of Earth Precesses Orbital Plane**
- Crosses Equator at 1:30 PM Local Solar Time



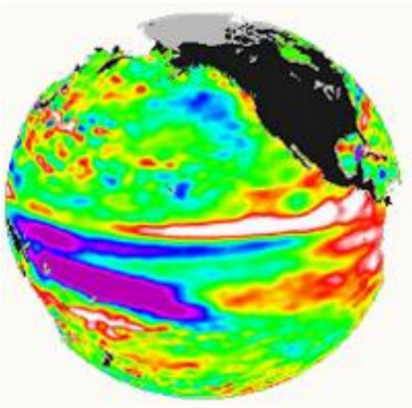


Approx equator crossing times

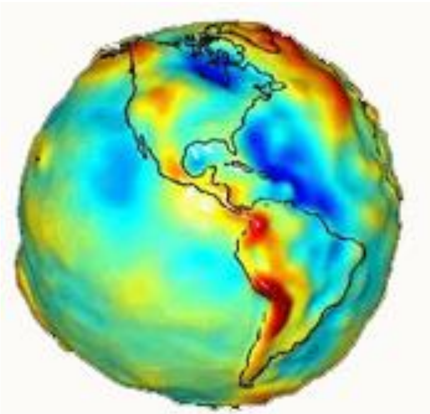
New ways to see a changing Earth with robotic remote sensing



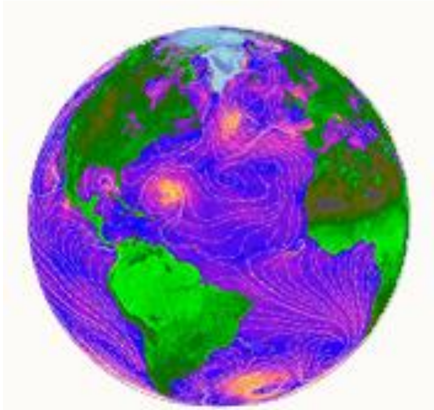
Atmospheric Infrared Sounder (AIRS) provides monthly global temperature maps



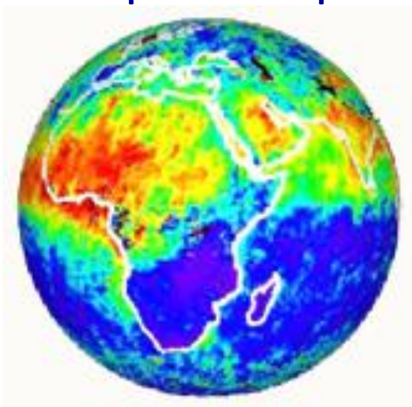
Jason provides global sea surface height maps every 10 days



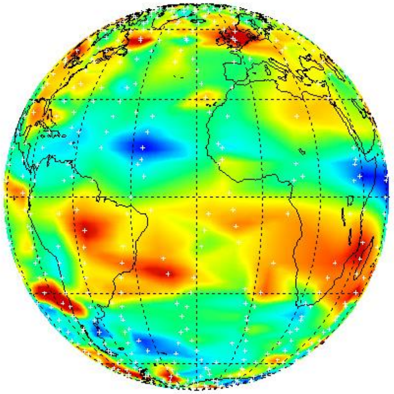
Gravity Recovery and Climate Experiment (GRACE) provides monthly maps of Earth's gravity



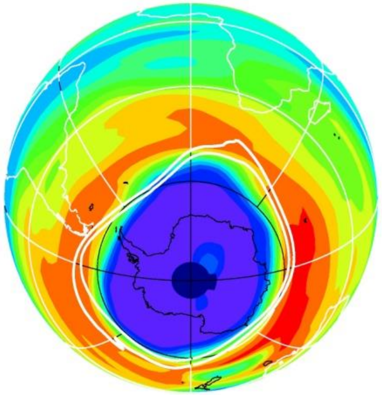
QuikSCAT provides near global (90%) ocean surface wind maps every 24 hours



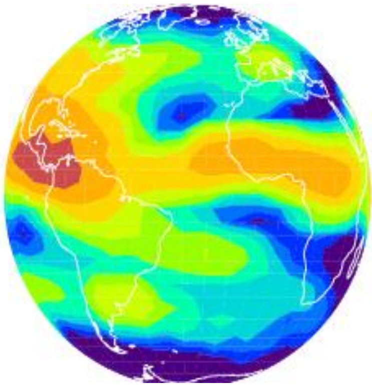
Multi-angle Imaging Spectro Radiometer (MISR) provides monthly global aerosol maps



Tropospheric Emission Spectrometer (TES) provides monthly global maps of Ozone

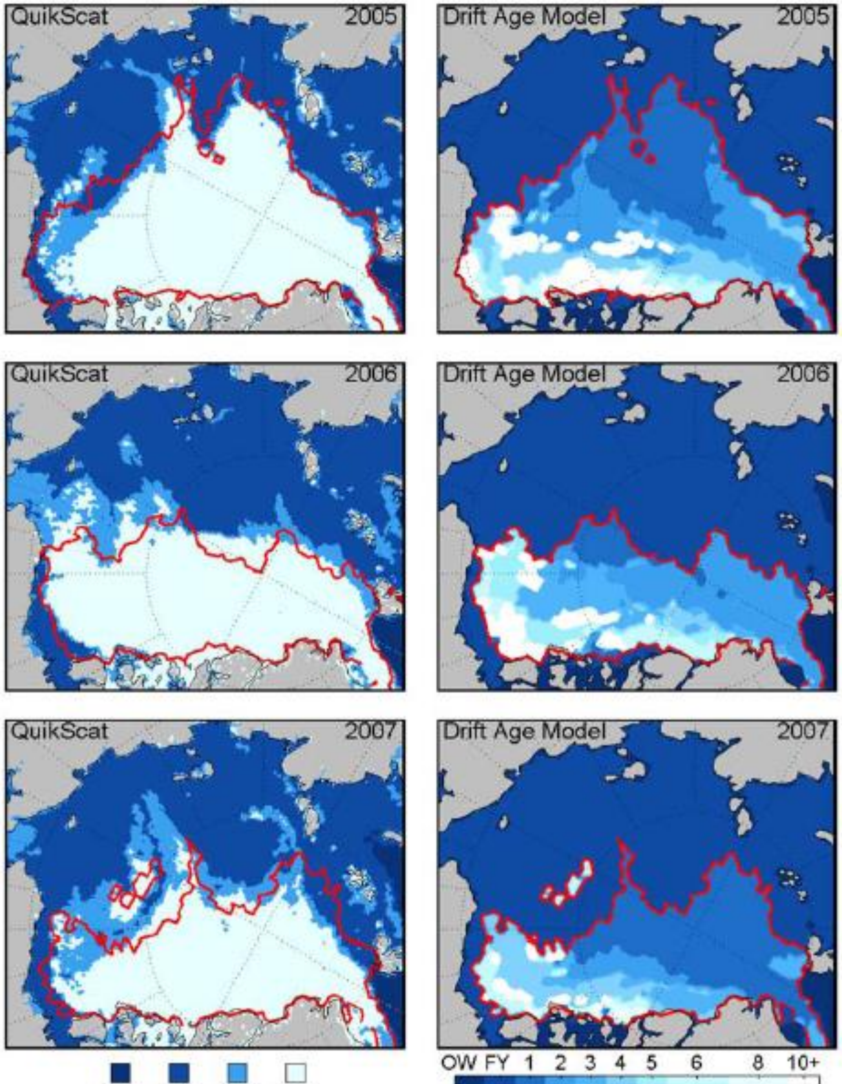


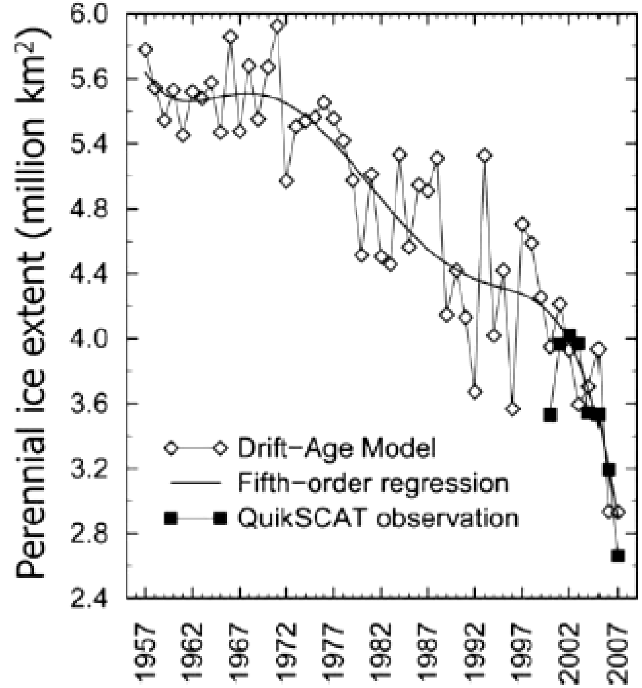
Microwave Limb Sounder (MLS) provides daily maps of stratospheric chemistry



CloudSat provides monthly maps of cloud ice water content

QuikSCAT observes sea ice loss



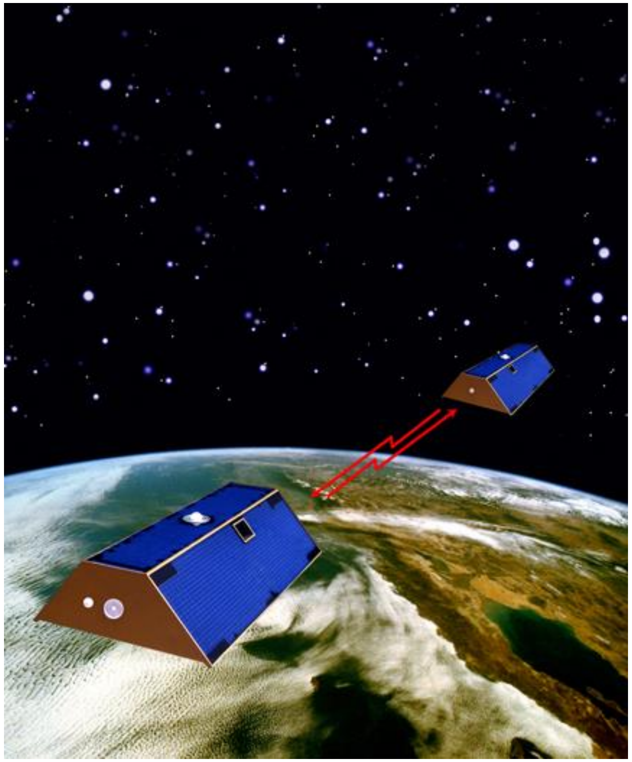


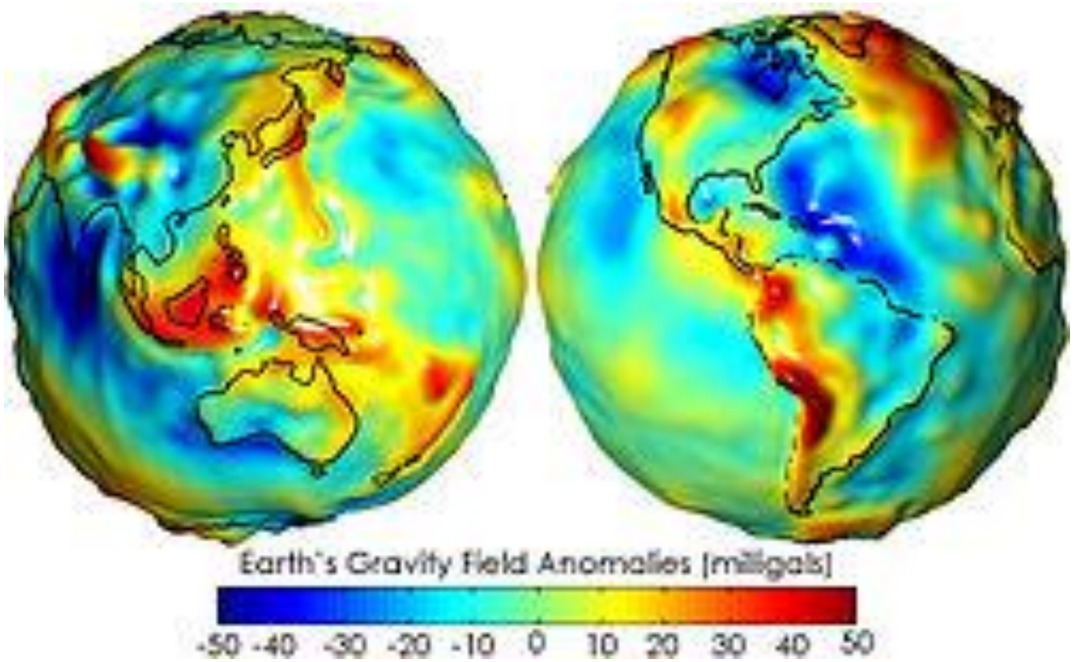
Continuous monitoring of Arctic Sea Ice by QuikSCAT shows trend of perennial Arctic sea-ice loss. Arctic wind conditions contributed to the acceleration of the recent losses.

Nghiem *et al*. 2007 *GRL*

Gravity Recovery and Climate Experiment (GRACE)

- Monthly gravity maps up to 1,000 times more accurate than previous maps
- Improved understanding of
  - Global ocean circulation
  - Thinning of ice sheets
  - Sea level rise
  - Changes in salinity



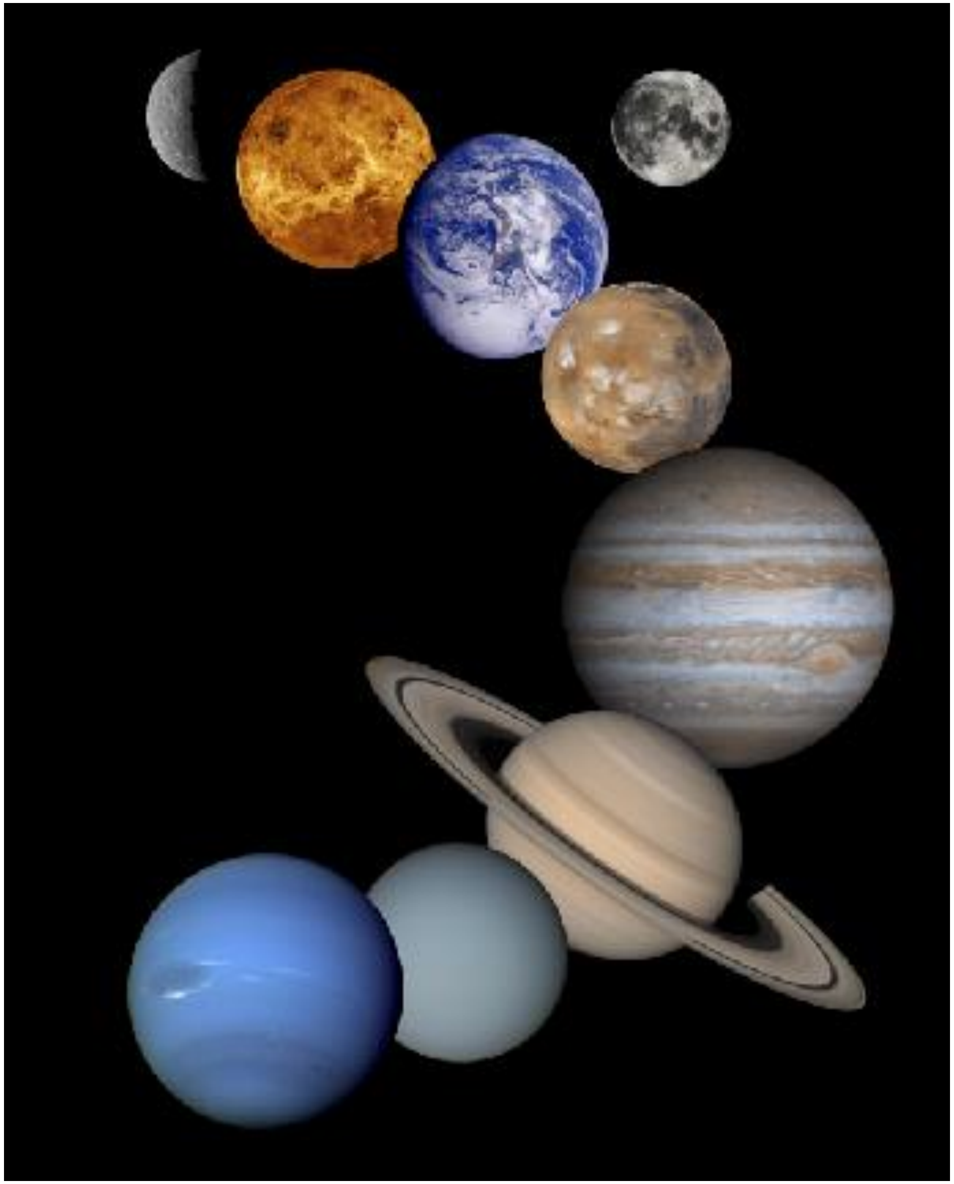


Break

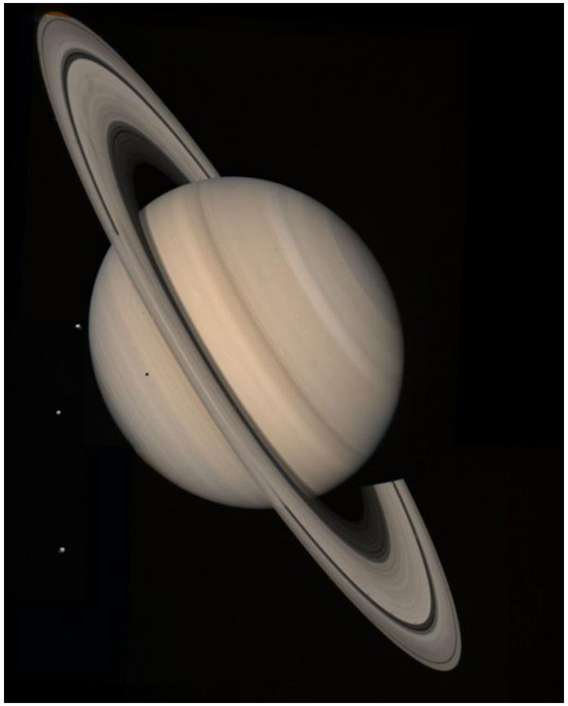
Next up:

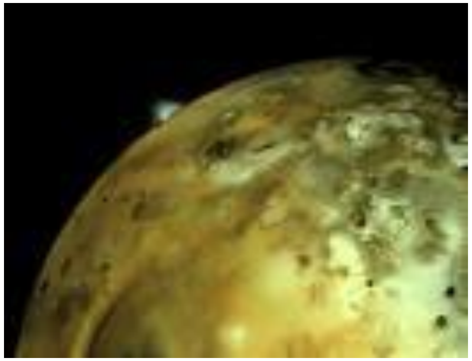
- Planetary Science Missions

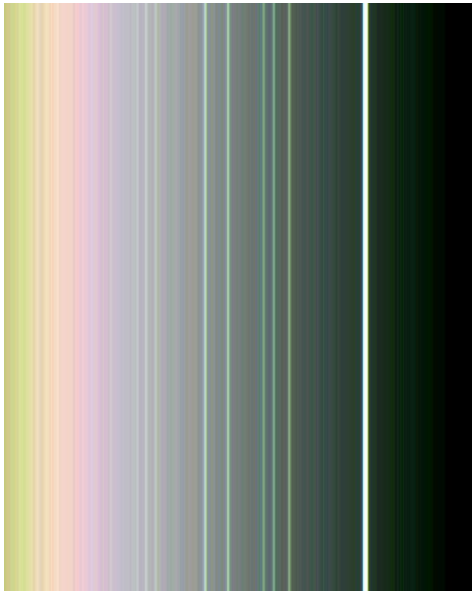
Planetary Science Missions

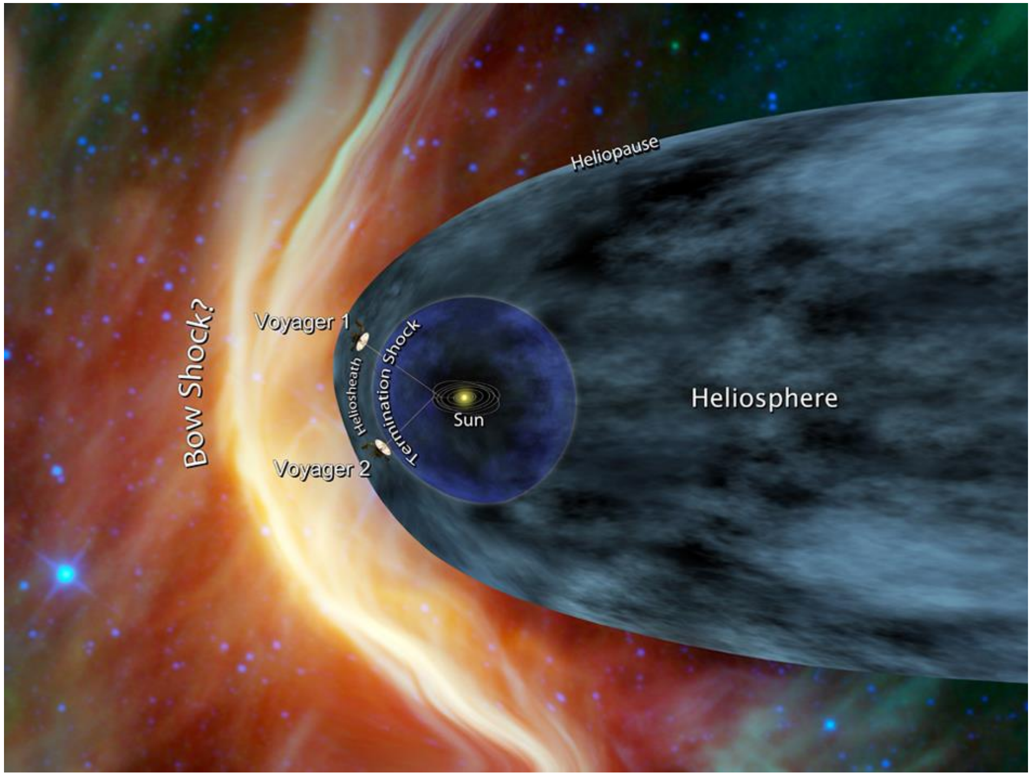


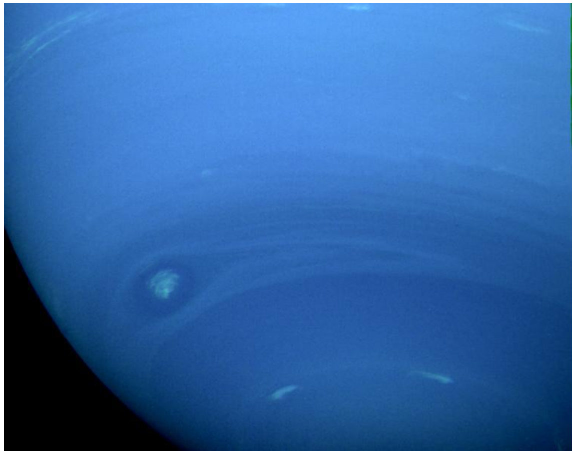
Voyager - 1979



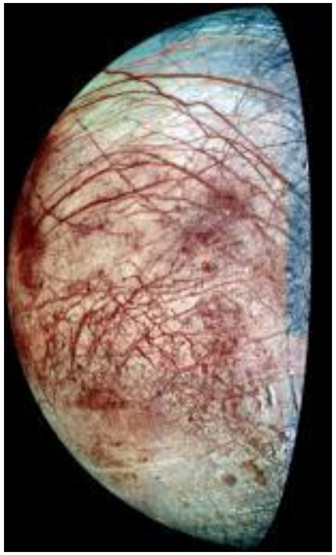


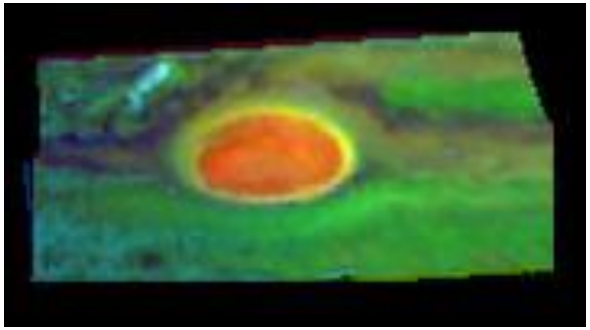


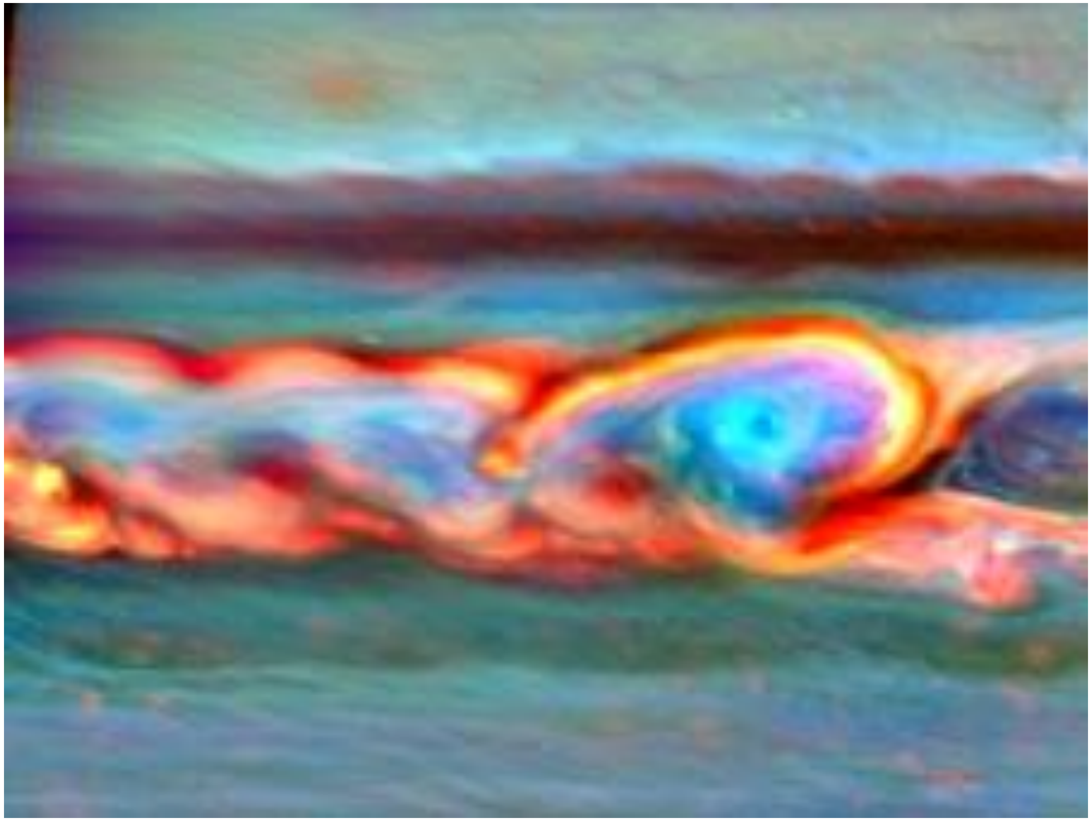
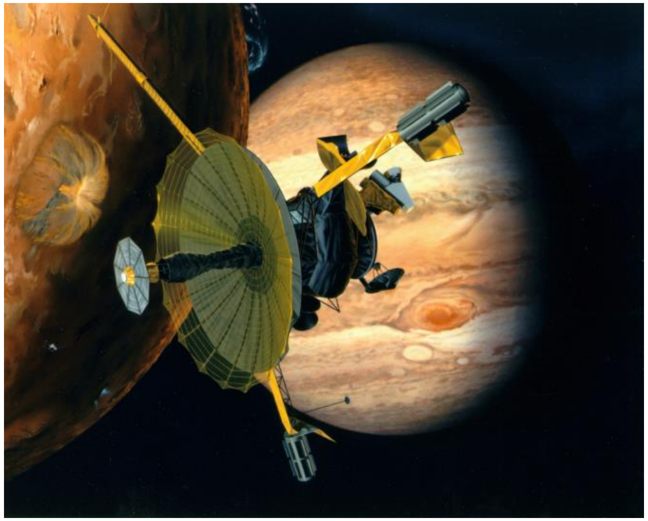




Galileo at Jupiter

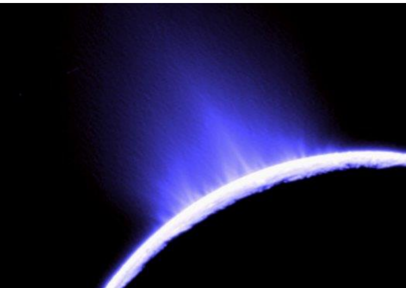


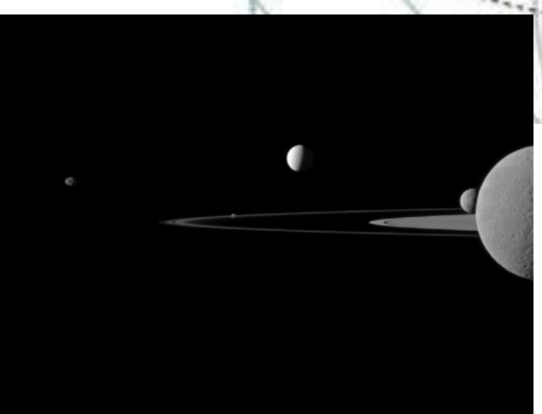


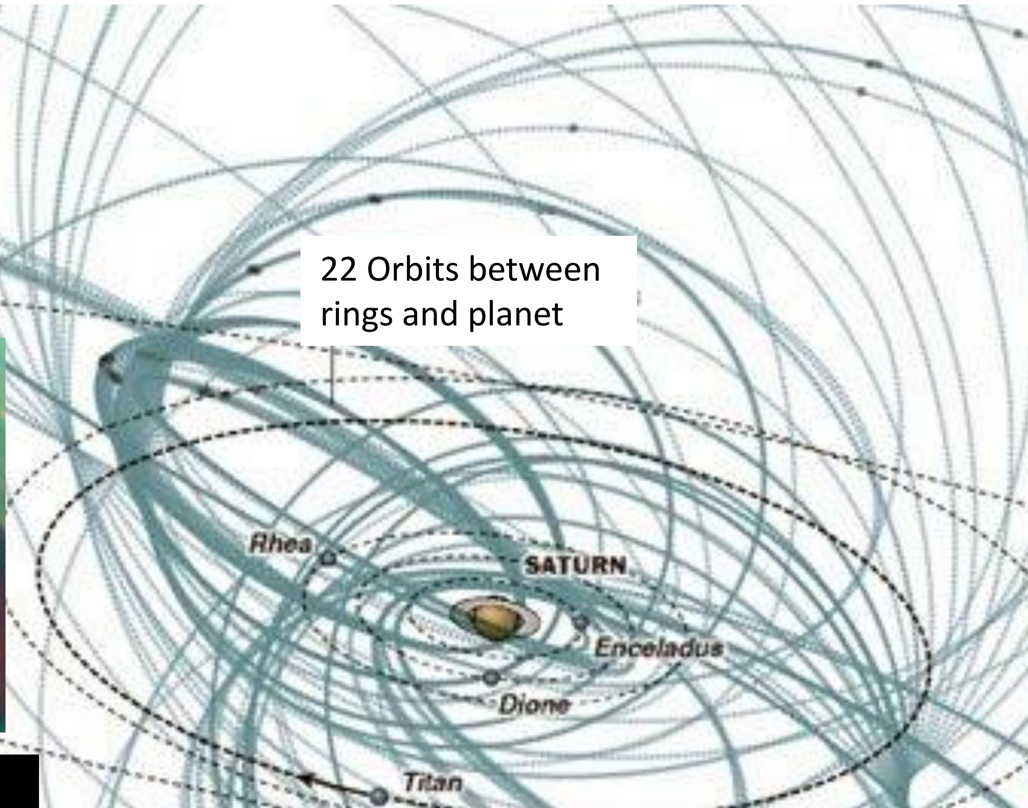



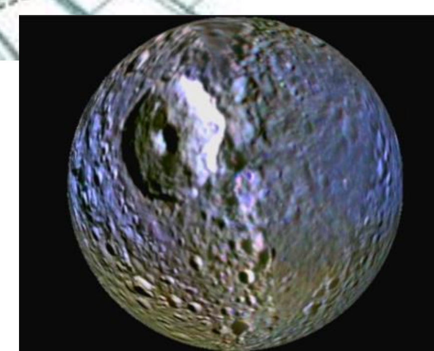
Cassini at Saturn

Complex Cassini Mission Operations



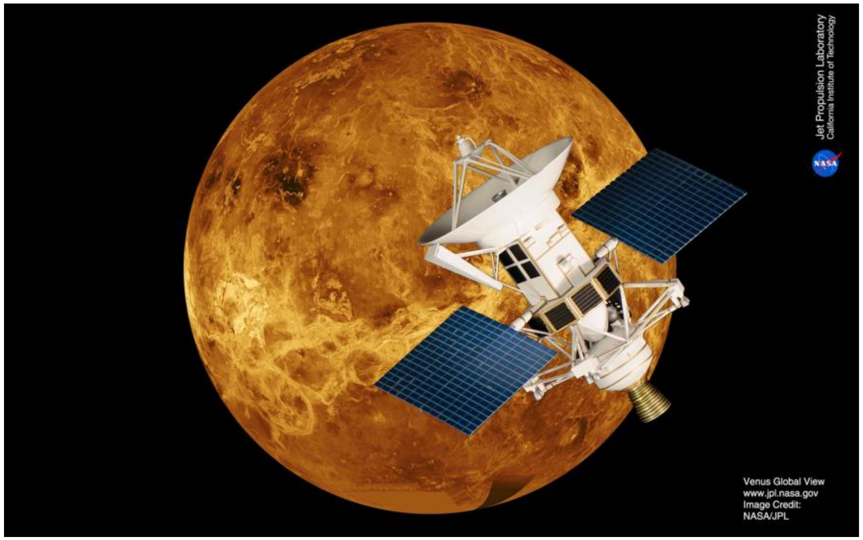


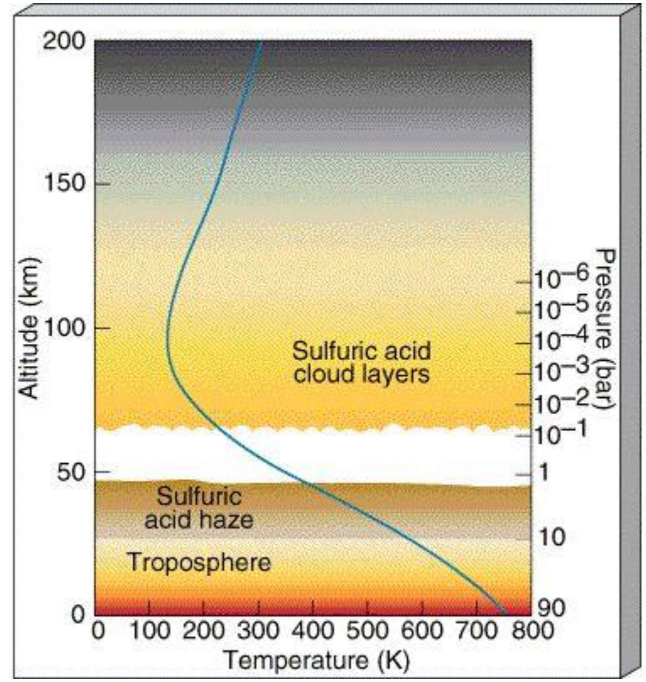


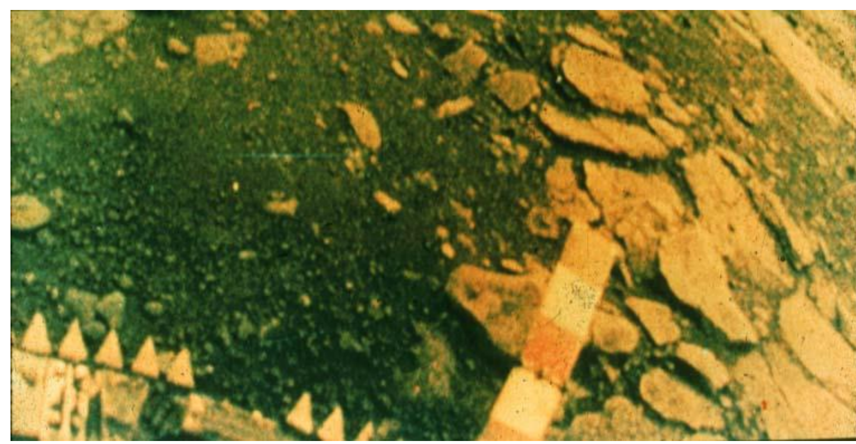


- Precision Navigation
- Precision Maneuvers

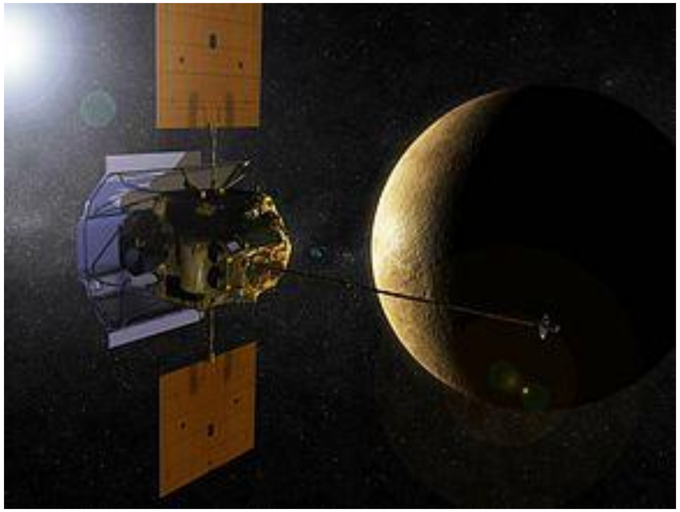
Russian and US Spacecraft at Venus

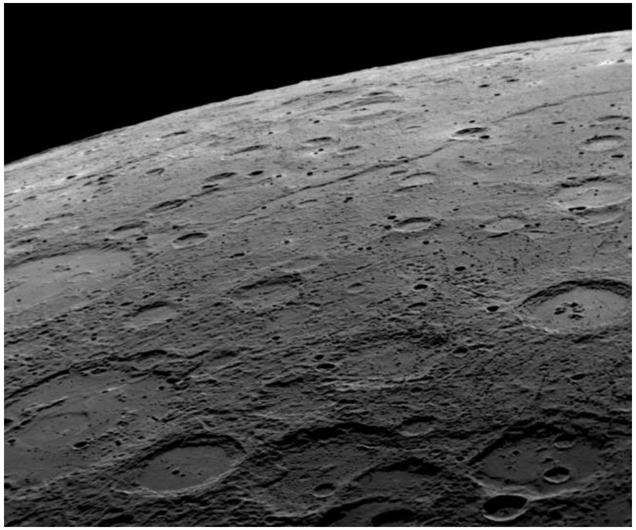


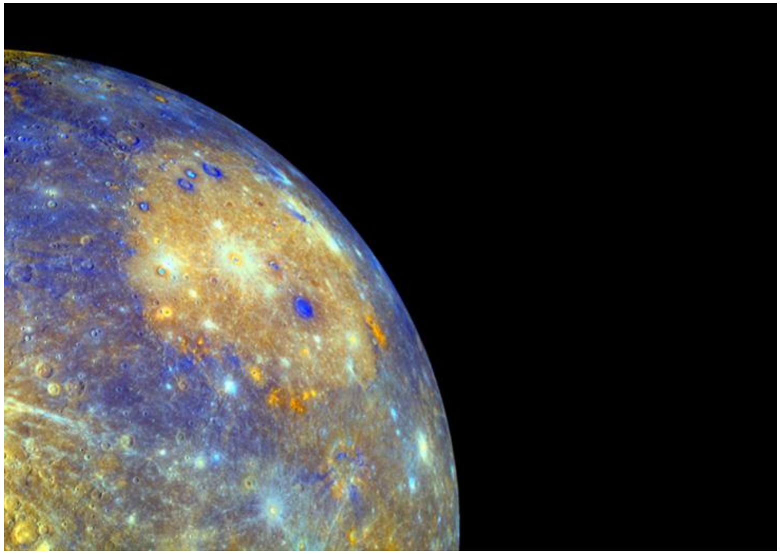


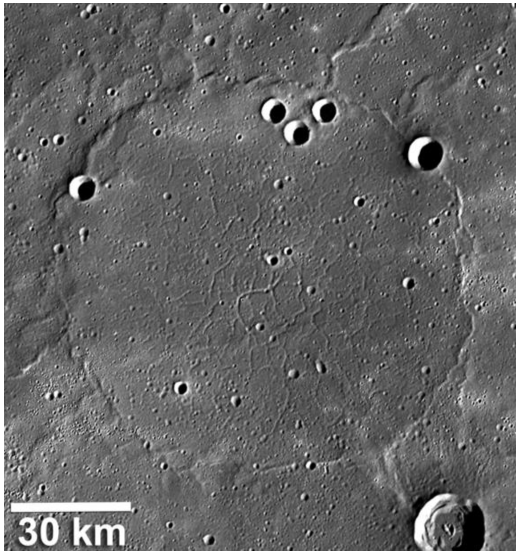


Messenger at Mercury

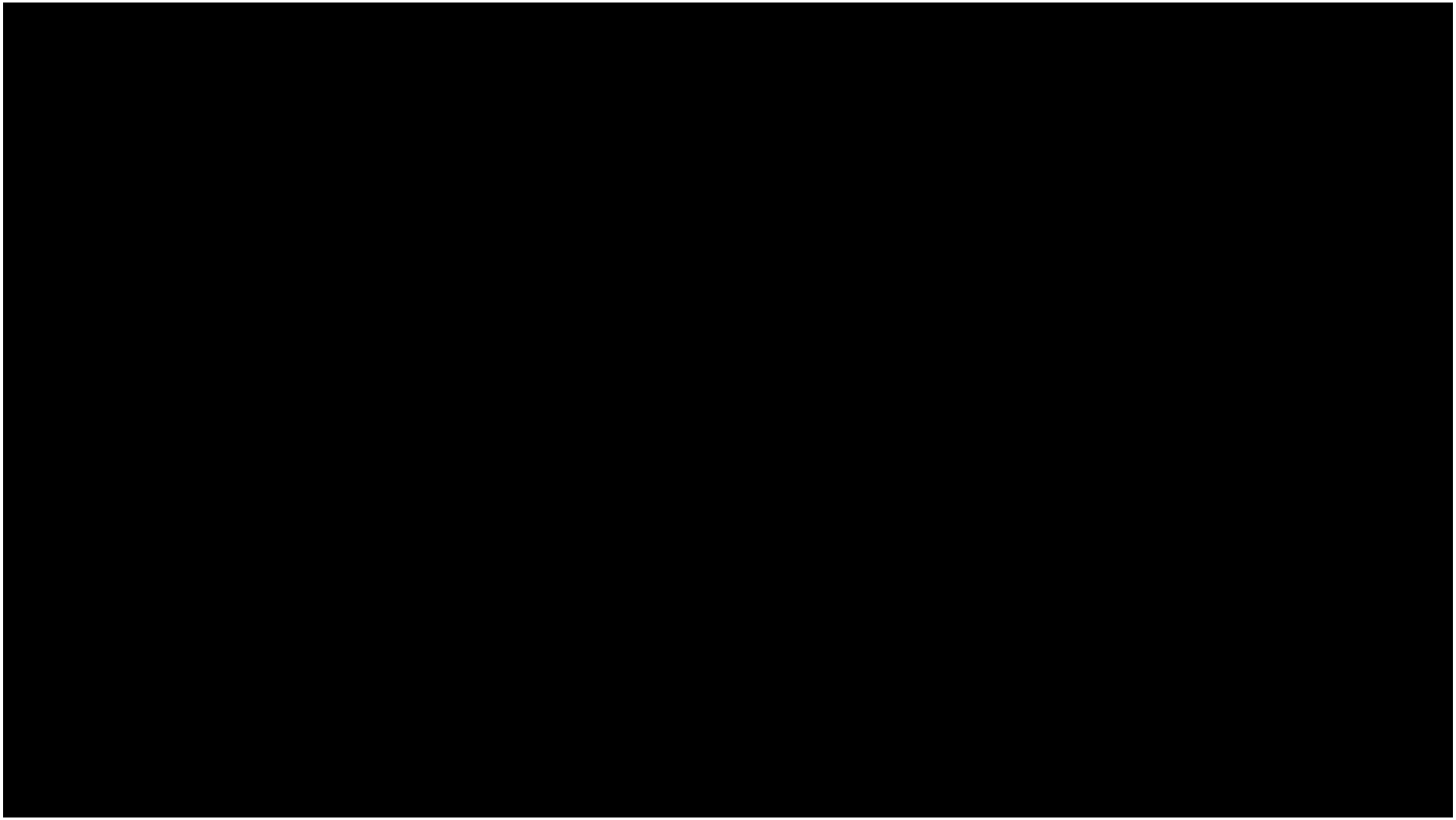




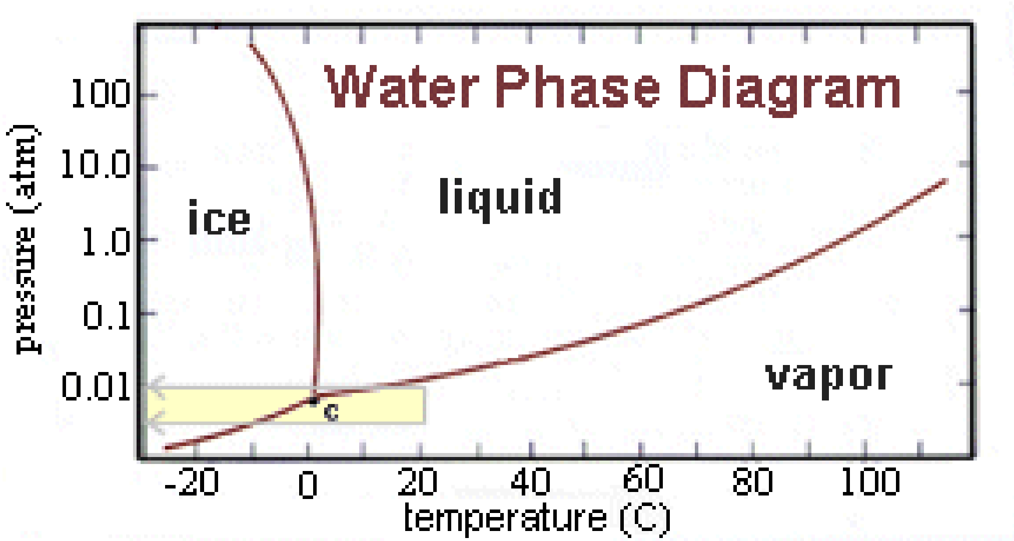


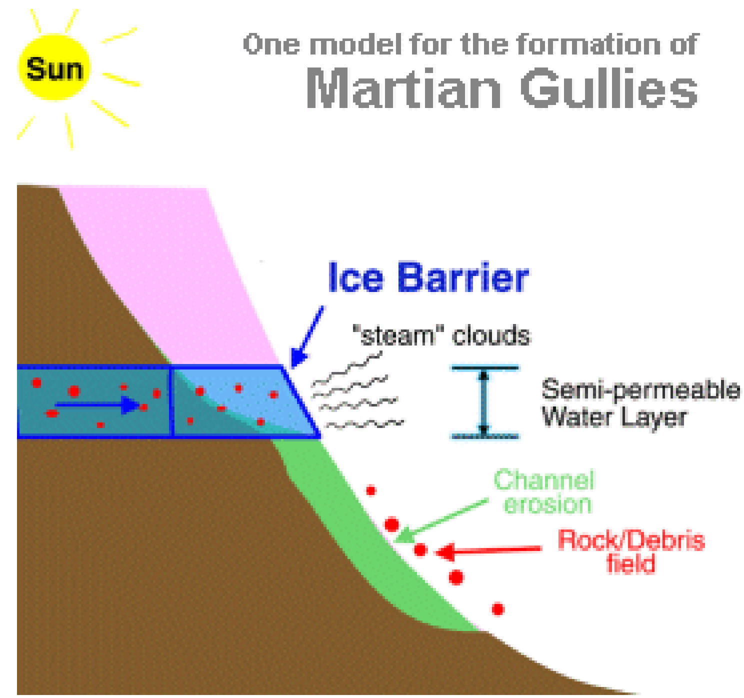


MRO at Mars - Possible Water Flows



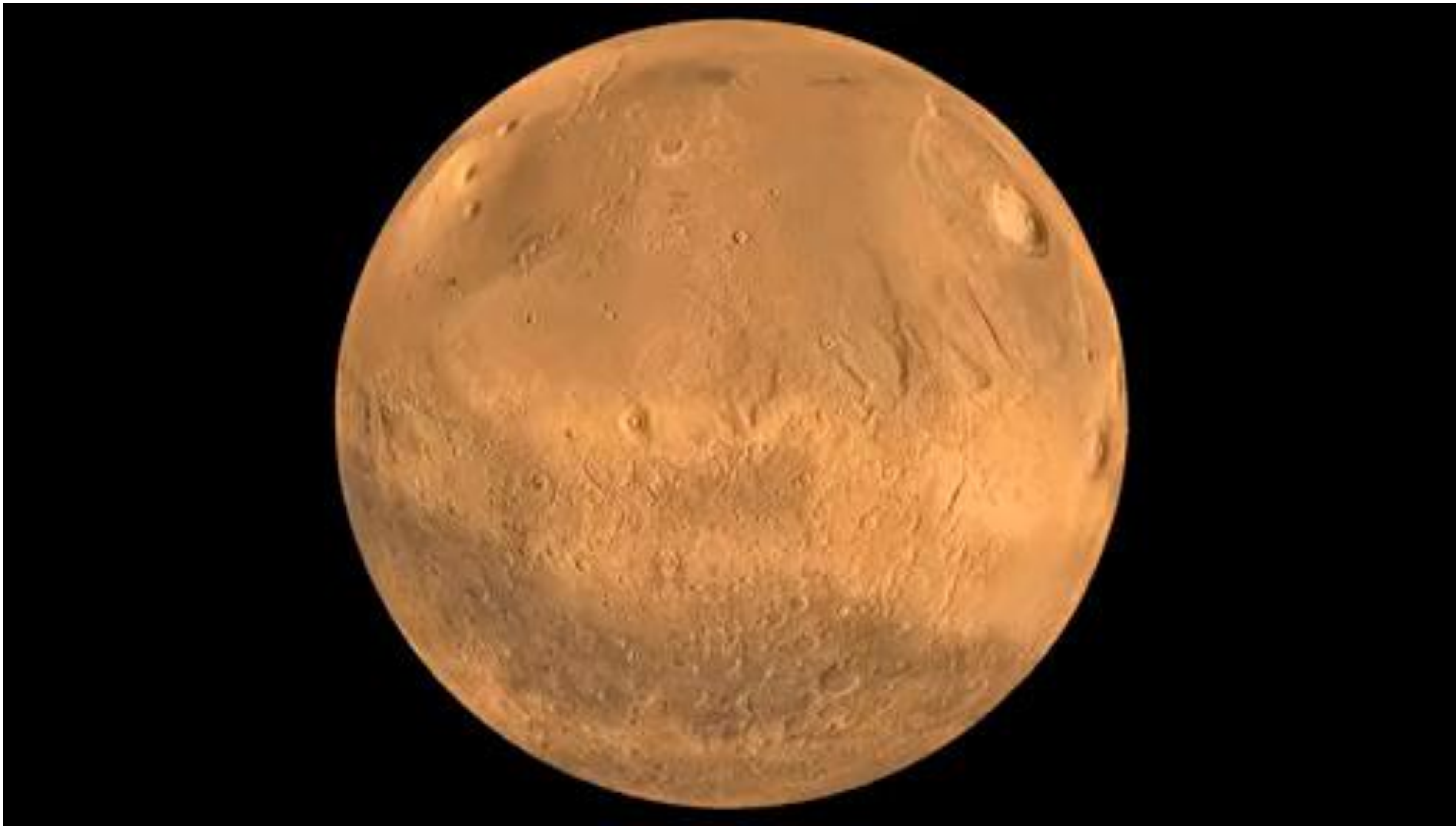
How Can Liquid Water Exist on Mars?





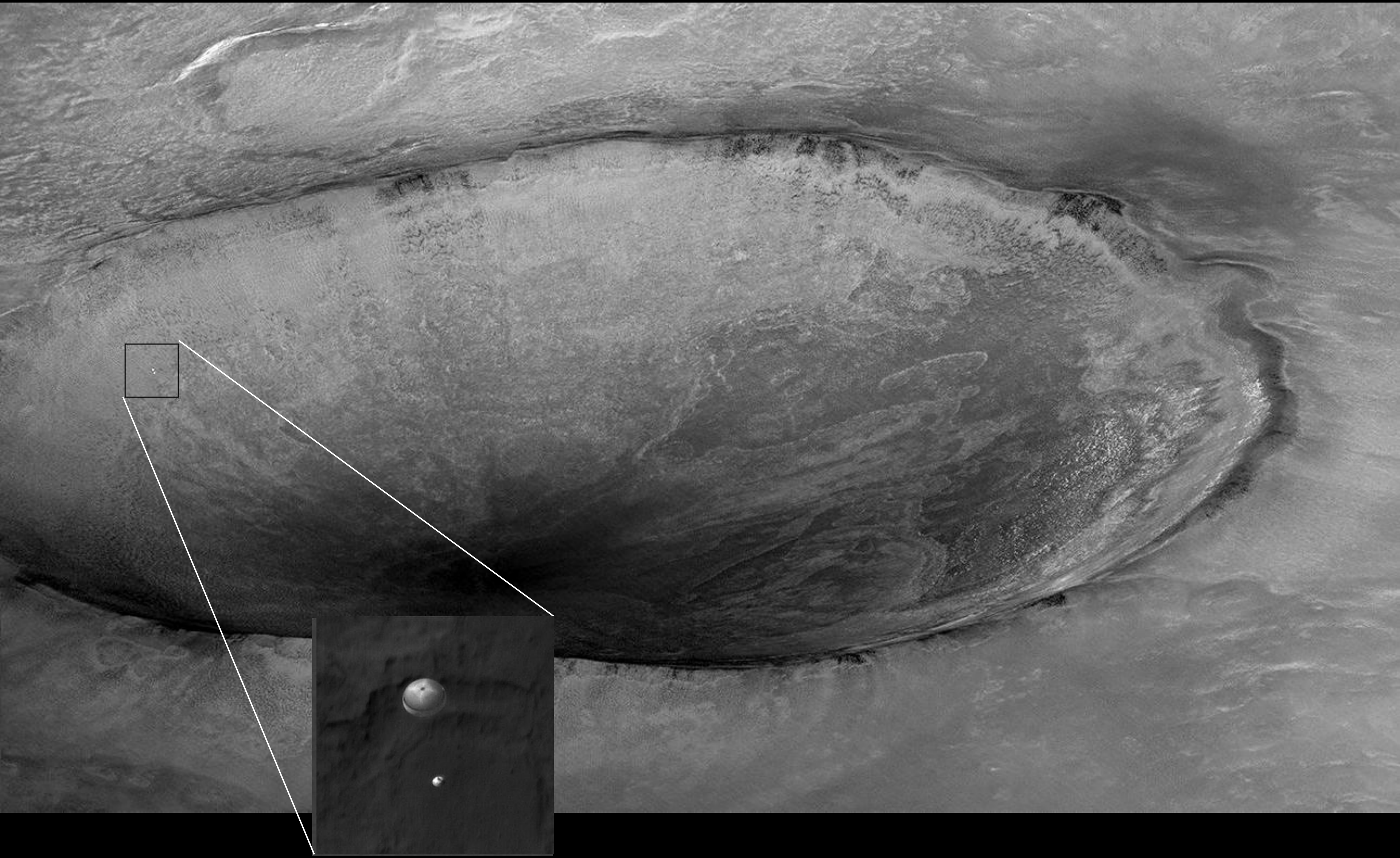
http://science.nasa.gov/science-news/science-at-nasa/2000/ast29jun_1m/

MRO at Mars - Dust Devils



MRO at Mars - Dry Ice and Dunes

MRO Captures Phoenix Parachute



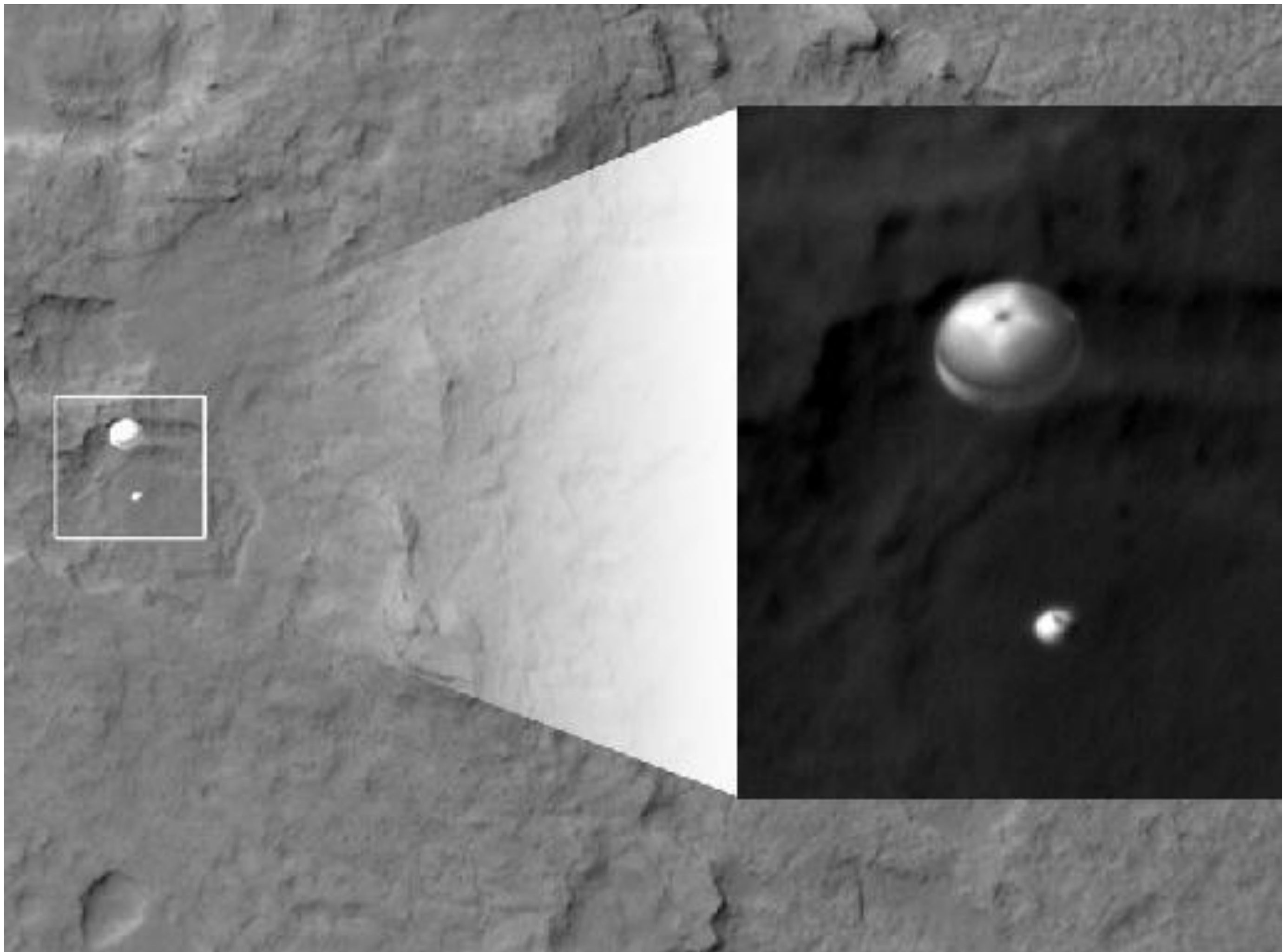
Phoenix – CO_2Ice

Mars Rover Family Family

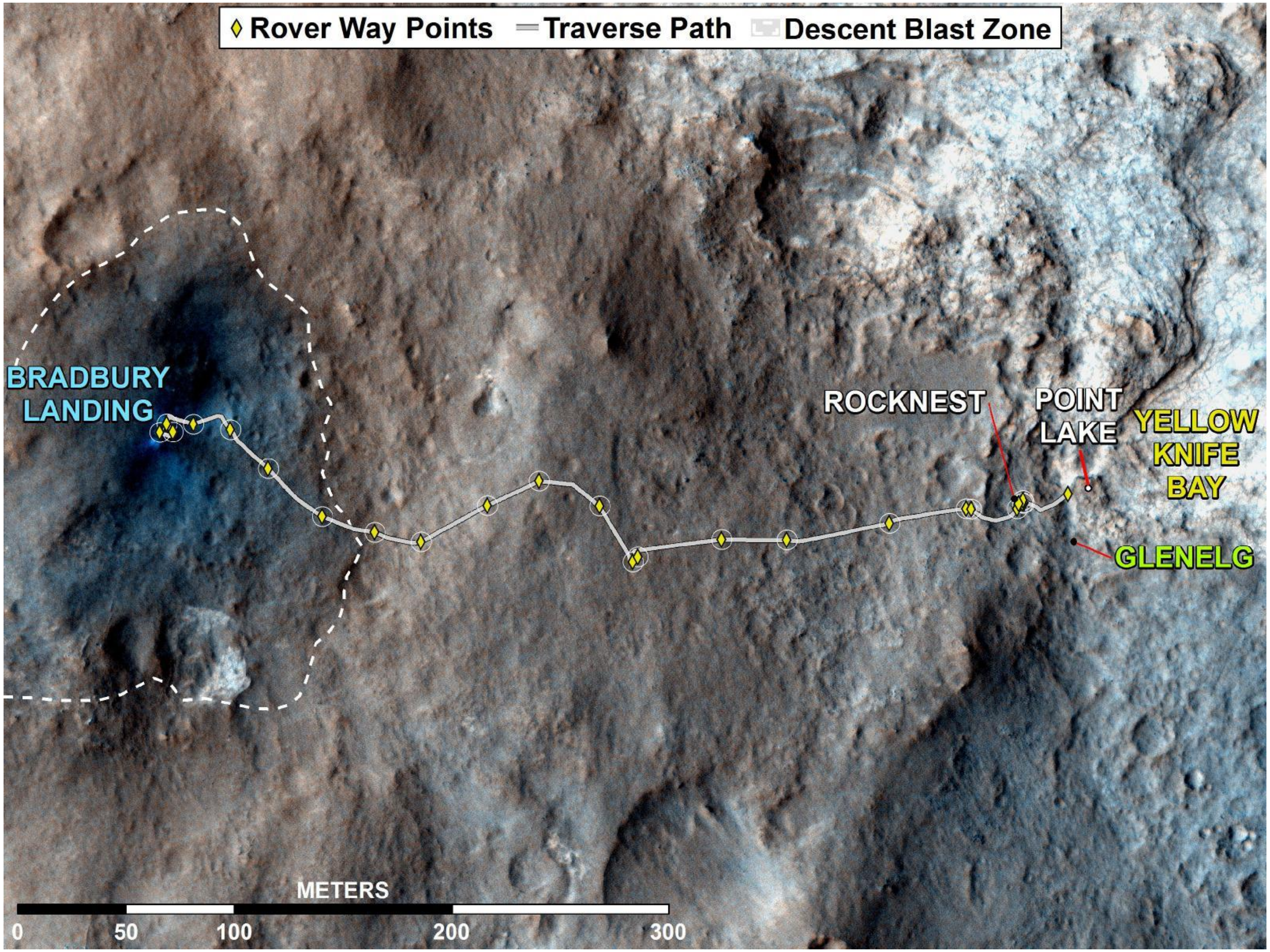
MSL (Curiosity) - Mobility Test

MSL Lander

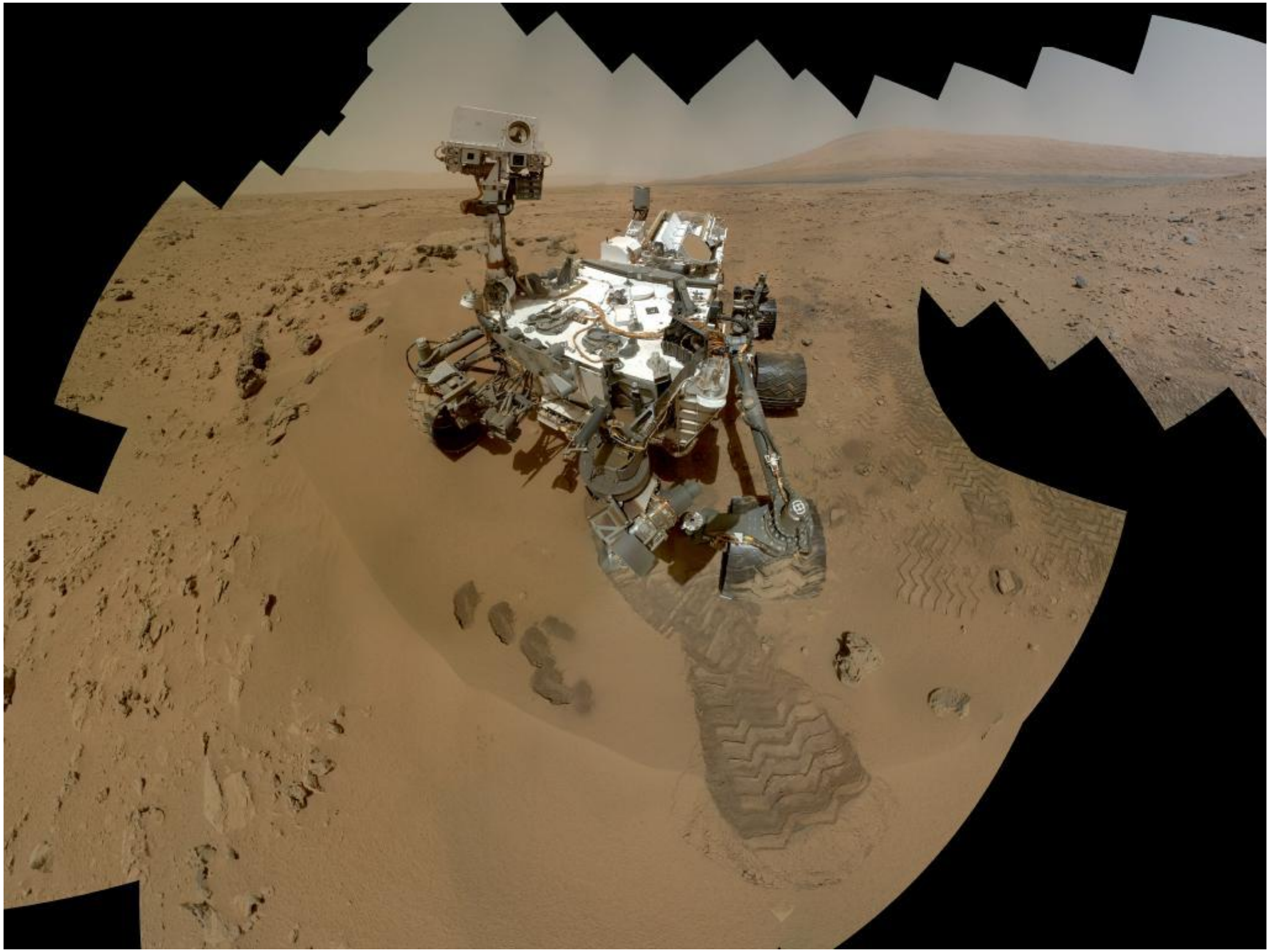
MRO Captures MSL Parachute



Curiosity Rover's Traverse

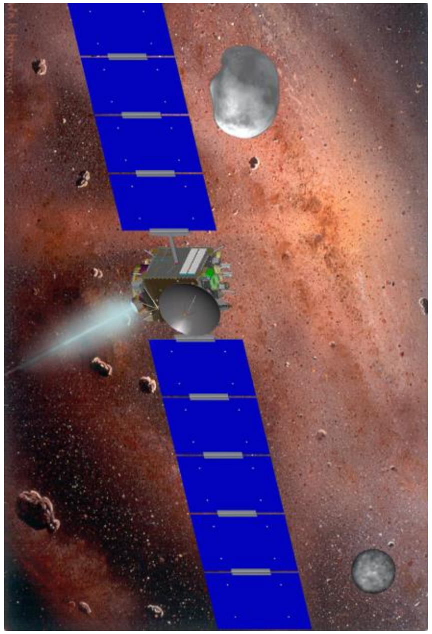


Curiosity Self Portrait

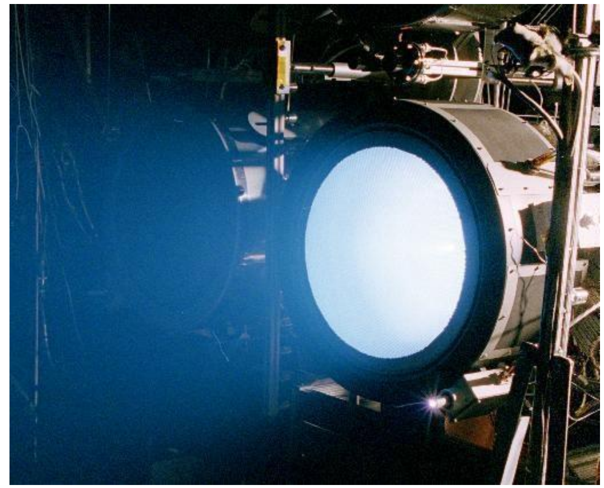


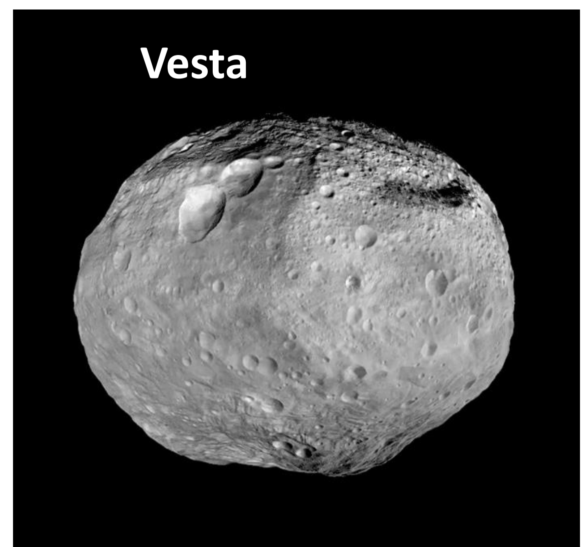
Future Mission? - Mars Airplane

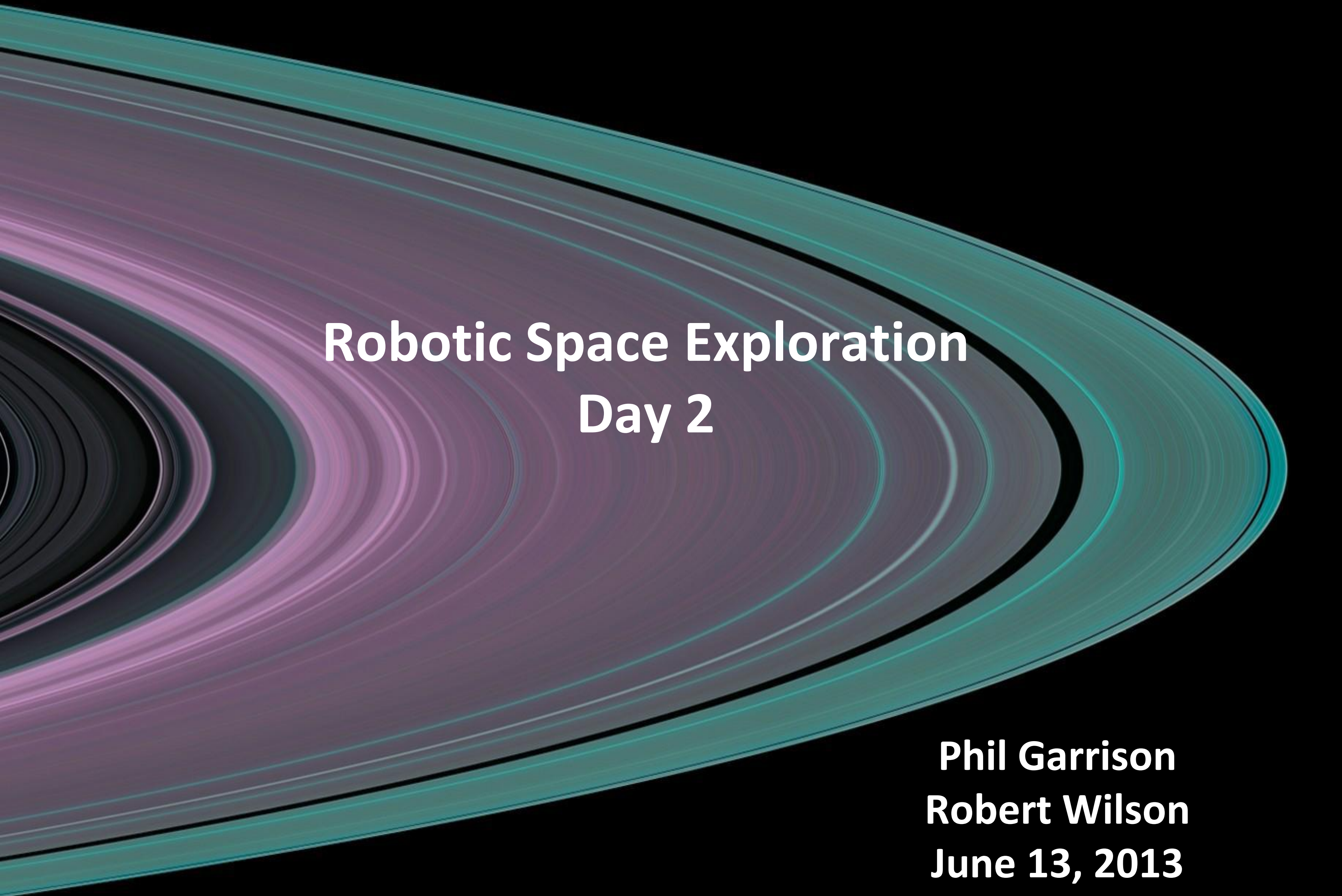
DAWN – Asteroid Mission



- Solar Electric Propulsion







Robotic Space Exploration
Day 2

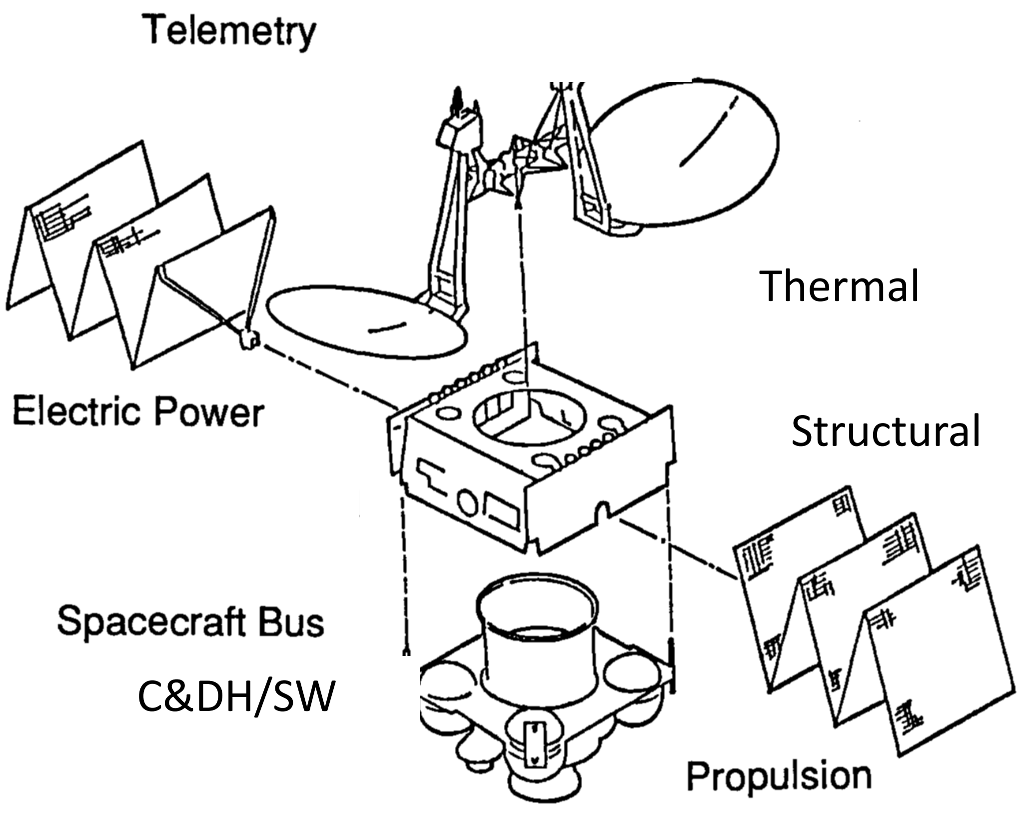
Phil Garrison
Robert Wilson
June 13, 2013

Course Outline

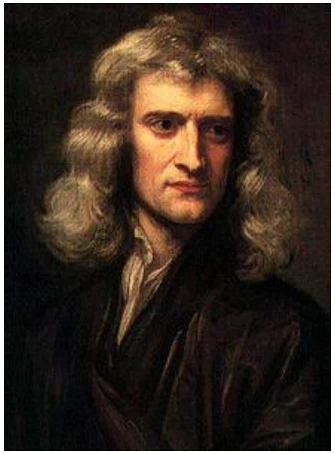
- Day 1
  - Program and Mission Development (1)
    - Program
    - Mission Design
    - System Design
  - Planetary and Earth Science Missions

- Day 2
  - Program and Mission Development (2)
    - Subsystem Development
    - Integration and Test
    - Mission Operations
  - Astrophysics and Heliophysics Missions

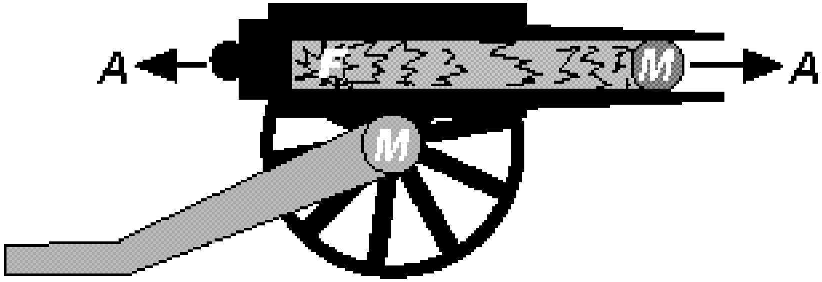
Typical Spacecraft Subsystems



Newton’s Laws of Motion

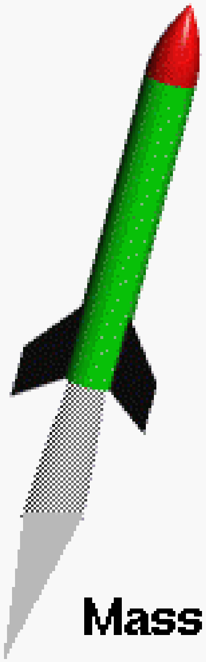


Sir Isaac Newton
1642-1726



1. A body will remain at rest or in motion in a straight line unless acted upon by a force.
2. Change in motion is proportional to the applied force and parallel to it.
3. To every action there is an equal and opposite reaction.

Ideal Rocket Equation



M = instantaneous mass of rocket

u = velocity of rocket

t = time

F = net force = thrust = $\dot{m}\ V_{eq}$

V_{eq} = equivalent engine exhaust velocity = Isp g_0

mf = full mass

me = empty mass

mp = mass of propellant

Isp = specific impulse

Newton's second law of motion: $\frac{d\ Mu}{dt} = F = V_{eq}\ \frac{d\ mp}{dt}$

$$M\ du + \cancel{u\ dM} = V_{eq}\ dmp$$

Assume we move with rocket --> u = 0

$$M\ du = -\ V_{eq}\ dM$$

Mass of rocket varies with time:

$M(t) = me + mp\ (t) \qquad dM = -\ d\ mp$

MR = propellant mass ratio = $\frac{mf}{me}$

$$du = -V_{eq}\ \frac{dM}{M}$$

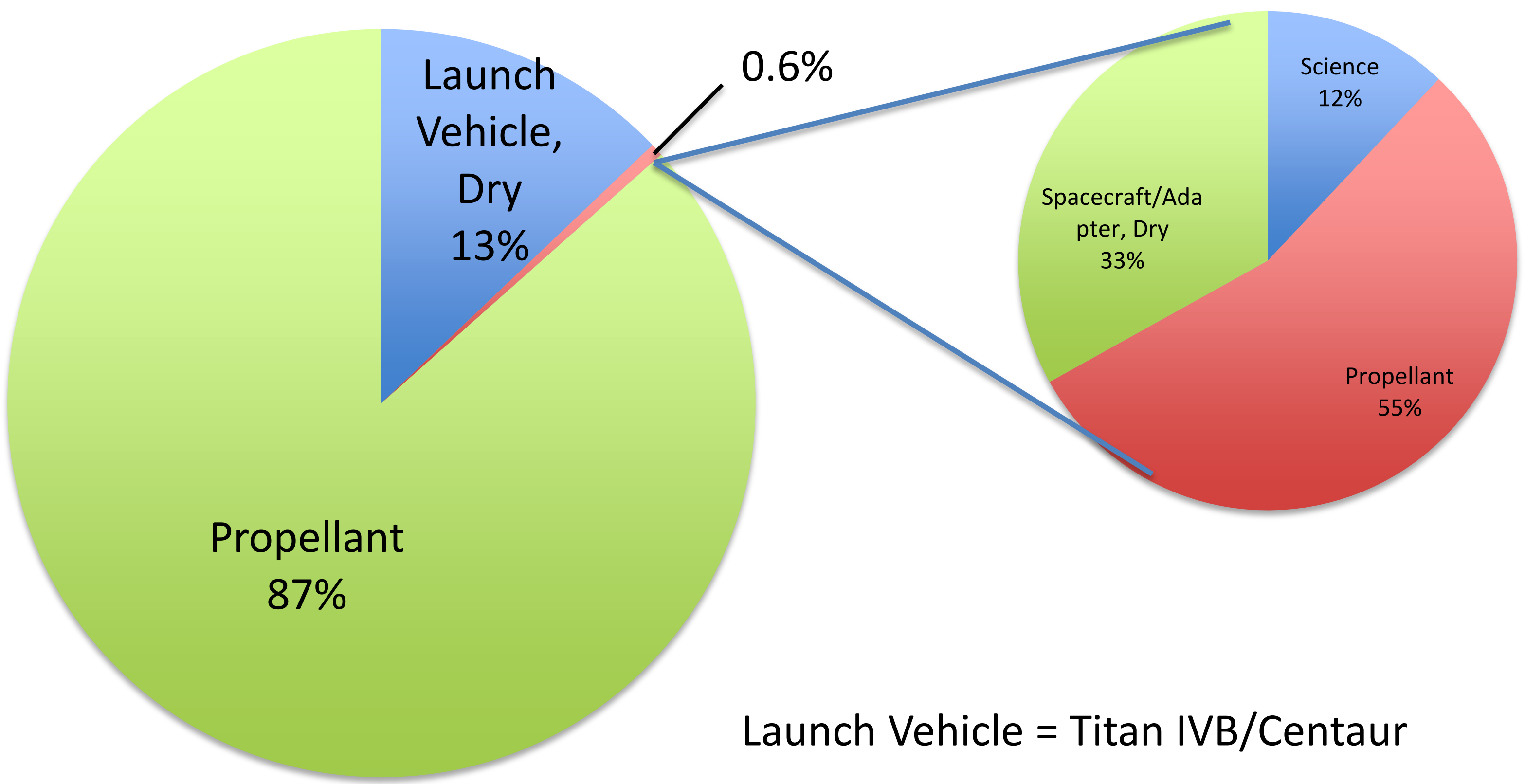
$$\Delta u = -V_{eq}\ \ln\ (M)\Big|_{mf}^{me}$$

$$\Delta u = V_{eq}\ \ln\left(\frac{mf}{me}\right) = V_{eq} \ln MR = Isp\ g_o \ln MR$$

Cassini Mission Mass Distribution

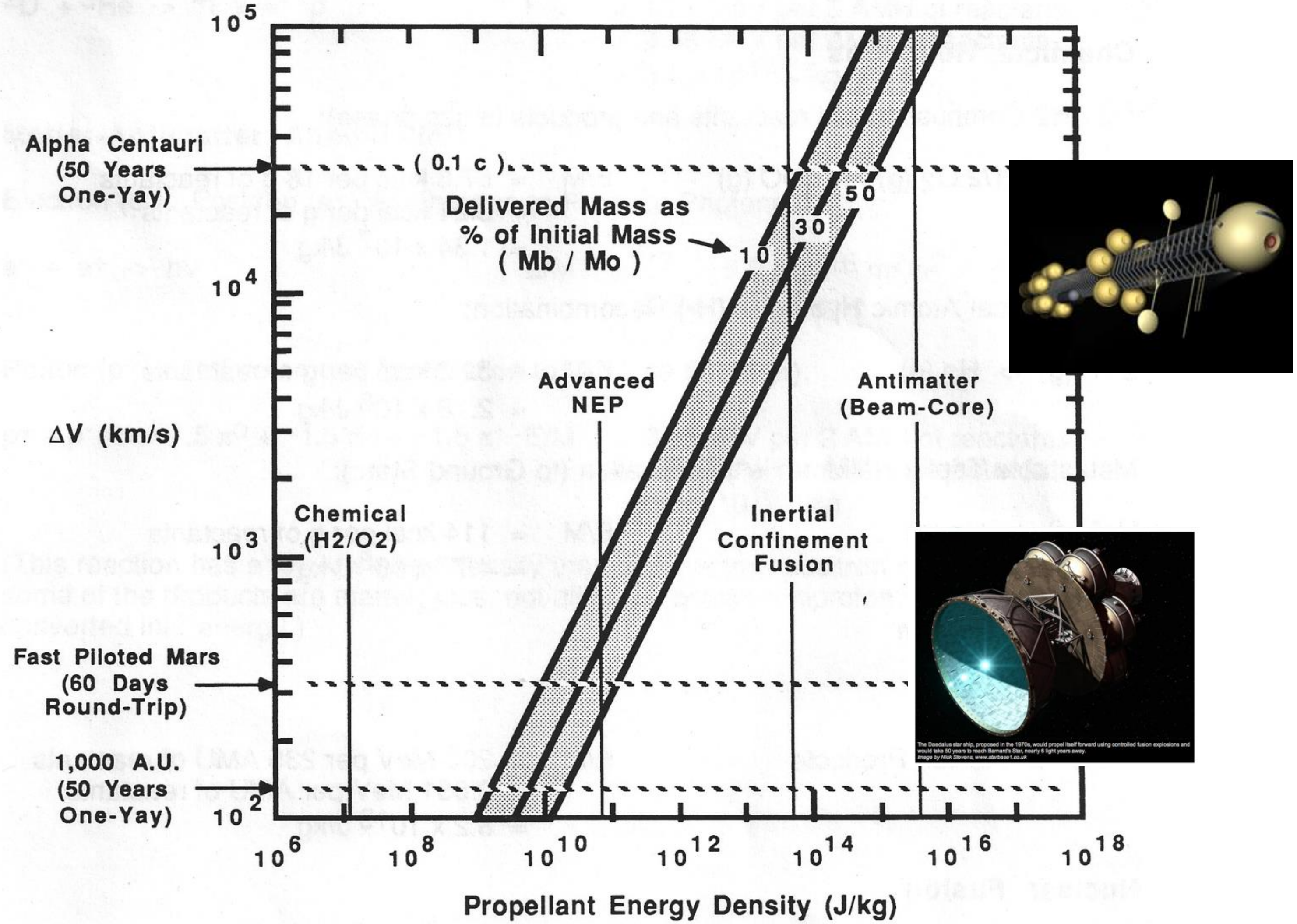
Launch Mass = 1,040,000 kg

Spacecraft Mass = 5720 kg



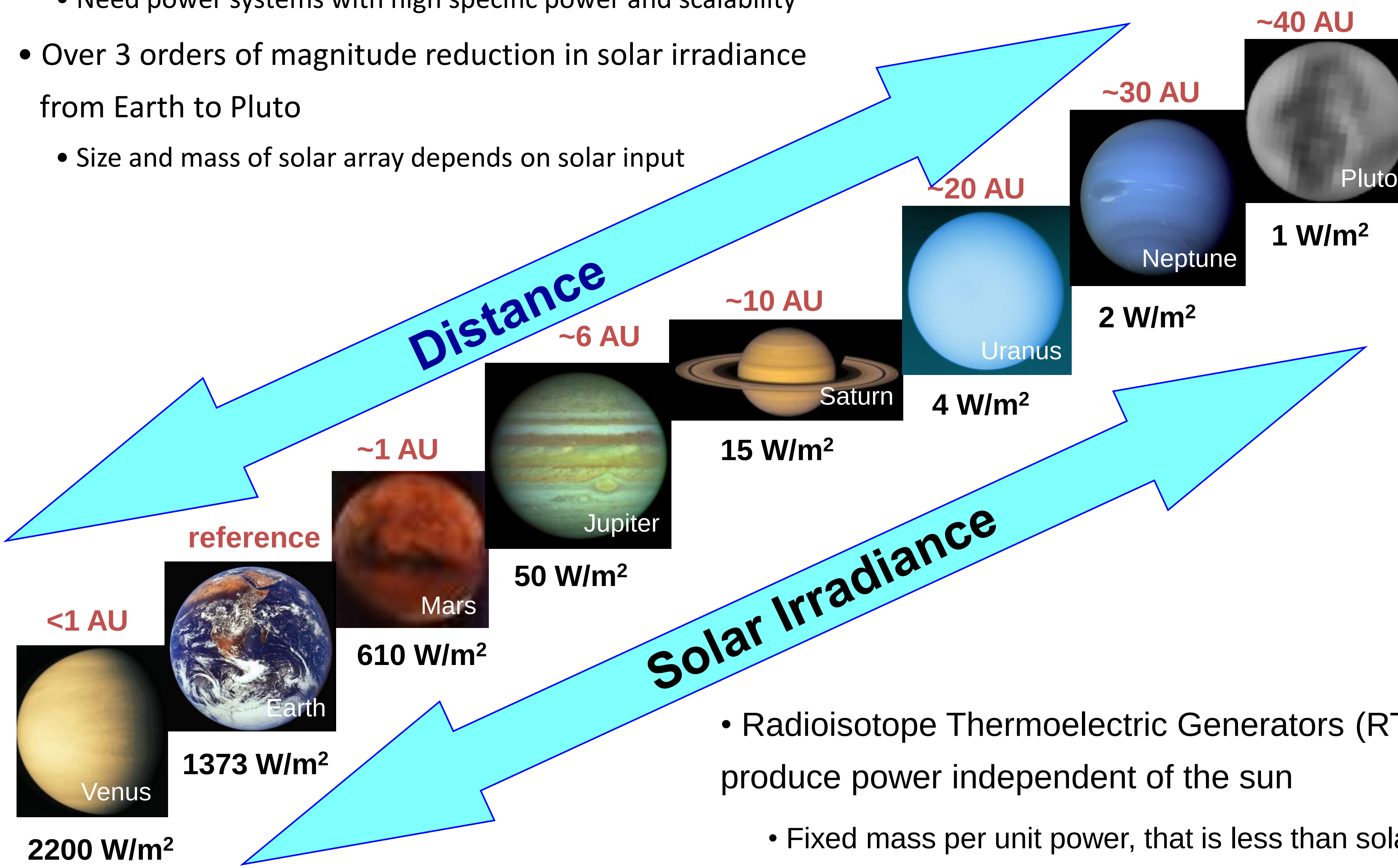
Launch Vehicle = Titan IVB/Centaur

Very High Energy Propulsion Required for Future Missions



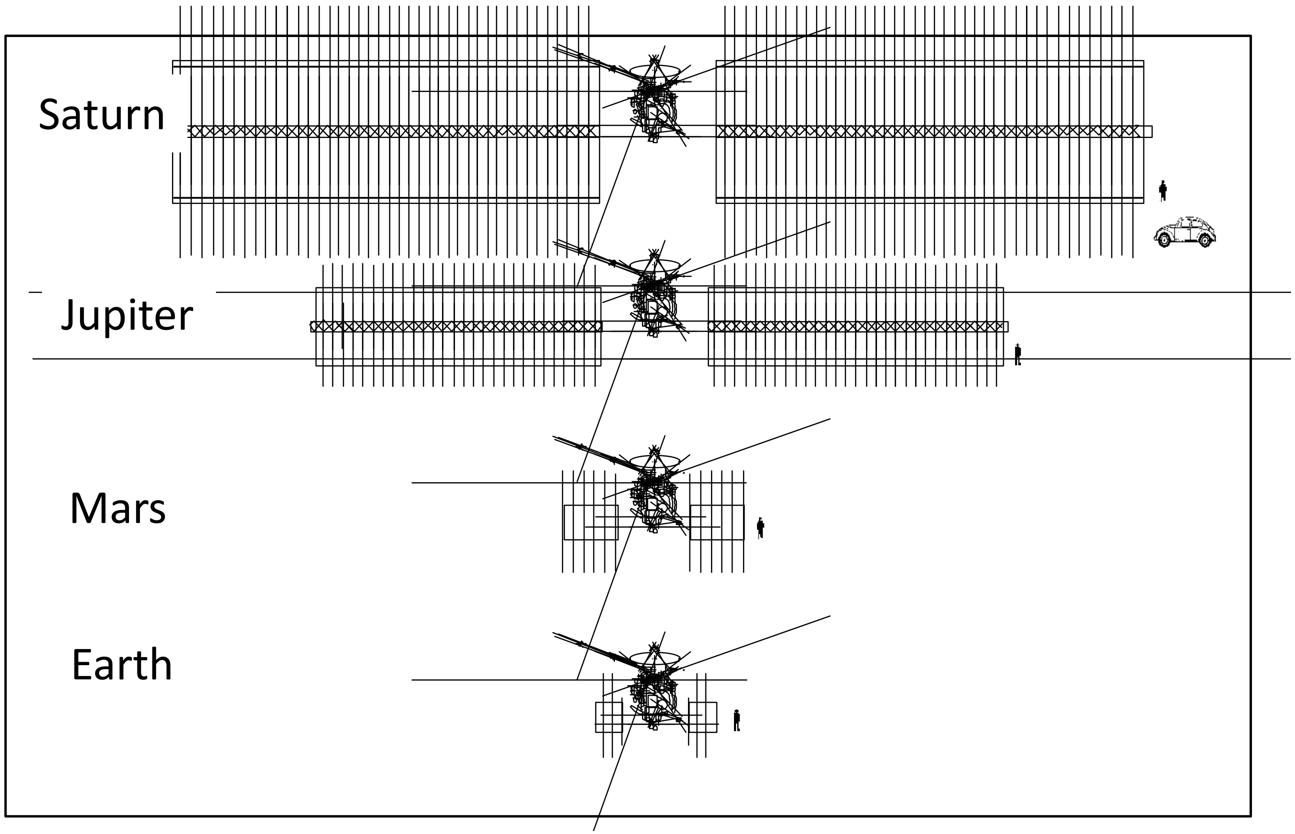
Electric Power for Solar System Missions

- Mass is at an absolute premium
  - Need power systems with high specific power and scalability
- Over 3 orders of magnitude reduction in solar irradiance from Earth to Pluto
  - Size and mass of solar array depends on solar input



- Radioisotope Thermoelectric Generators (RTG) produce power independent of the sun
  - Fixed mass per unit power, that is less than solar arrays at about 5 AU and beyond.

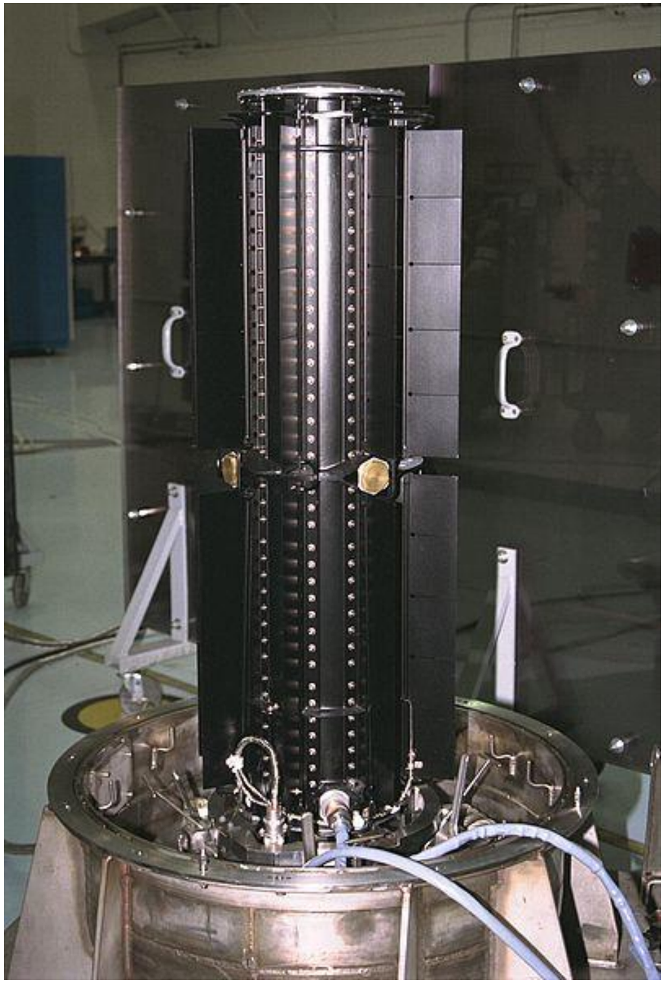
Solar Array Size Prohibitive for Deep Space Missions



- Cassini Power Requirement = 700 W
- GaAs Photovoltaic Cells

Other Problems:
- LILT

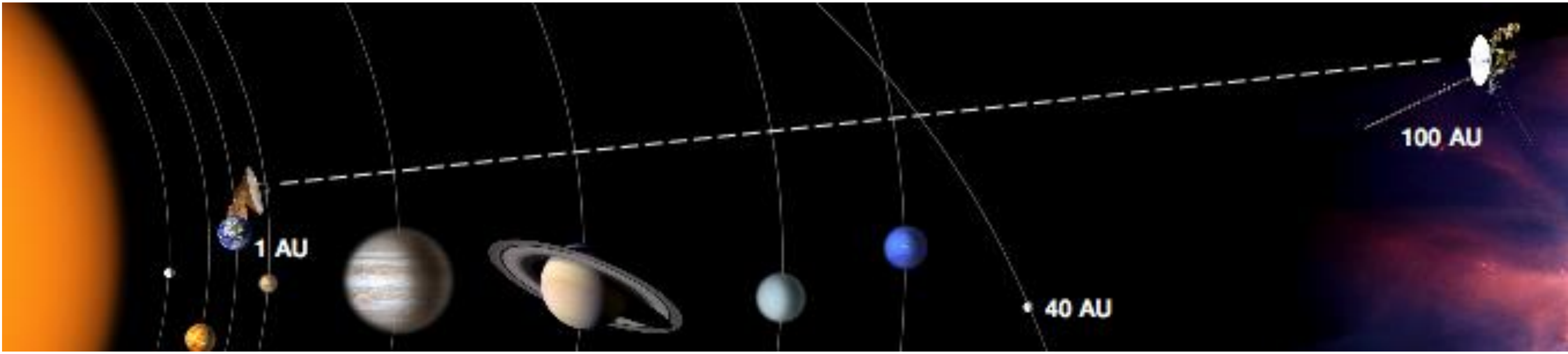
Cassini Radioisotope Thermoelectric Generator (RTG)



- 3 RTGs
- 33 kg of plutonium-238 (plutonium dioxide)
- Thermoelectric Power Conversion (6-7% Efficiency)
- 600-700 Watts of Electrical Power at End of Life

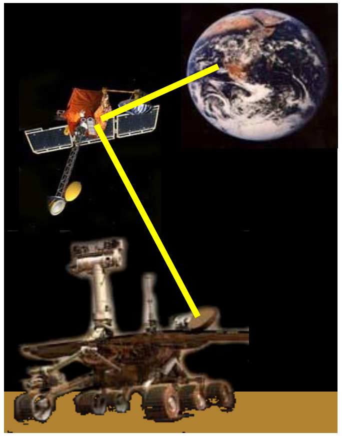
Deep Space Communications

Power received by 70m DSN antenna from Voyager is so small that if it were to be accumulated for 10 trillion years it could power a refrigerator light bulb for one second!



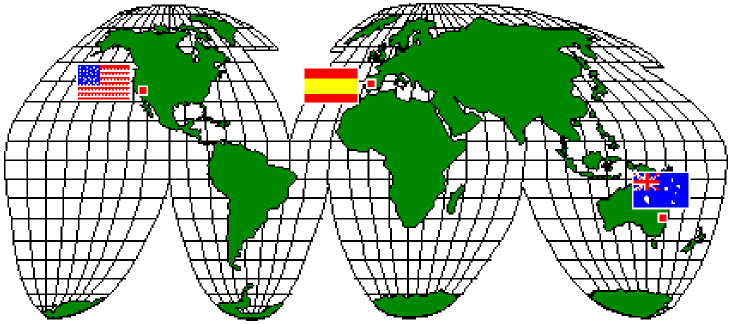
Orbiting Mars relays enabled a 5X increase in science

– Nearly all data from Mars' surface comes via relays today



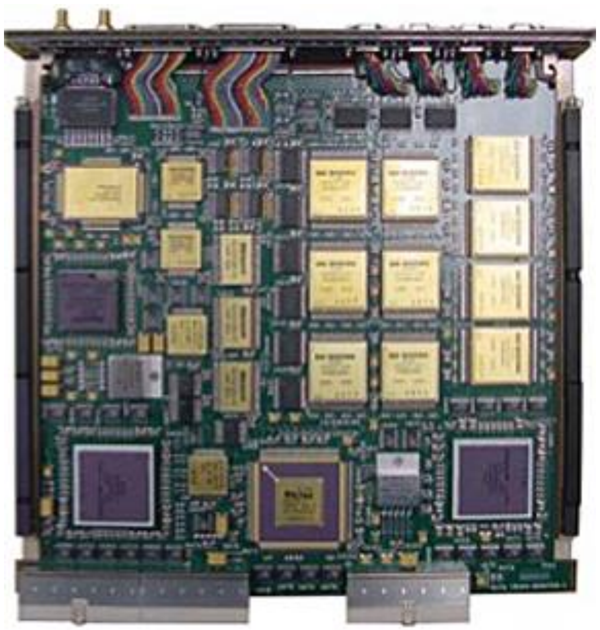
Deep Space Network

- 3 stations distributed equidistance around the Earth
  - Goldstone, USA
  - Madrid, Spain
  - Canberra, Australia
- 70 m, 34 m, and 26 m antennas



DSN Antennas in Madrid, Spain

Spacecraft Computers Slow but Rugged



- Curiosity uses PowerPC RAD750 Microprocessors
  - Redundant, 200 MHz, 2GB Flash, 256 MB RAM, 256 MB EEPROM << Smart Phone
  - Highly Resistant to Radiation Damage (Ions and Protons)
    - One Upset in 15 Years
  - Wide Operating Temperature Range (-55 C to +125 C)
  - Built by BAE Systems

Software is Critical to Robotic Spacecraft Missions

- Long missions require on-board spacecraft capability to reload/update flight software in flight
- Long one way light times and intermittent communications require reliable software that is able to safe the spacecraft and phone home when there are failures
- Mission critical events require autonomy to carry out the activity successfully without ground-in-the-loop
- Mission cost constraints requires autonomy to reduce size of operations teams

Curiosity Autonomy

– Limited traverse distances without "ground-in-the-loop"

– 3-sol cycle to approach a rock or soil target

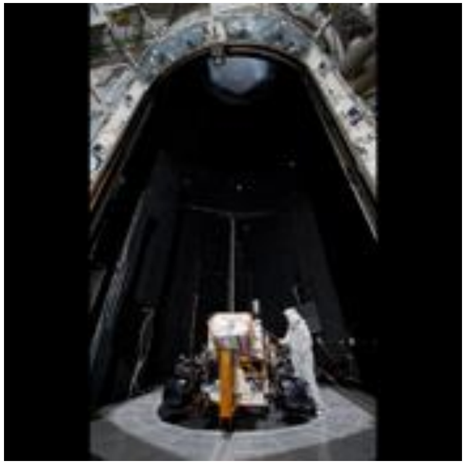
– Traverse 40-50 m/sol

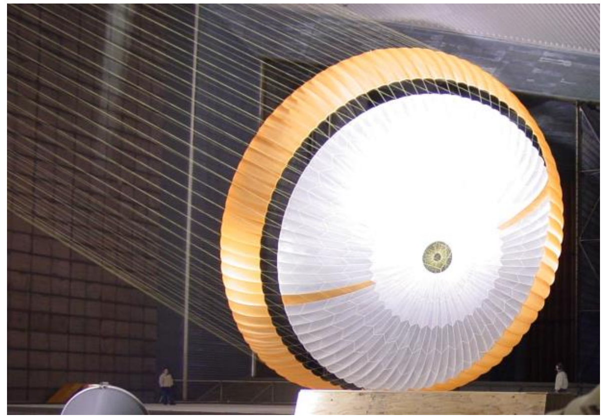
– Traverse autonomy-ability to safely drive outside of Navcam images

– Location science autonomy

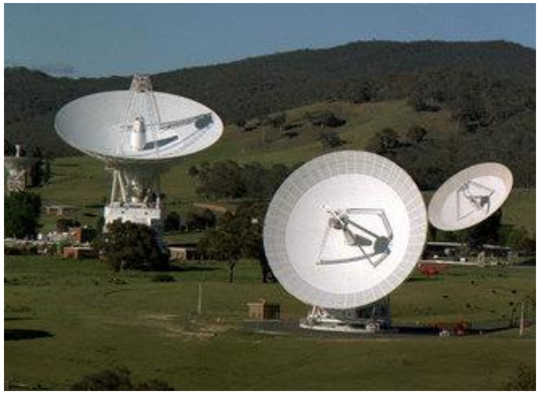
  Allows approach of rock or soil to occur from 10m distance to within 1 cm of target in about 1 hour (no "ground-in-the-loop")

Integration, Assembly and Test





Mission Control

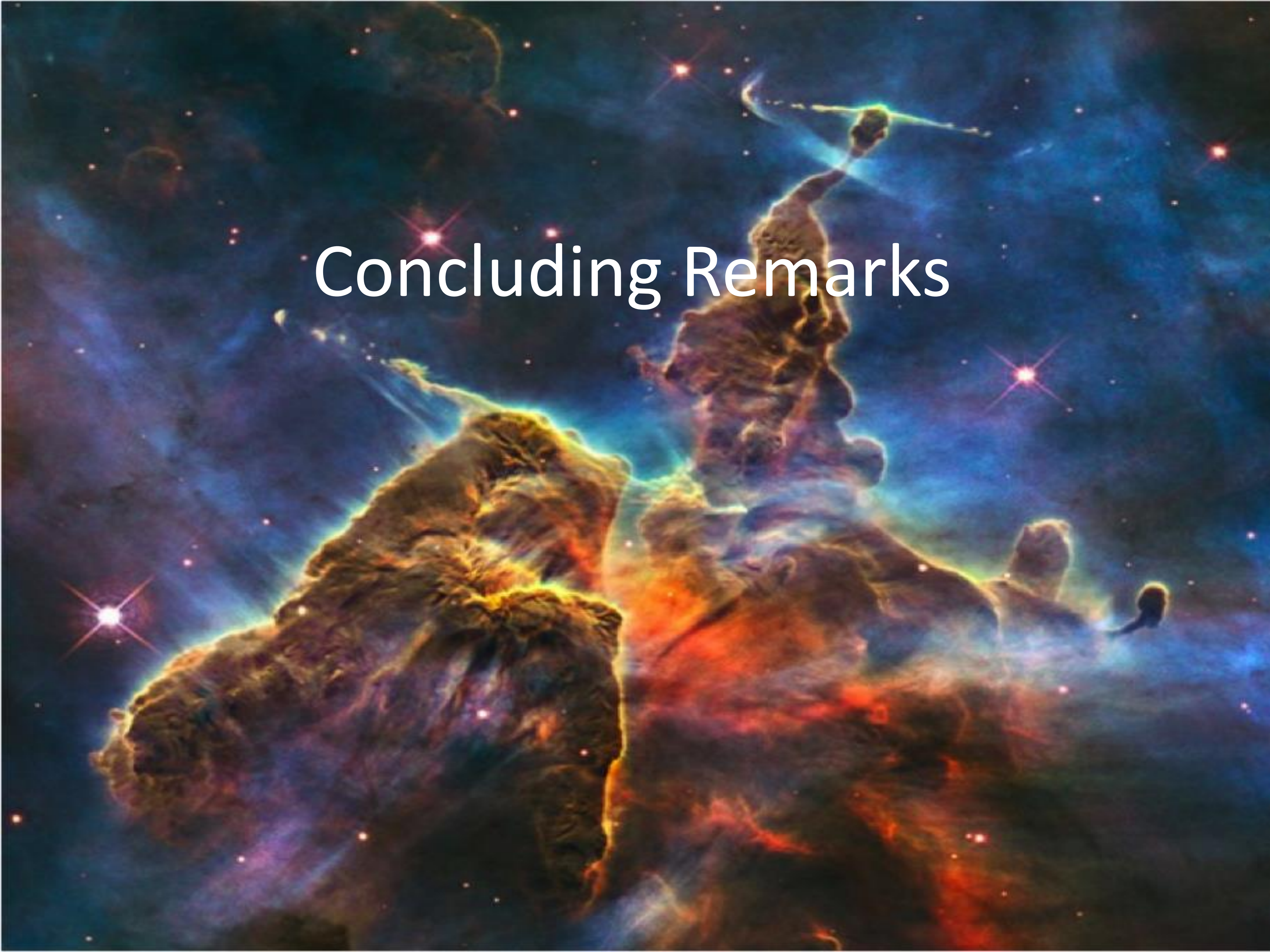


Break

Next up:

- Heliophysics Missions
- Astrophysics Missions

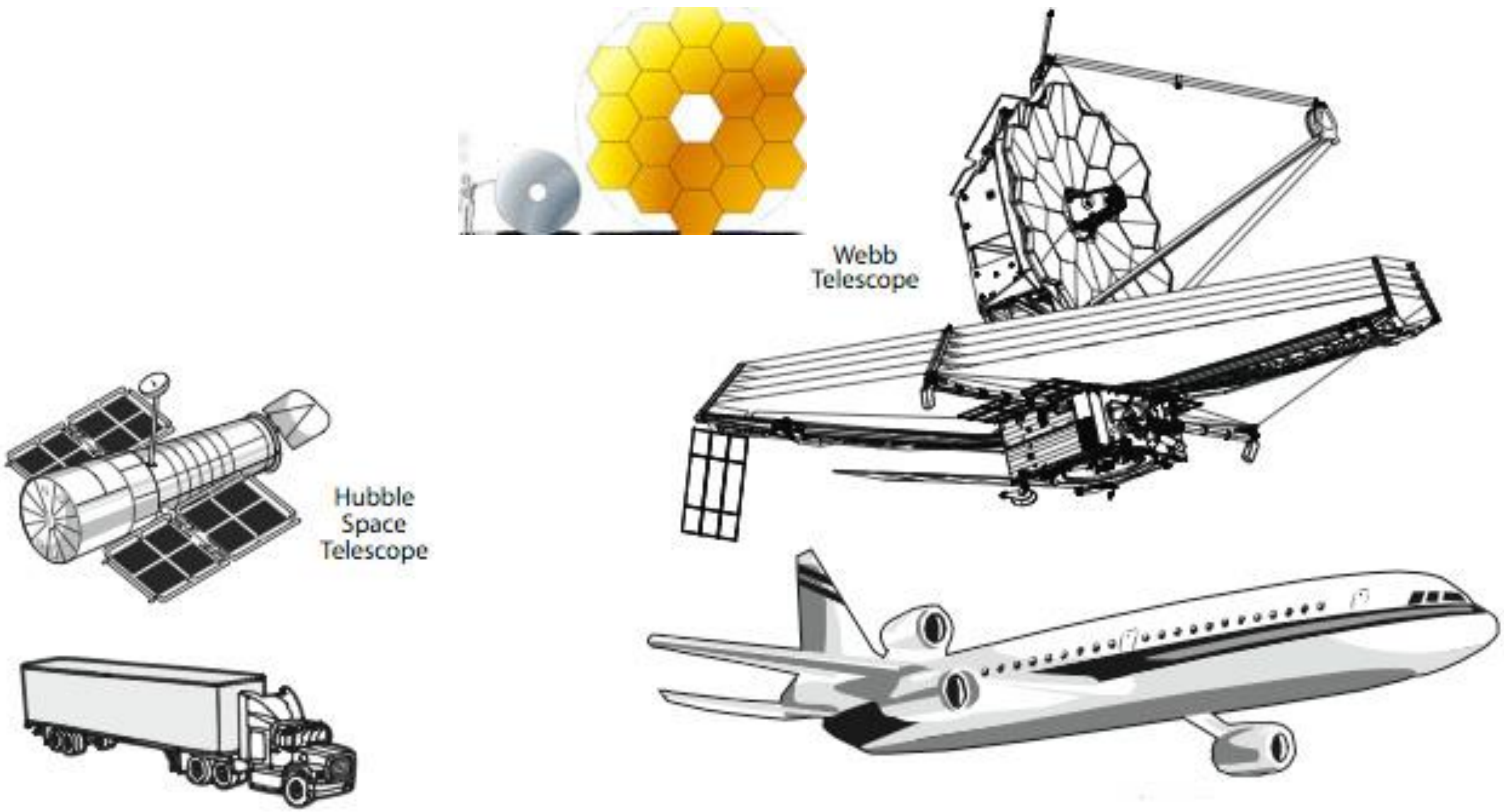
Concluding Remarks



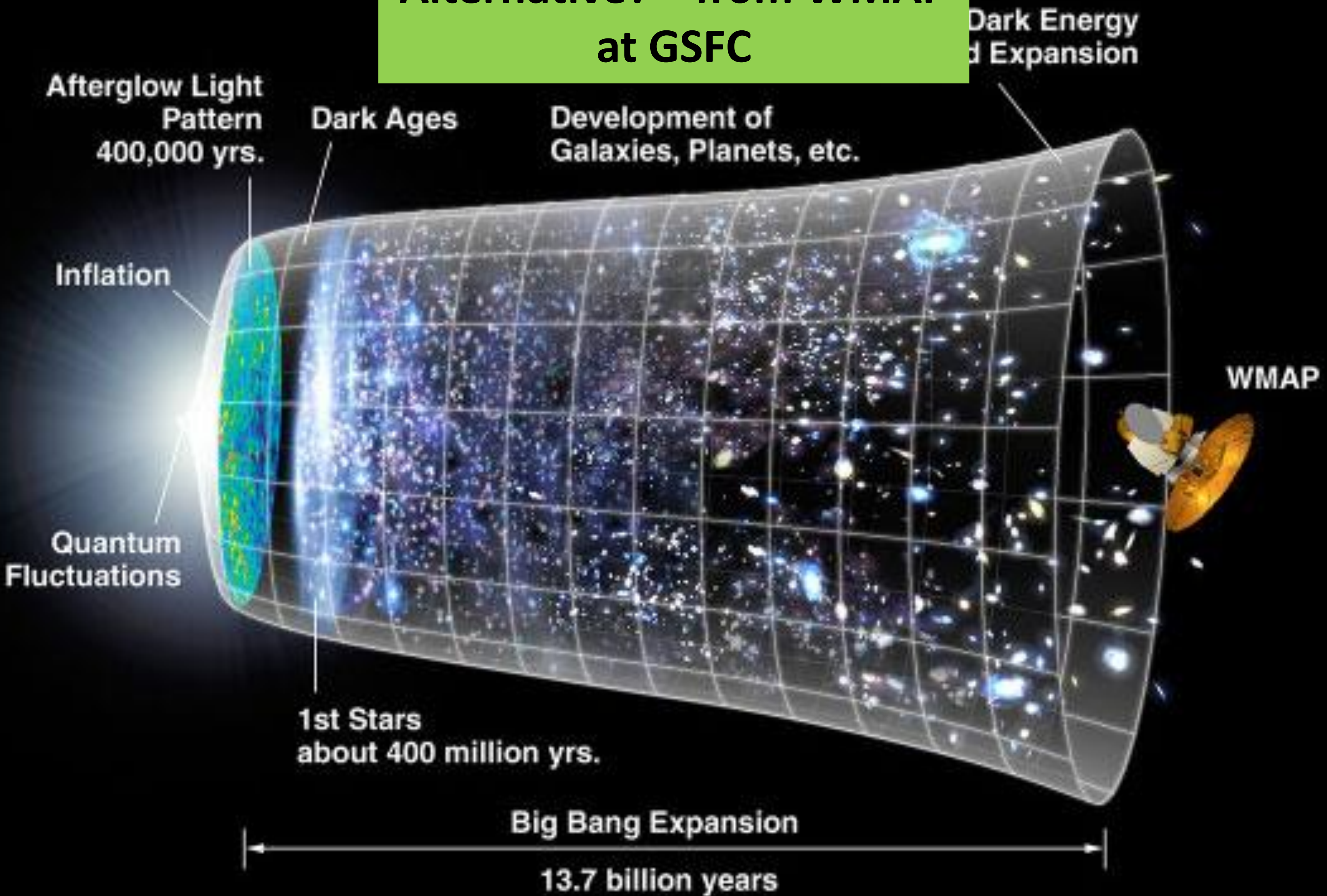
Back Up Slides

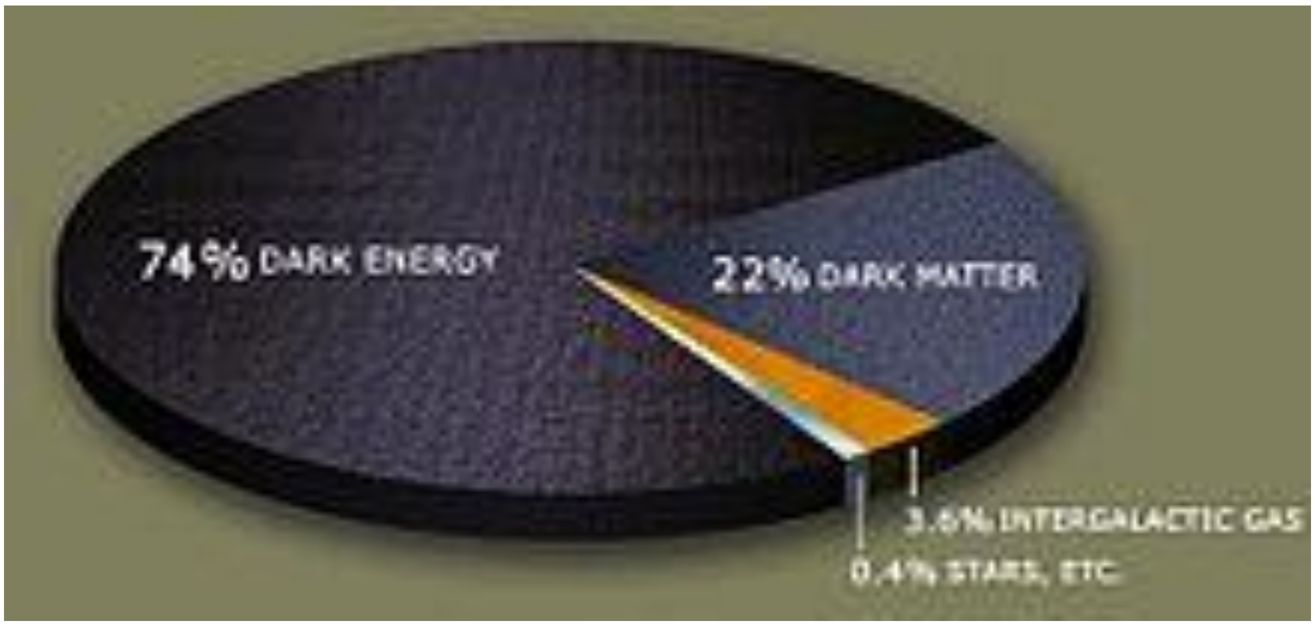
HUBBLE vs JWST

(http://www.jwst.nasa.gov/comparison.html)

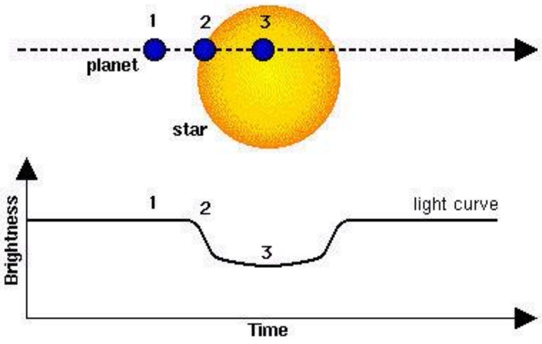


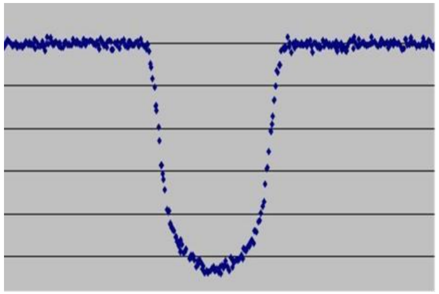
Alternative?—from WMAP at GSFC

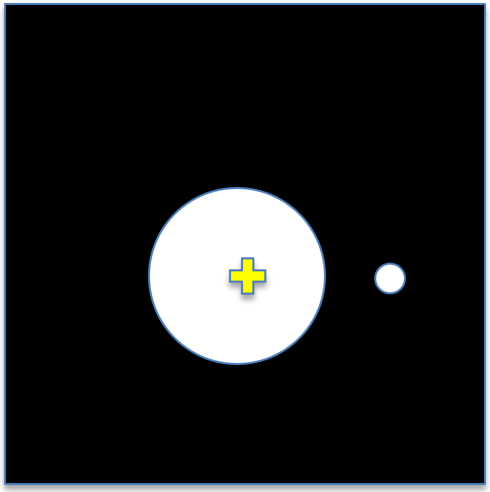


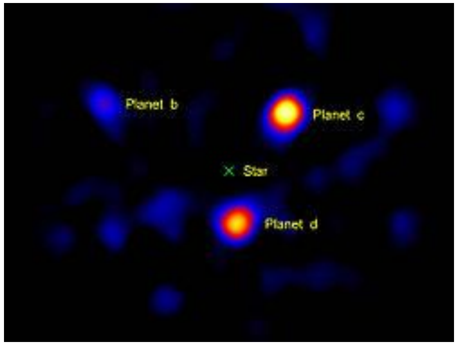

74% DARK ENERGY
22% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC

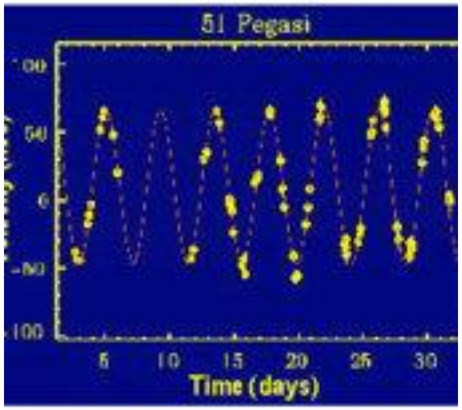
Extra Solar Planetary Detection





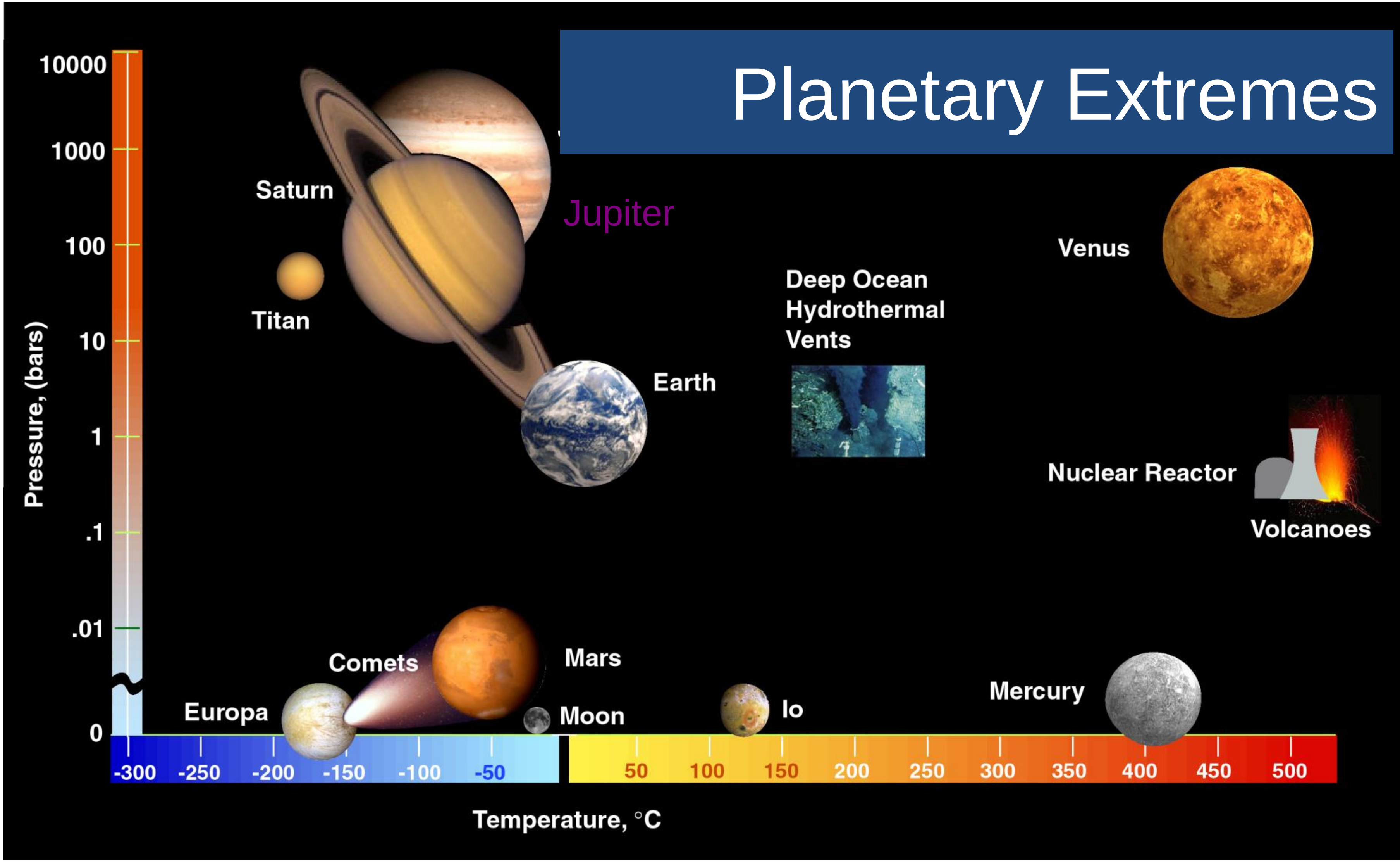






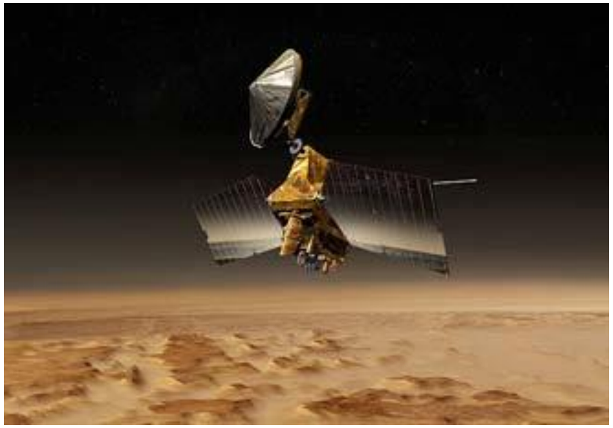
Radial Velocity

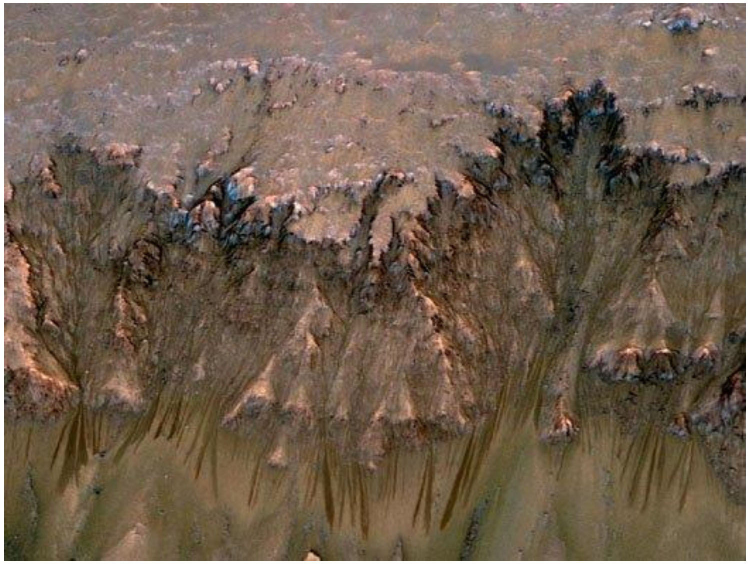
Unique Environmental Challenges

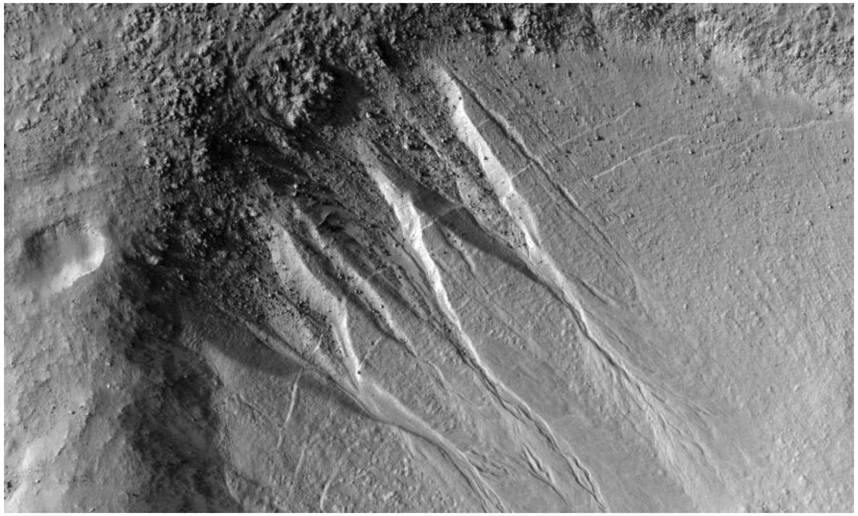


Challenged by extremes of temperature, pressure, radiation, and distance

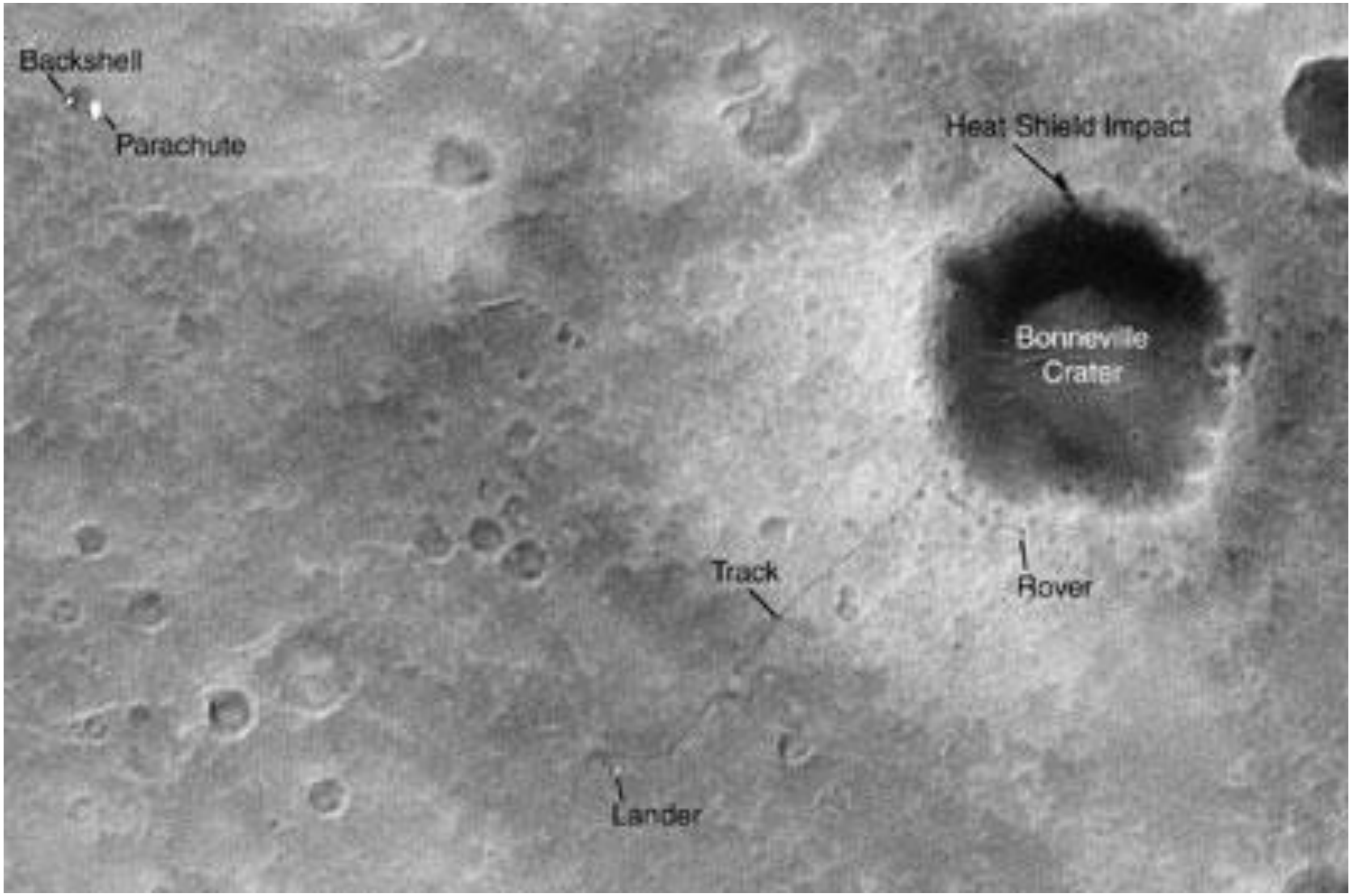
MRO at Mars

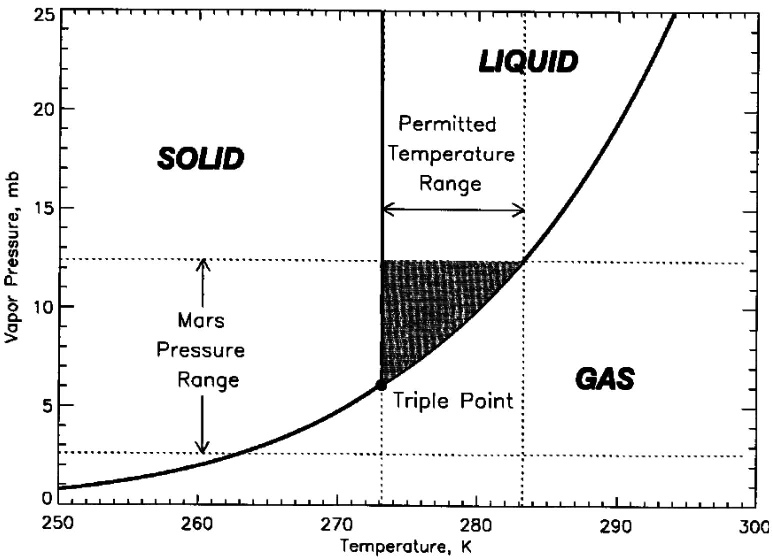






Spirit (MER) Hardware on Mars





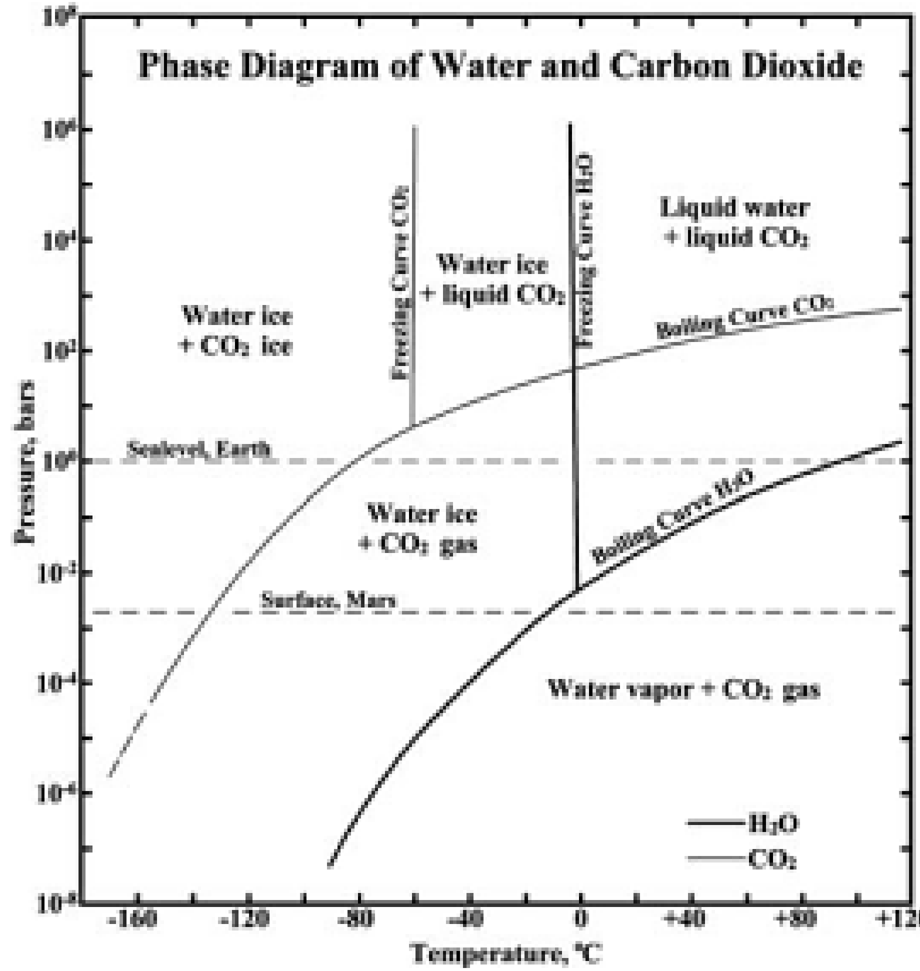
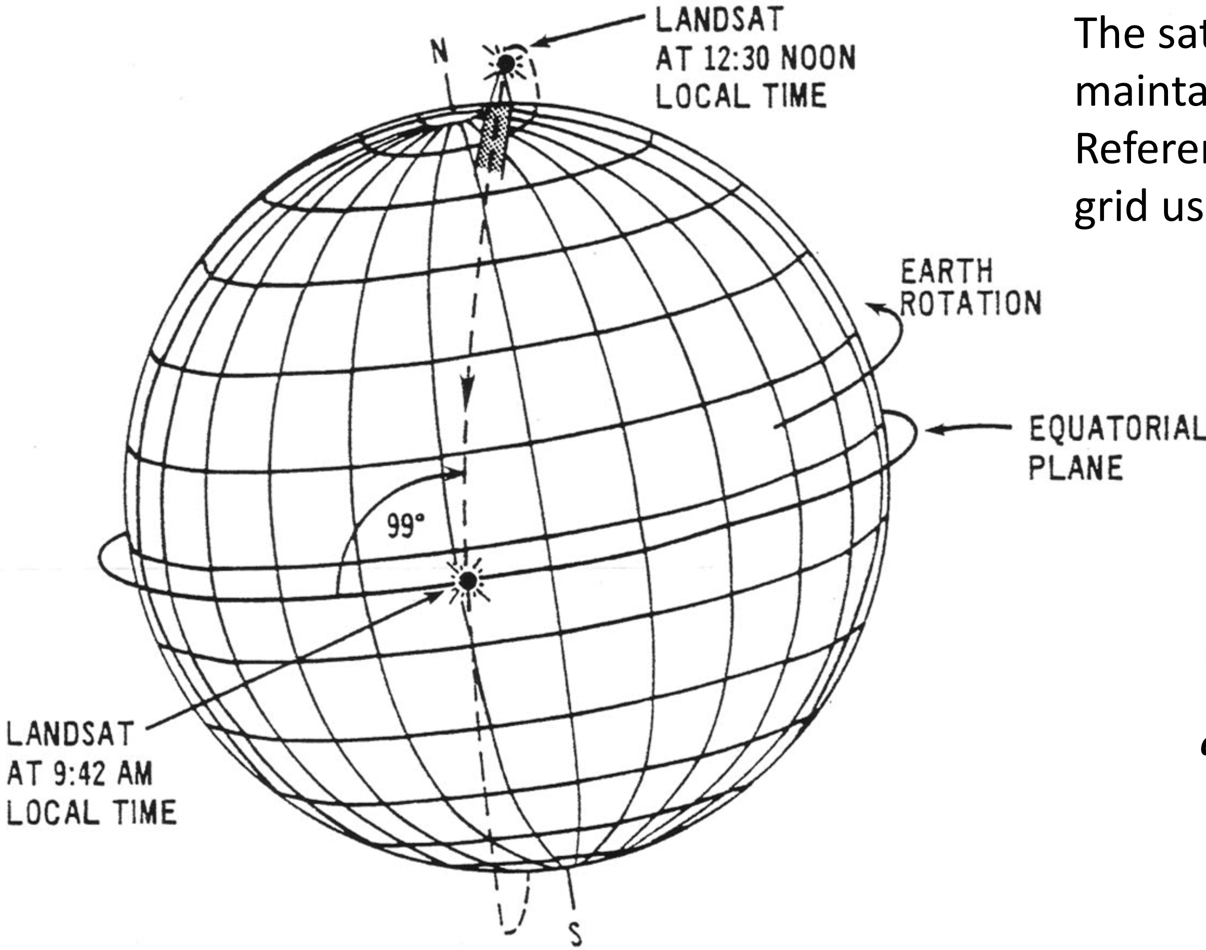


Figure 12.17. The stability fields of solid, liquid, and gas phases of water and carbon dioxide are defined by their boiling-temperature and the freezing-temperature curves. By superimposing the phase diagrams of these two compounds the stability fields can be labeled in terms of the phases of both compounds that can coexist together. The triple point of water (T = +0.010 °C; P = 0.0060 atm) permits liquid water to exist on the Earth but not on Mars.



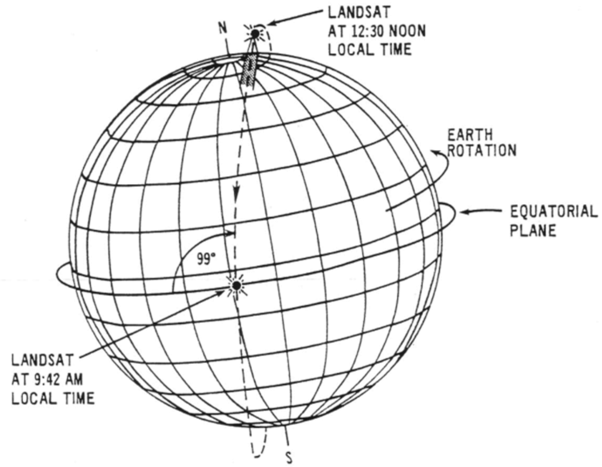
The satellites in the A-Train are maintained in orbit to match the World Reference System 2 (WRS-2) reference grid used by Landsat.

CloudSat and CALIPSO travel within 15 seconds of each other so that both instrument suites view the same cloud area at nearly the same moment. This is crucial for studying clouds which have lifetimes often less than 15 minutes.

The constellation has a nominal orbit altitude of 705 km and inclination of 98^{o}.

Aqua leads the A-train with an equatorial crossing time of about 1:30 pm.

CloudSat and CALIPSO lag Aqua by 1 to 2 minutes separated from each other by 10 to 15 seconds.

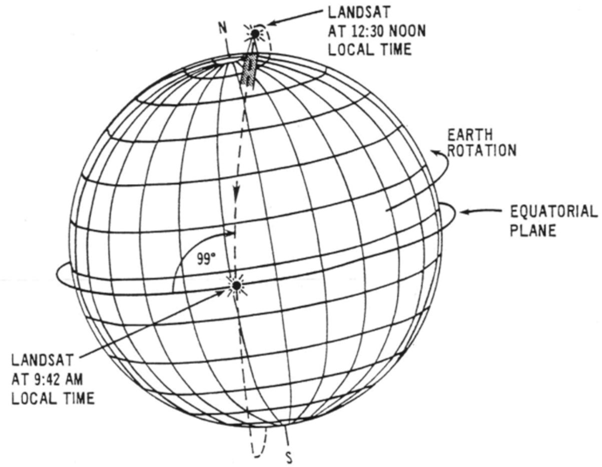


The World Reference System 2 (WRS-2) was developed to facilitate regular sampling patterns by remote sensors in the Landsat program.

Landsat-7 and Terra are "morning" satellites in the same orbit as the A-train.

Each satellite completes 14.55 orbits per day with a separation of 24.7 degrees longitude between each successive orbit at the equator.

The orbit tracks at the equator progress westward 10.8 degrees on succeeding days, which over a 16-day period produces a uniform WRS grid over the globe. The WRS grid pattern of 233 orbits with separation between orbits at the equator of 172 km.



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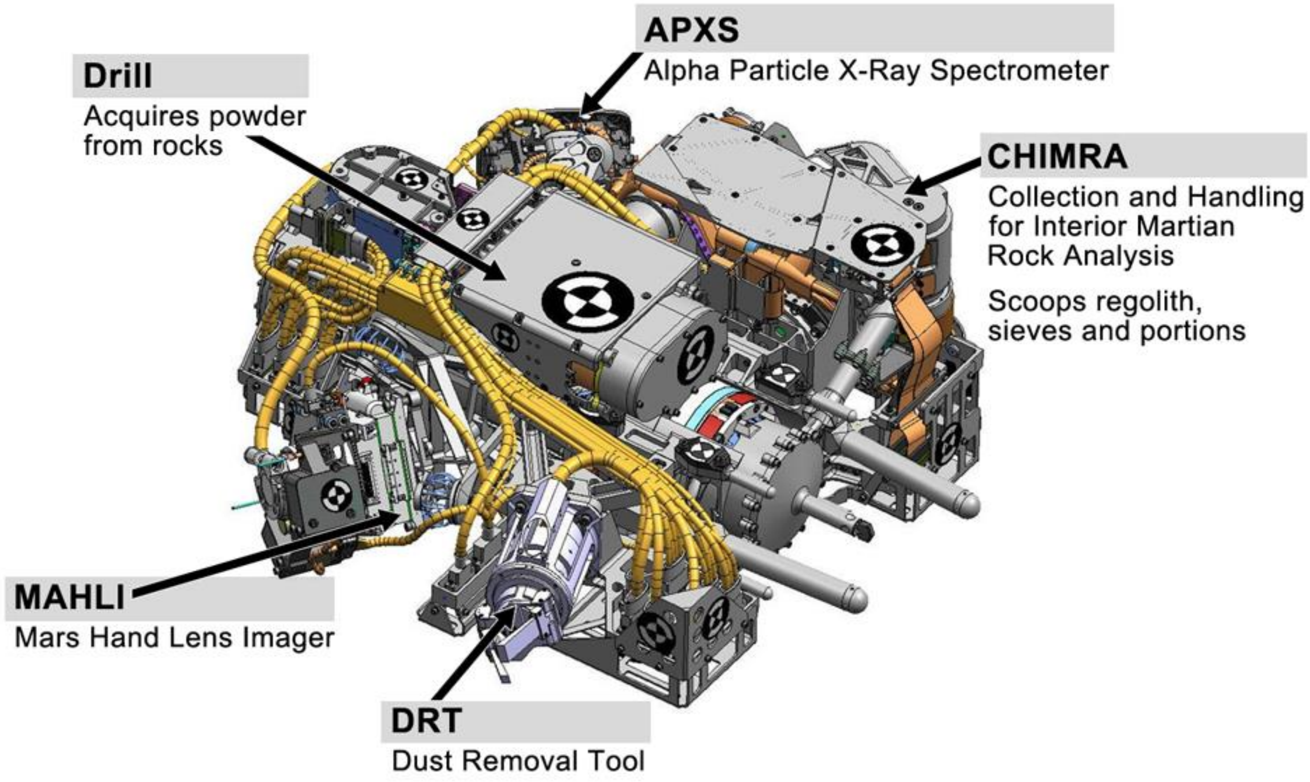
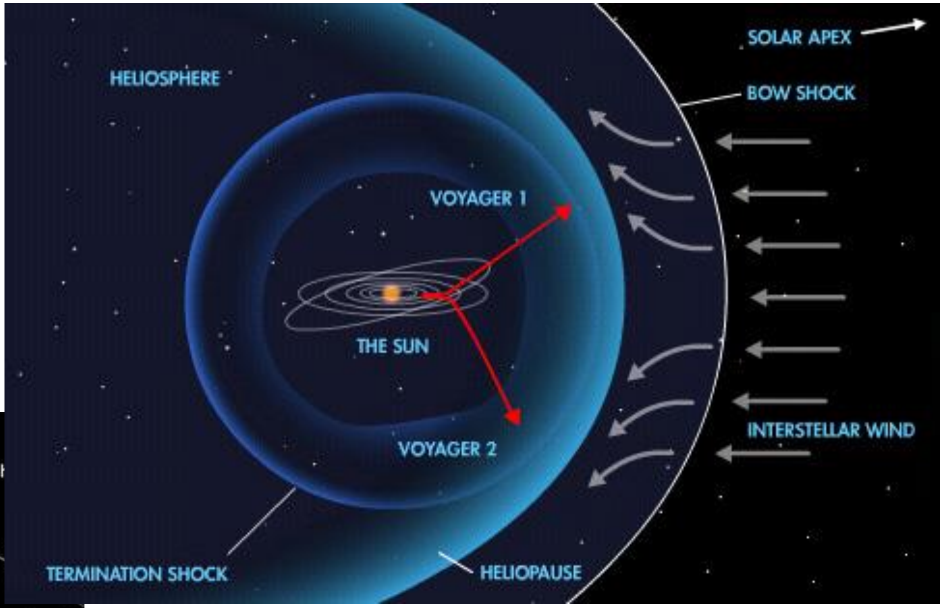
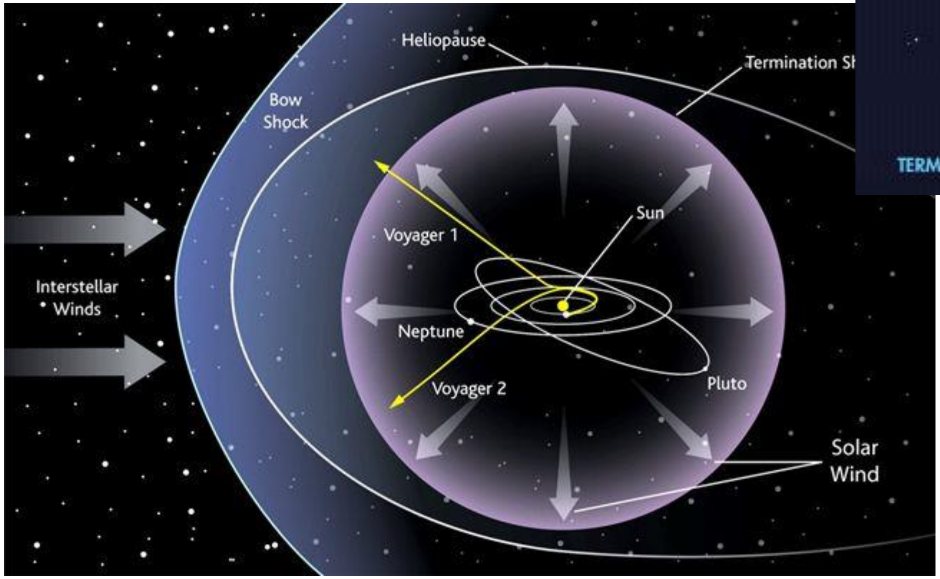
The Aqua satellite will be controlled to the WRS grid to within +/- 10 km.

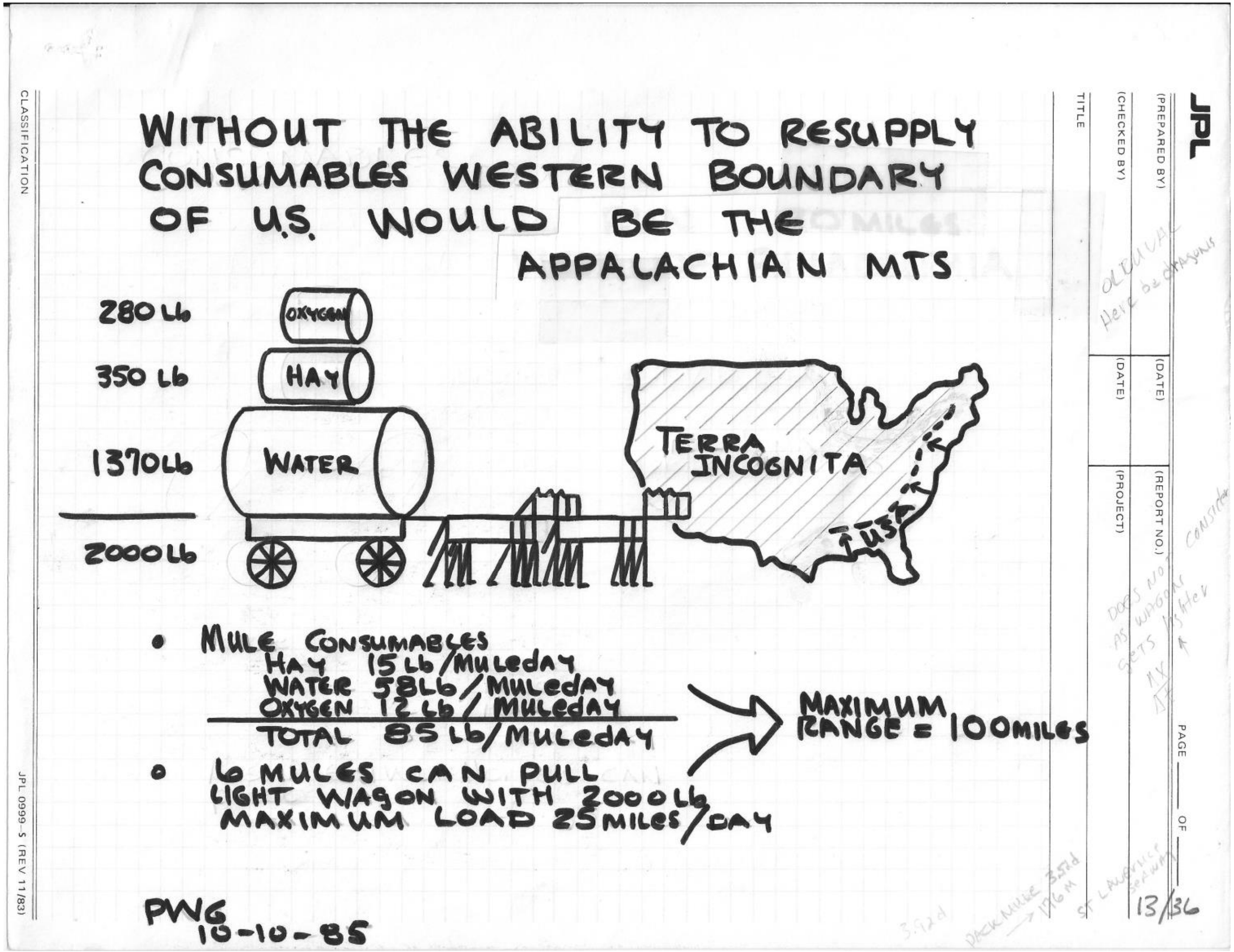
Curiosity Rover Arm Instruments



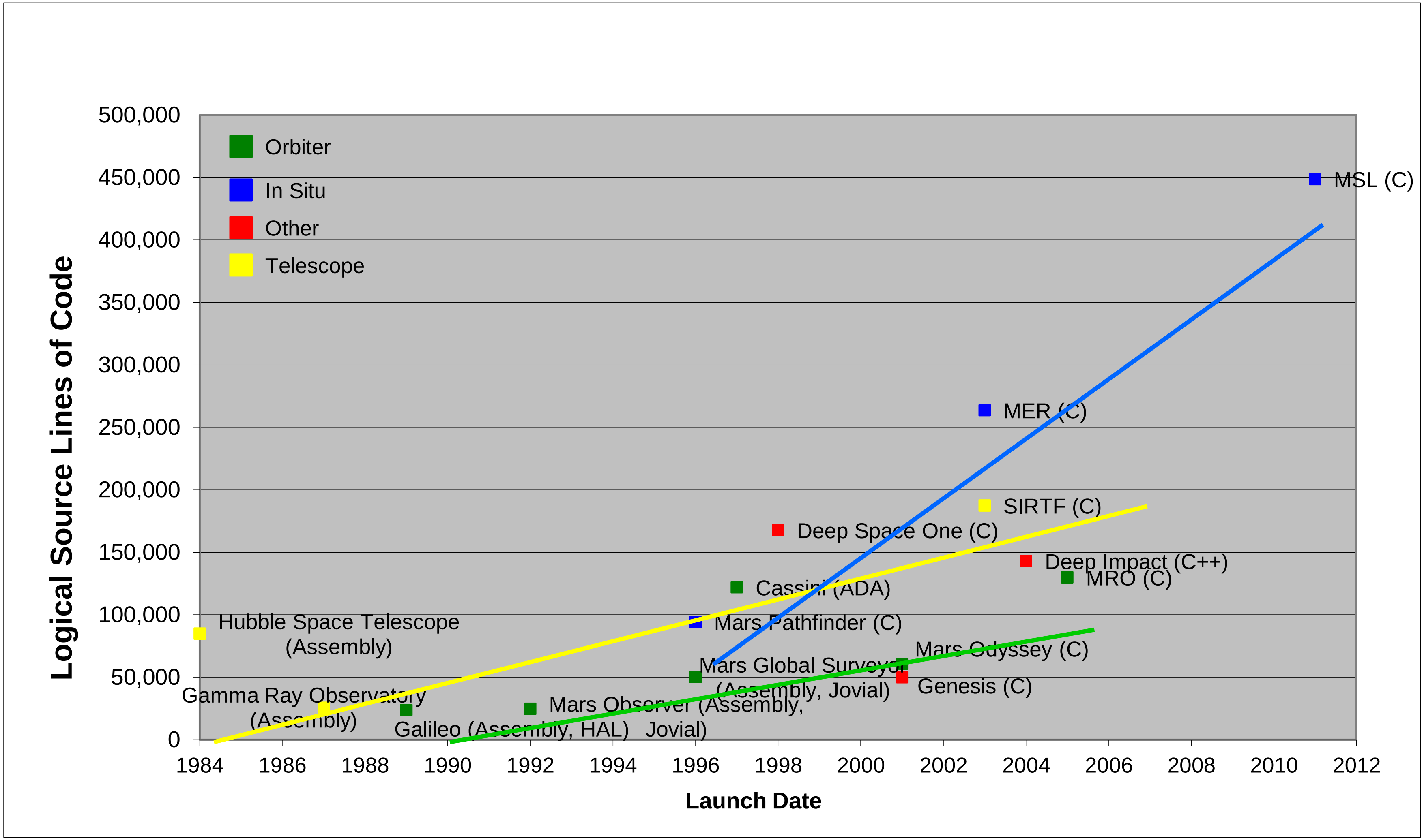

SOLAR APEX
HELIOSPHERE
BOW SHOCK
VOYAGER 1
THE SUN
VOYAGER 2
INTERSTELLAR WIND
TERMINATION SHOCK
HELIOPAUSE


Heliopause
Termination
Bow Shock
Interstellar Winds
Sun
Voyager 1
Neptune
Voyager 2
Pluto
Solar Wind

Future Missions Must Utilize Extraterrestrial Resources

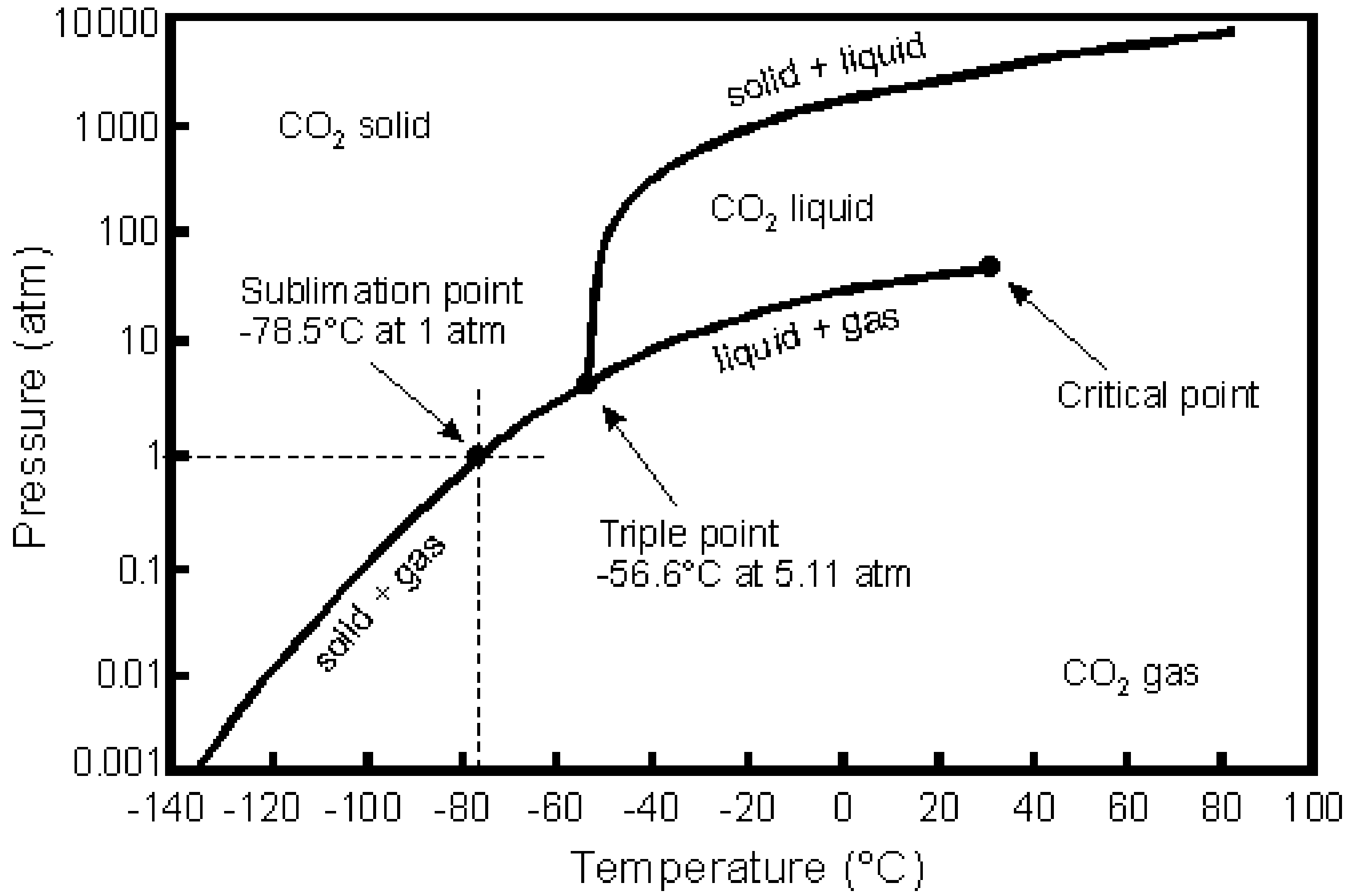


Flight Software Growth



ESD Mission Software: State of Software Report 2008 - excludes auto-generated code

CO_2 Phase Diagram



Pressure-Temperature phase diagram for CO_2.