

Hypersonic Interplanetary Flight: Aero Gravity Assist

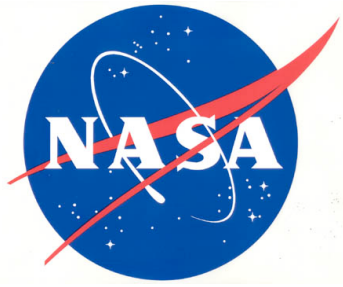
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NASA Jet Propulsion Laboratory

Cal Poly Pomona
31 Oct 2006



Gravity Assist

Al Bowers & Dan Banks



Mission



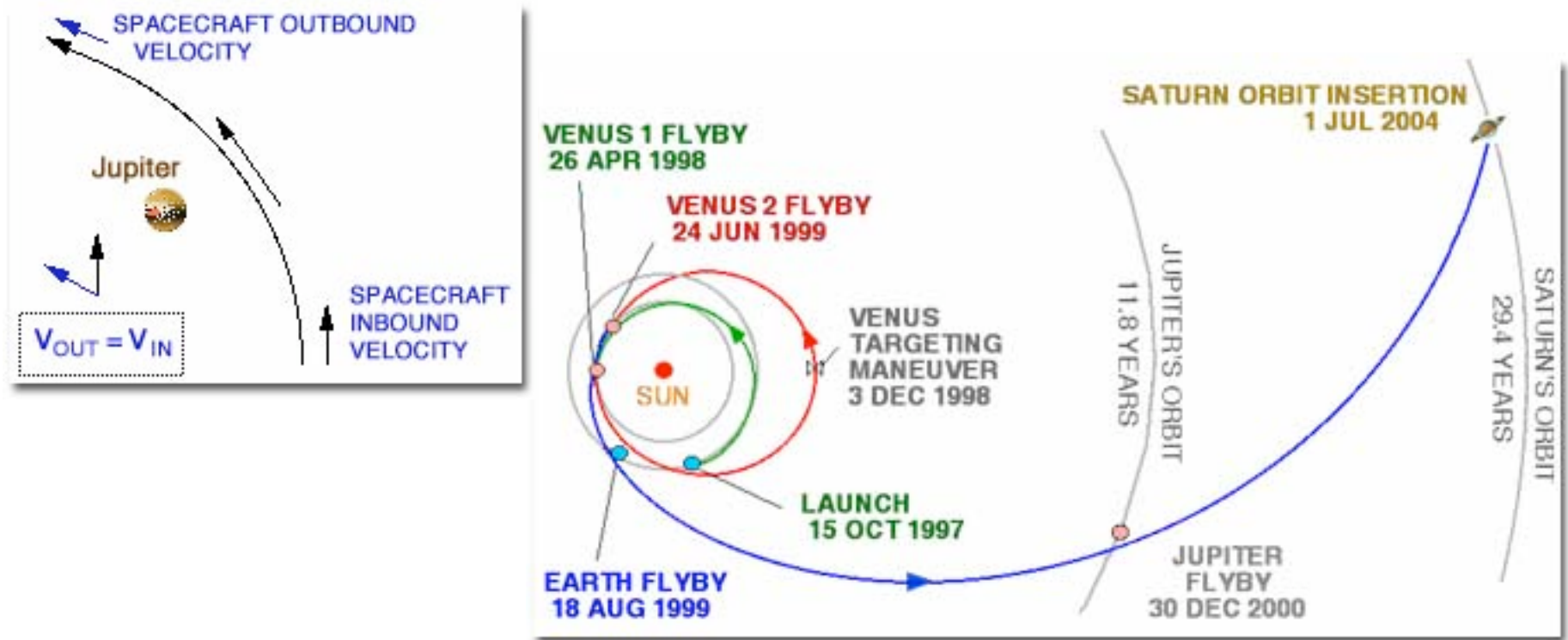
- NASA's Mission
 - To understand our home planet
 - To explore the Universe & search for life
 - To inspire the next generation of explorers
- Dryden's Mission
 - To fly what others can only imagine

Gravity Assist & Aero Gravity Assist

- The Past: Gravity Assist
 - the idea
 - Grand Tour of the Planets: Pioneer 10/11 & Voyager 1/2
- The Future: Aero Gravity Assist
 - large v small planets for gravity assist
 - AGA trajectories
 - launch opportunities
 - planetary waverider performance

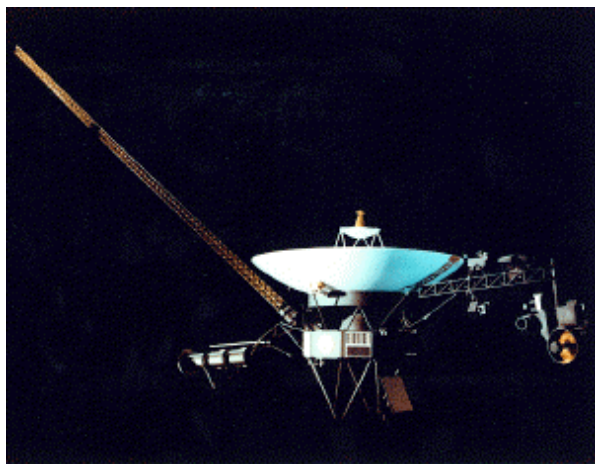
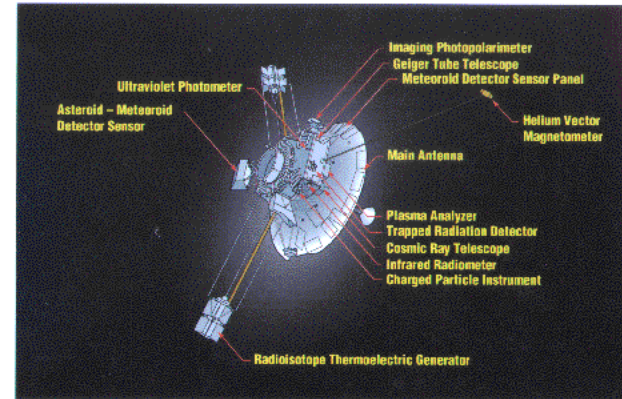
Gravity Assist - The Idea

- Planet-centric speed doesn't change, only direction
- Heliocentric radial speed does change, boost to a higher orbit

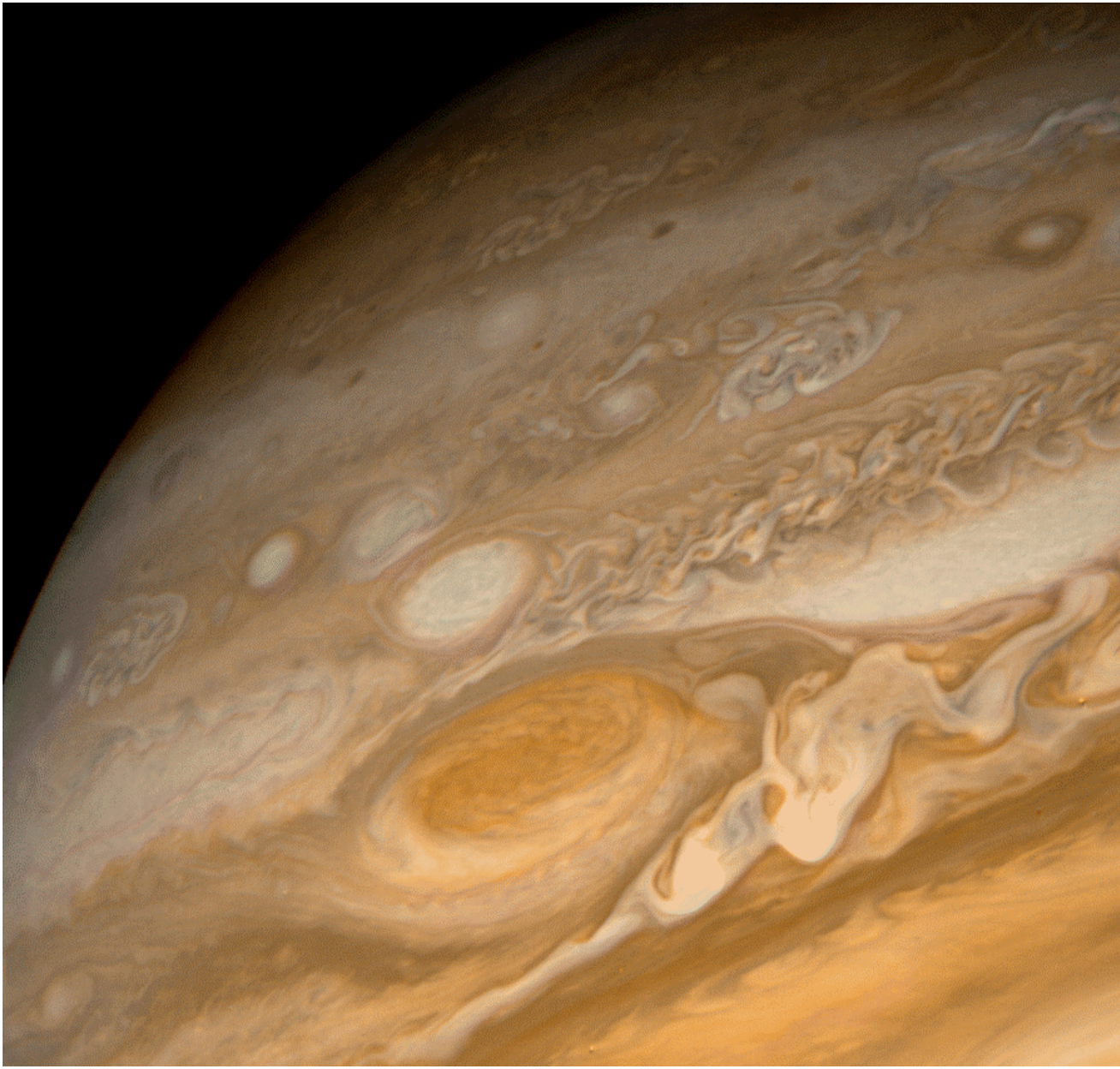


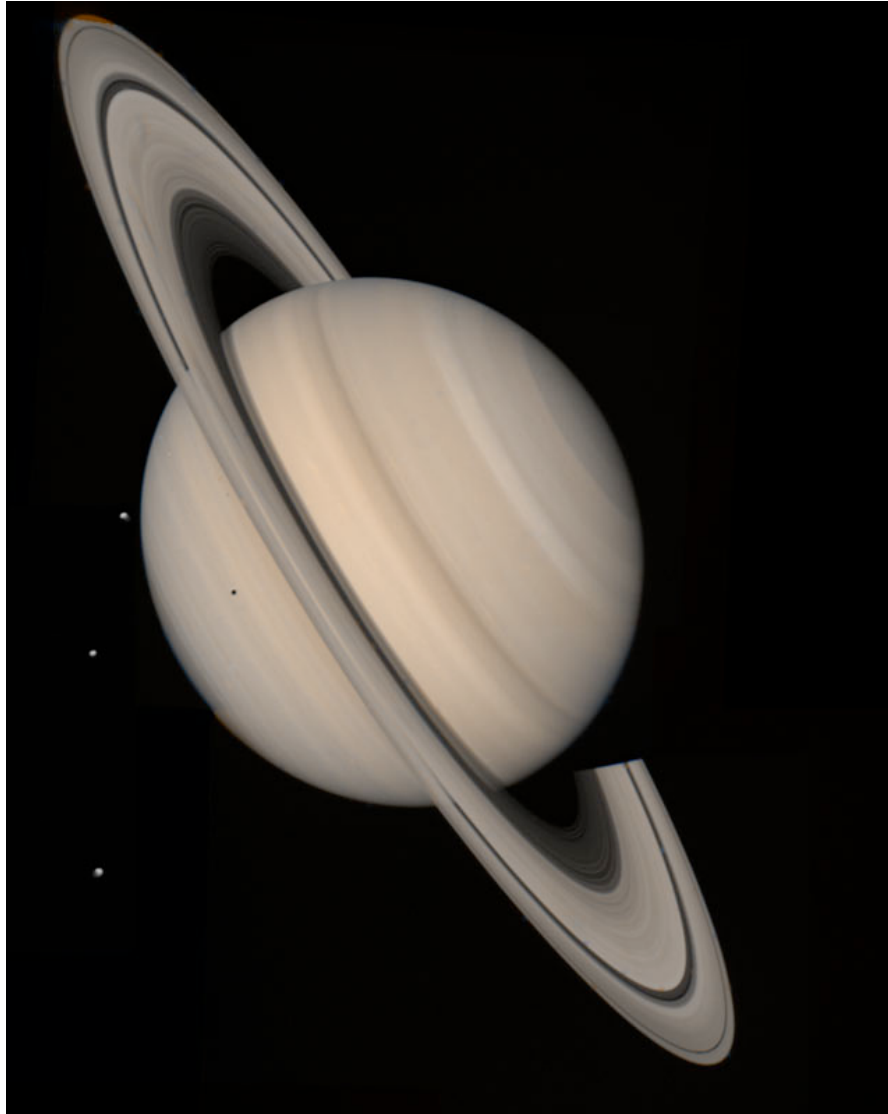
Pioneer 10/11 & Voyager 1/2

- Pioneer 10/11
 - Pioneer 10 to Jupiter
launched 02 Mar 72
Jupiter 03 Dec 73
 - Pioneer 11 to Jupiter & Saturn
launched 05 Apr 73
Jupiter 02 Dec 74
Saturn 01 Sep 79

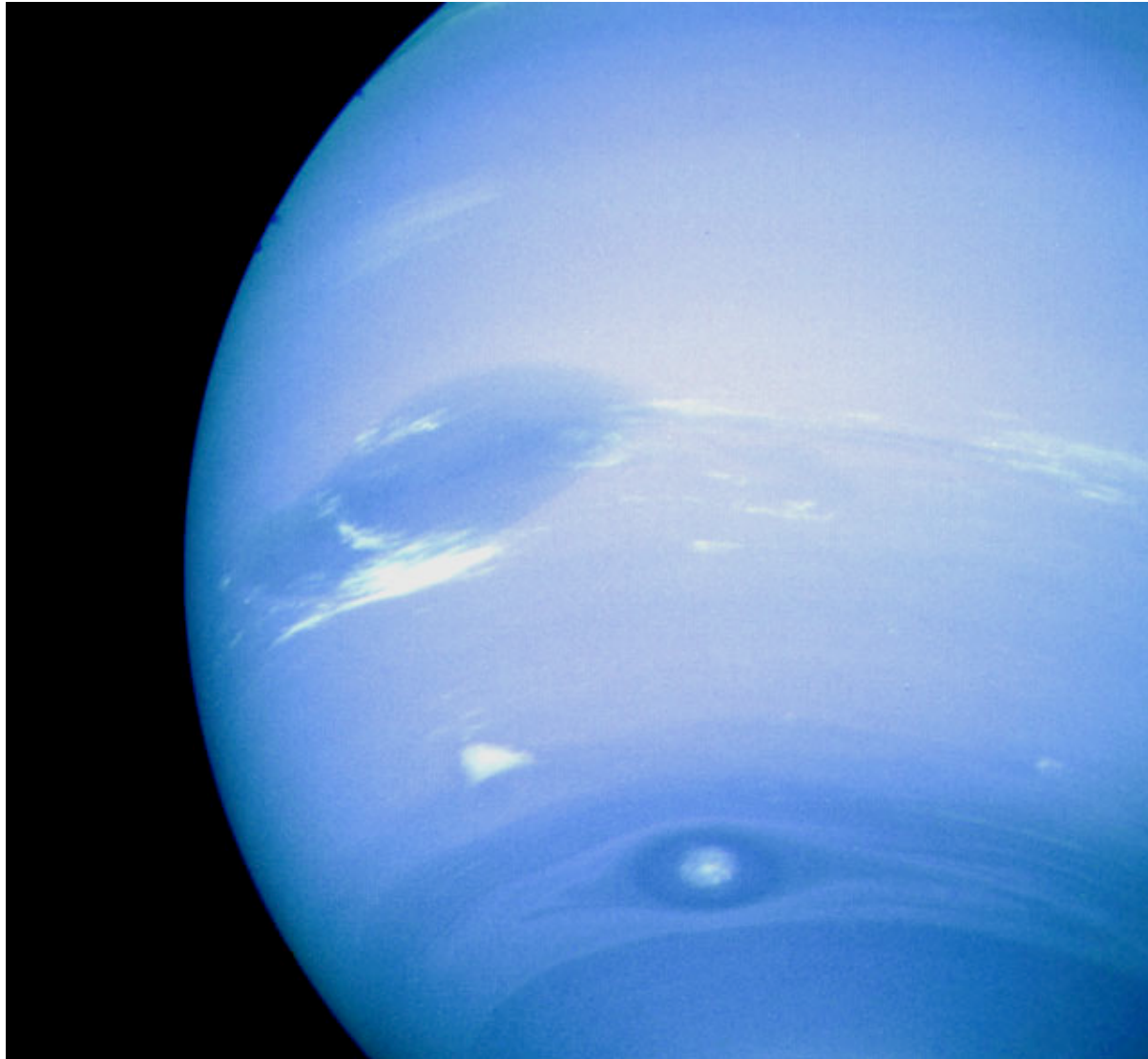


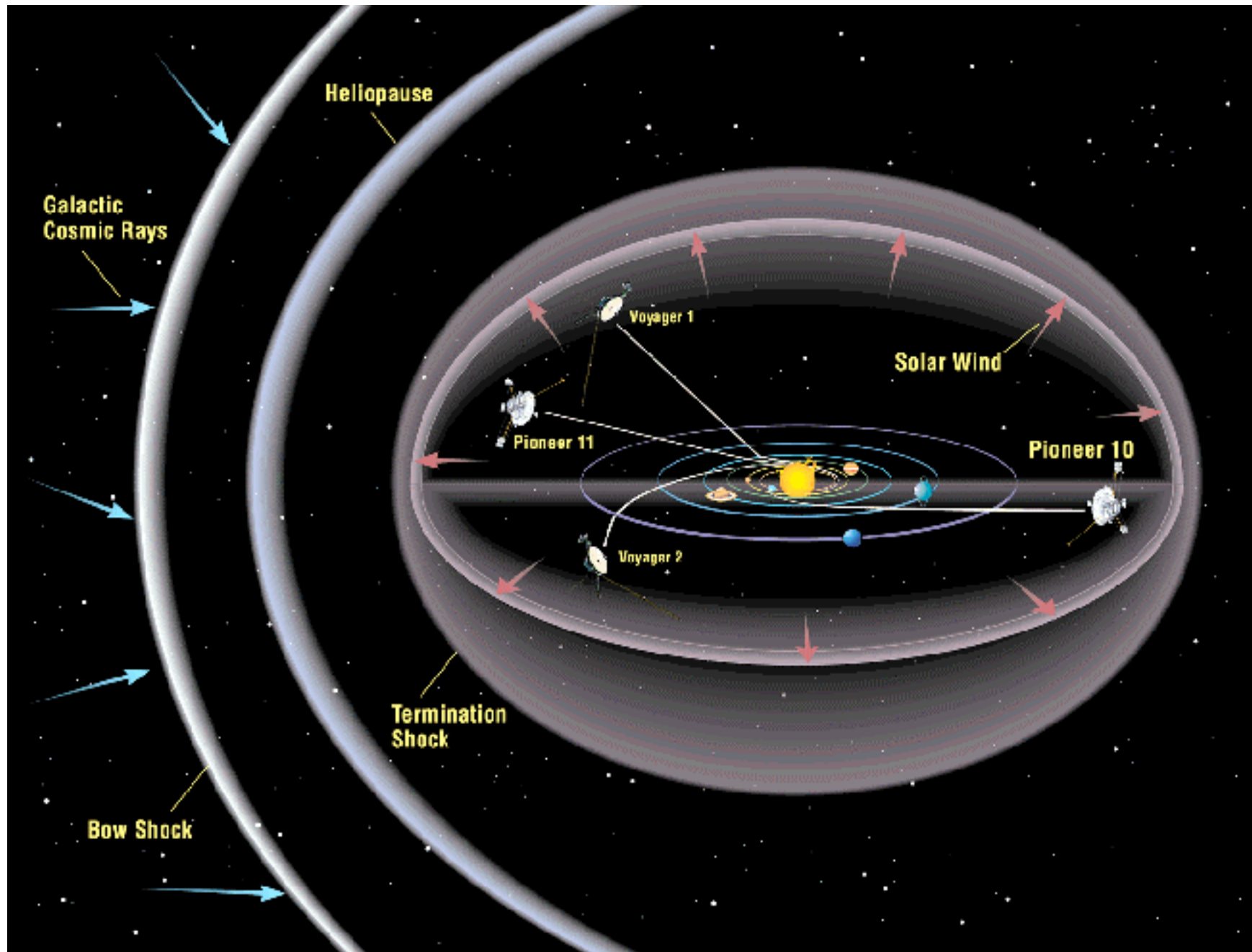
- Voyager 1/2
 - Voyager 1 to Jupiter & Saturn
launched 05 Sep 77
Jupiter 05 Mar 79
Saturn 12 Nov 80
 - Voyager 2 to Jupiter, Saturn, Uranus & Neptune
launched 20 Aug 77
Jupiter 09 Jul 79
Saturn 25 Aug 81
Uranus 24 Jan 86 & Neptune 25 Aug 89













Pluto System

Hubble Space Telescope ACS



May 15, 2005



May 18, 2005

NASA, ESA, H. Weaver (JHU/APL), A. Stern (SwRI),
and the HST Pluto Companion Search Team

STScI-PRC05-19a

TYPICAL PLANETARY GRAVITY-ASSIST TRAJECTORIES

• USING LARGE OUTER PLANETS

LARGE **G** , LARGE BENDING ANGLES, **LARGE ΔV**

HIGH LAUNCH ENERGY ($C_3 = 80 - 120 \text{ km}^2/\text{sec}^2$)

LONG DURATION TO THE CLOSEST PLANET (e.g. JUPITER)

RADIATION DANGER IN THE MAGNETOSPHERES OF GAS GIANTS

• USING SMALL TERRESTRIAL PLANETS

SMALL **G**, SMALL BENDING ANGLES, **SMALL ΔV**

LOW LAUNCH ENERGY ($C_3 = 10 - 30 \text{ km}^2/\text{sec}^2$)

LOW INTERPLANETARY VELOCITIES ($<10 \text{ km/sec}$)

LONG DURATION : MULTIPLE FLYBYS TO GET REASONABLE VELOCITIES

AERO-GRAVITY ASSIST (AGA) TRAJECTORIES

- **TERRESTRIAL PLANETS FOR AGA MANEUVERS**

USING ATMOSPHERE TO INCREASE BENDING ANGLE AND ΔV

SMALL LAUNCH ENERGY ($C_3 \sim 10 - 30 \text{ km}^2/\text{sec}^2$)

AGA RESULTS IN HIGH INTERPLANETARY VELOCITIES ($\gg 10 \text{ km/sec}$)

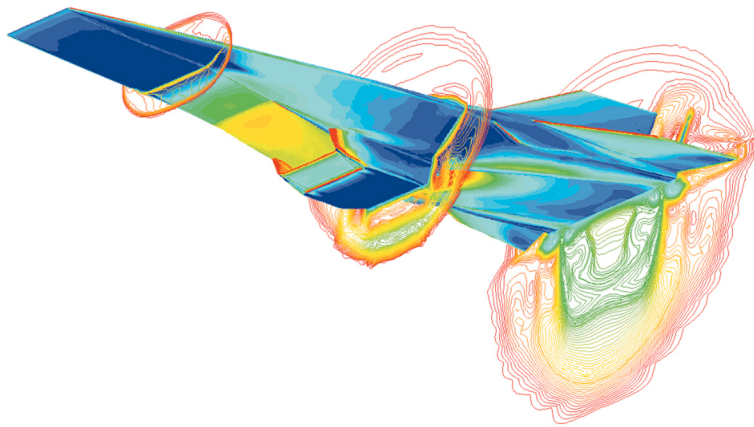
SHORTENED MISSION DURATIONS TO DISTANT TARGETS

- **WAVERIDER APPLICATION**

AEROASSIST VEHICLE WITH HIGH LIFT/DRAG AT HIGH MACH NUMBERS

MINIMUM DRAG LOSS DURING THE ATMOSPHERIC PASS

LARGE AERODYNAMIC CONTROL AUTHORITY FOR PRECISE NAVIGATION

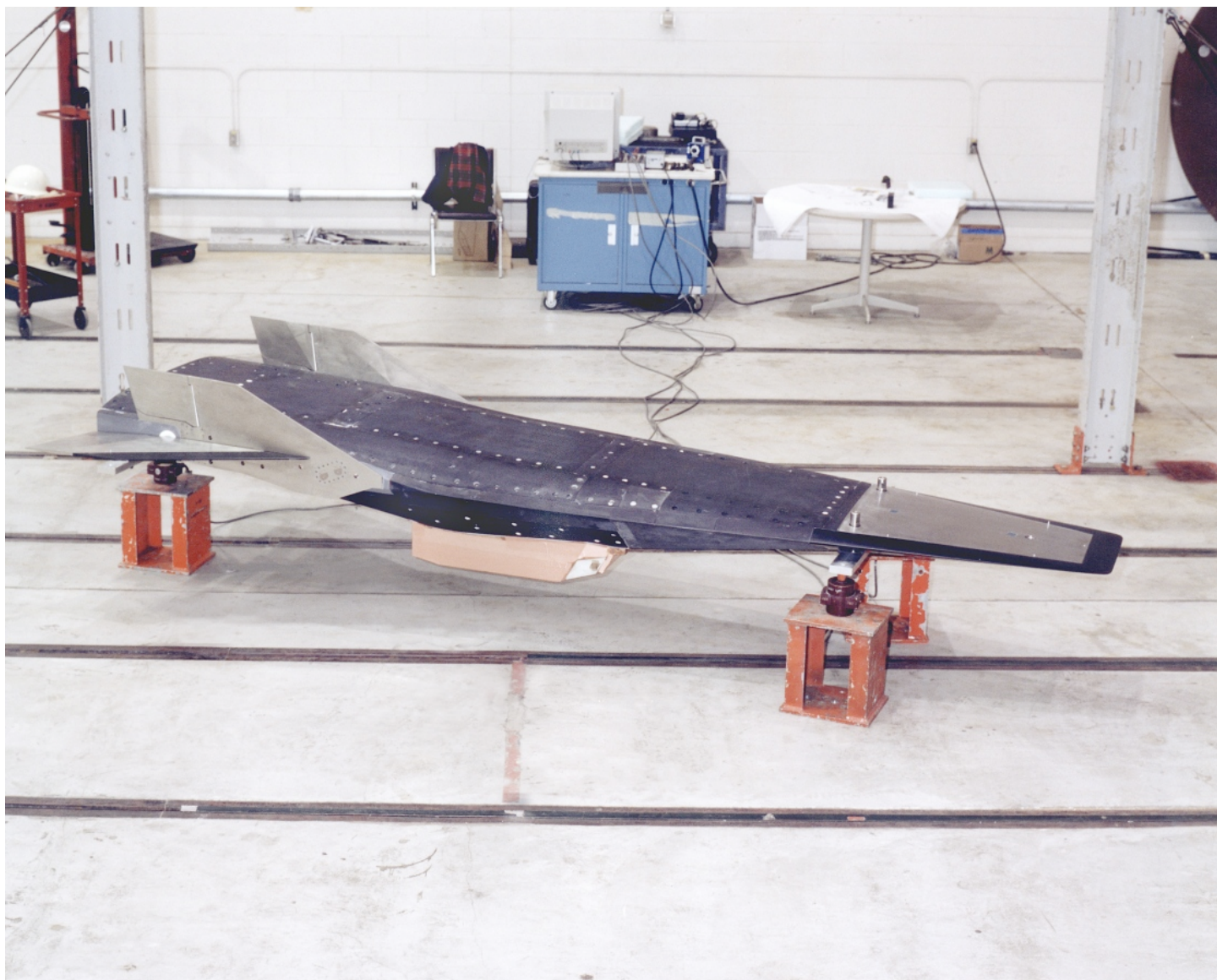



 Dryden Flight Research Center ED97 43968-01
 HYPER-X AT MACH 7: This computational fluid dynamic (CFD) image is of the Hyper-X vehicle at the Mach 7 test condition with the engine operating. 



NASA Dryden Flight Research Center Photo Collection
<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>
 NASA Photo: ED04-0082-2

Mach 7 wind tunnel test of the full-scale X-43A model with spare flight engine in Langley's 8-Foot High Temperature Tunnel.



NASA Dryden Flight Research Center Photo Collection
<http://www.dfrc.nasa.gov/gallery/photo/index.html>
NASA Photo: EC99-45265-23 Date: December 1999 Photo by: Tom Tschida

X-43A Vehicle During Ground Testing



NASA Dryden Flight Research Center Photo Collection

<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>

NASA Photo: EC04-0091-39 Date: March 26, 2004 Photo By: Tony Landis

NASA's B-52B launch aircraft at sunset with the second X-43A hypersonic research vehicle attached to a modified Pegasus rocket under its right wing.



NASA Dryden Flight Research Center Photo Collection
<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>
NASA Photo: EC04-0325-32 Date: November 16, 2004 Photo By: Carla Thomas

A modified Pegasus rocket drops away after release from NASA's B-52B
before accelerating the X-43A over a Pacific Ocean test range on Nov.
16, 2004.



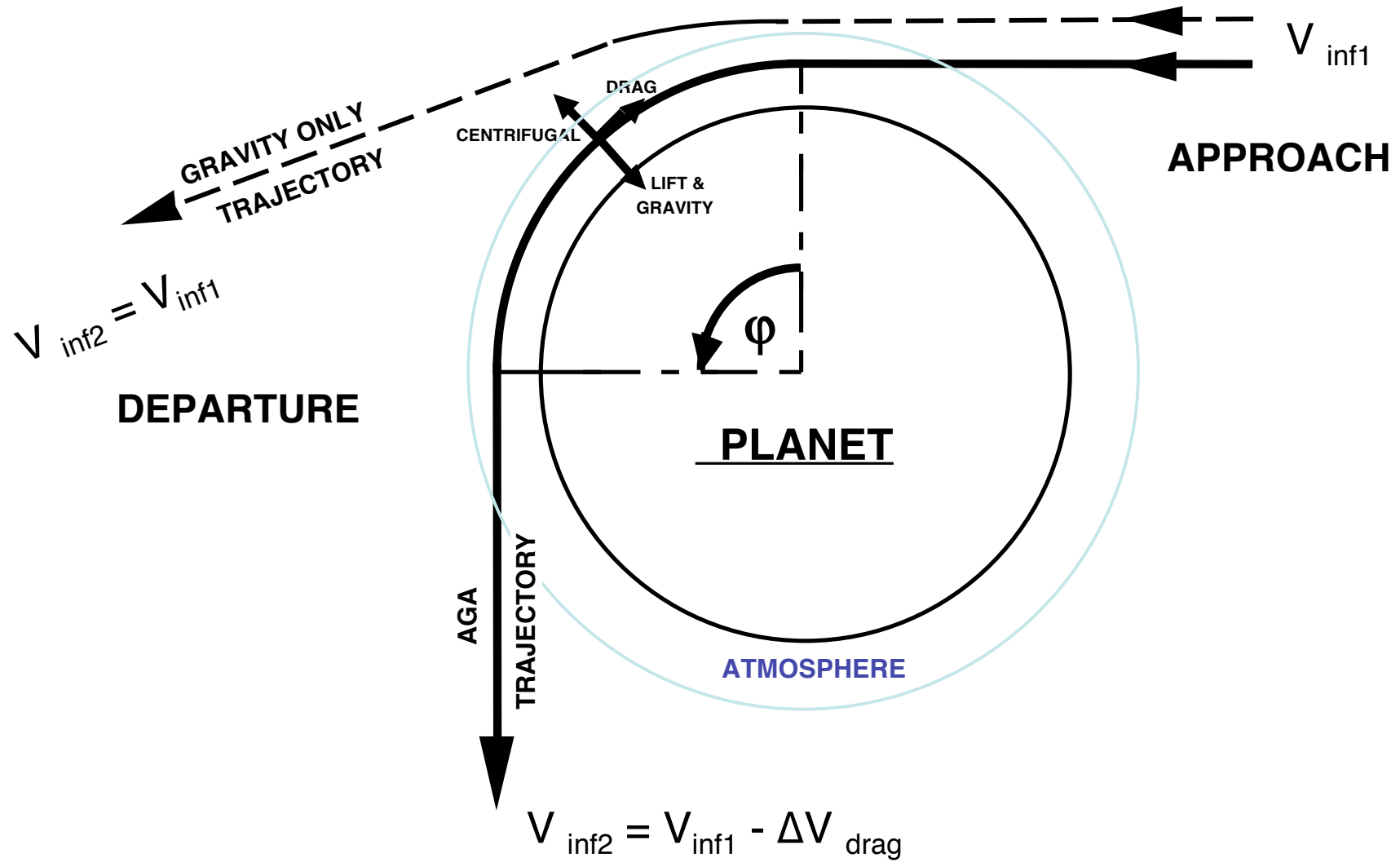
NASA Dryden Flight Research Center Photo Collection

<http://www.dfrc.nasa.gov/Gallery/Photo/index.html>

NASA Photo: EC04-0092-39 Date: March 27, 2004 Photo By: Jim Ross

The second X-43A and its modified Pegasus booster rocket accelerate after launch from NASA's B-52B launch aircraft over the Pacific Ocean.

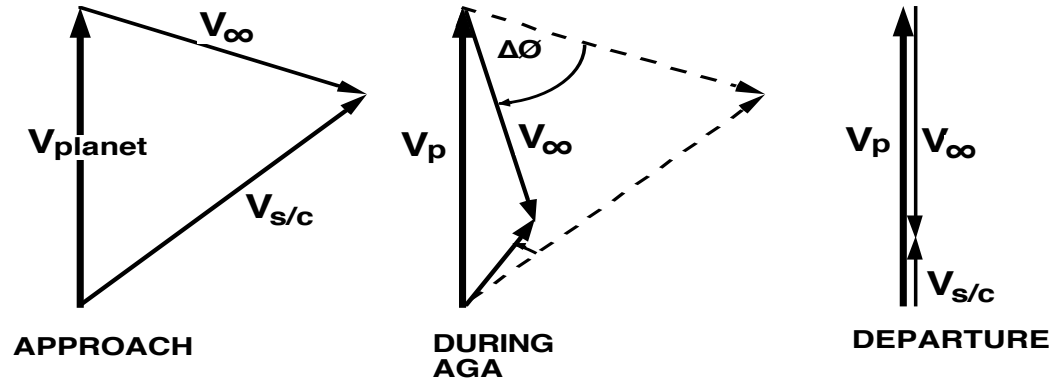
PLANET CENTERED TRAJECTORY COMPARISON



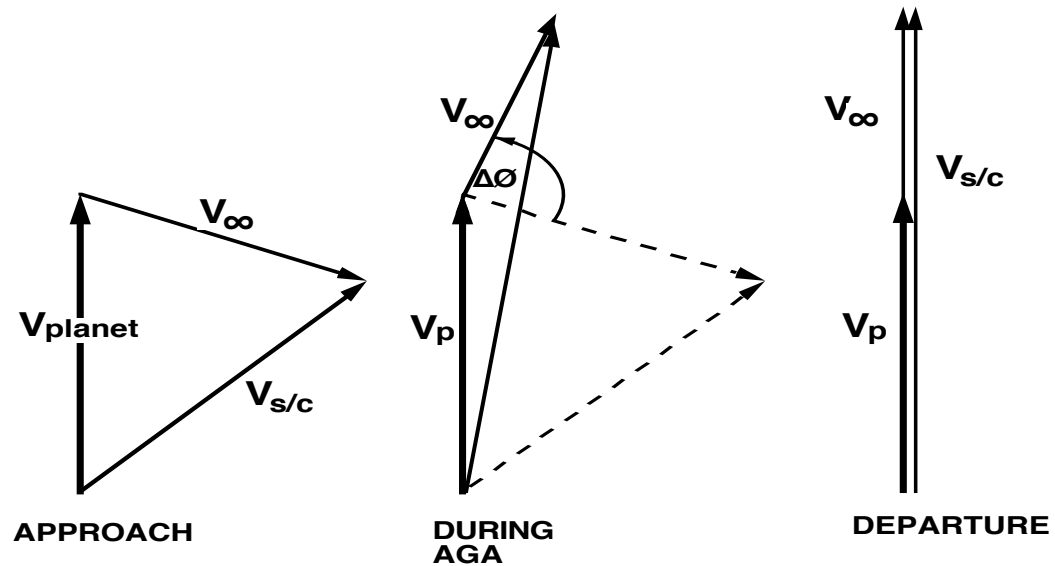
AGA Velocity Triangles

$$V_{S/C} = V_{PLANET} + \rightarrow V_{\infty}$$

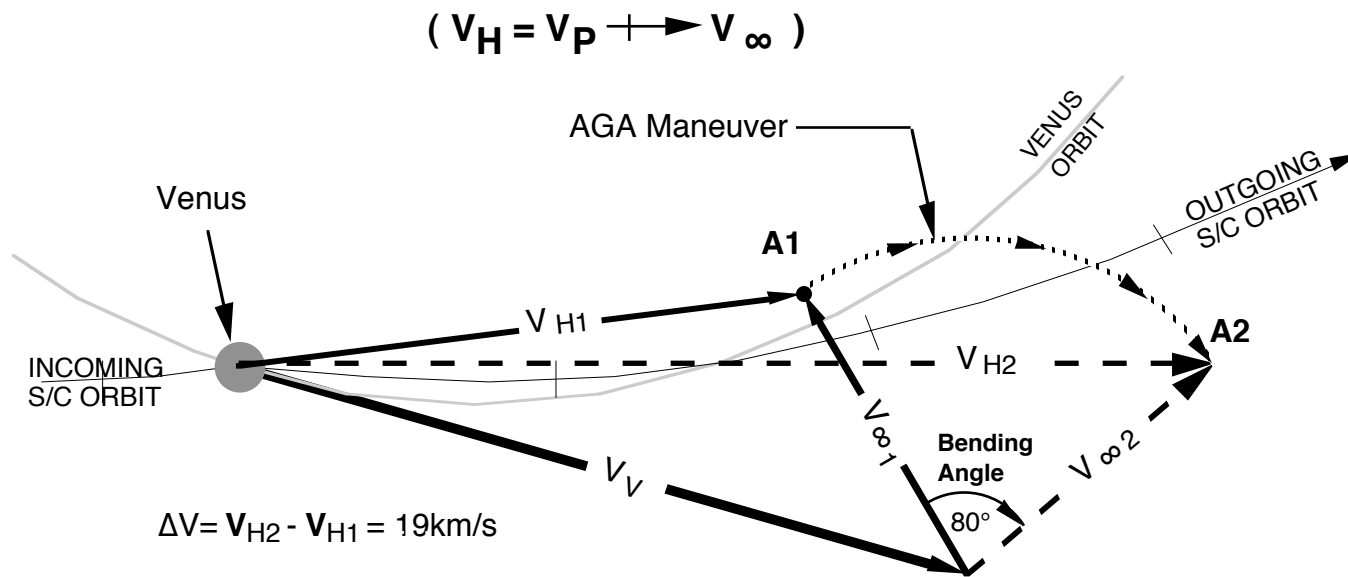
a. DECREASE VELOCITY (e.g. SOLAR PROBE)



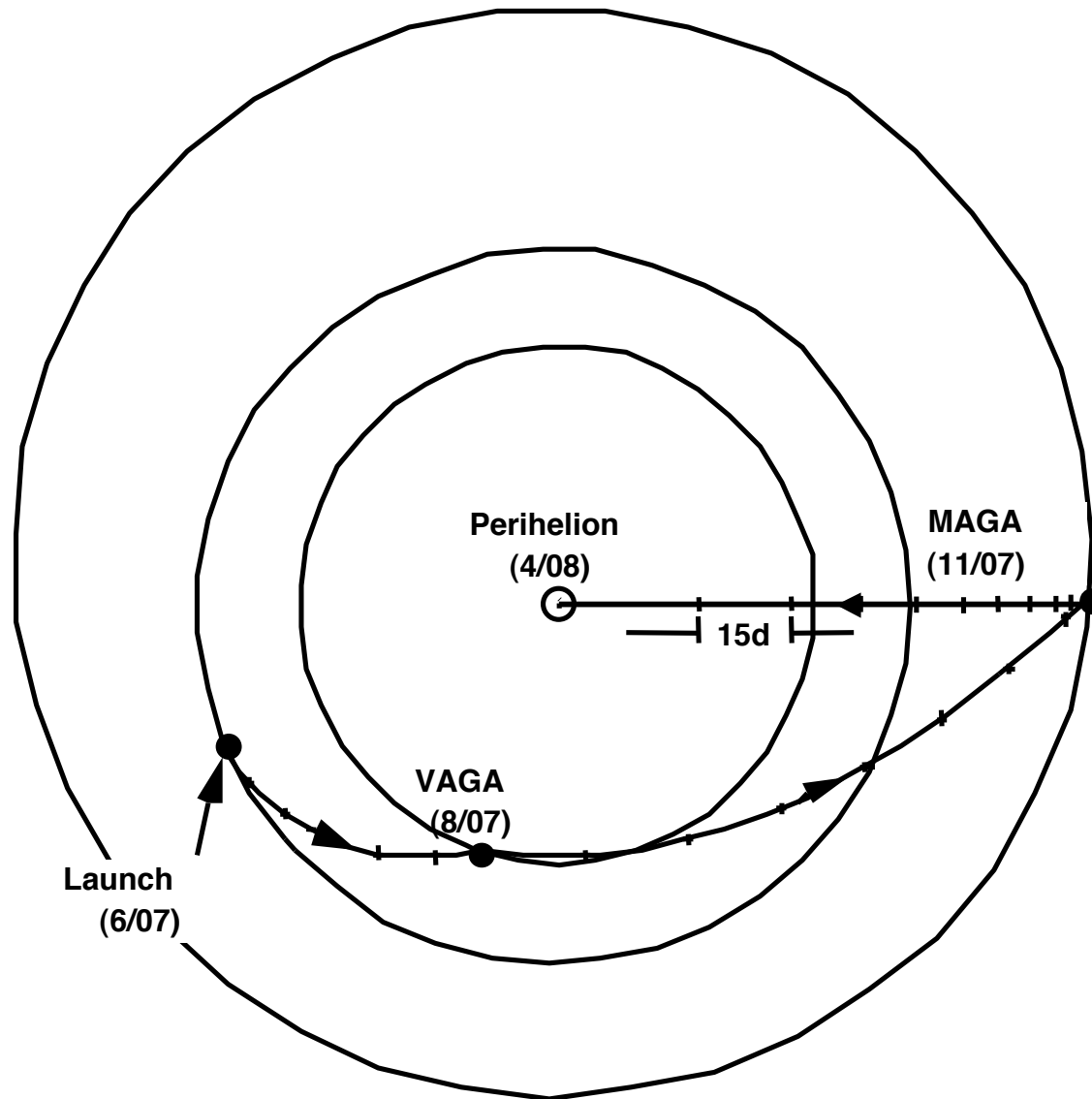
b. INCREASE VELOCITY (e.g. OUTER PLANETS MISSION)



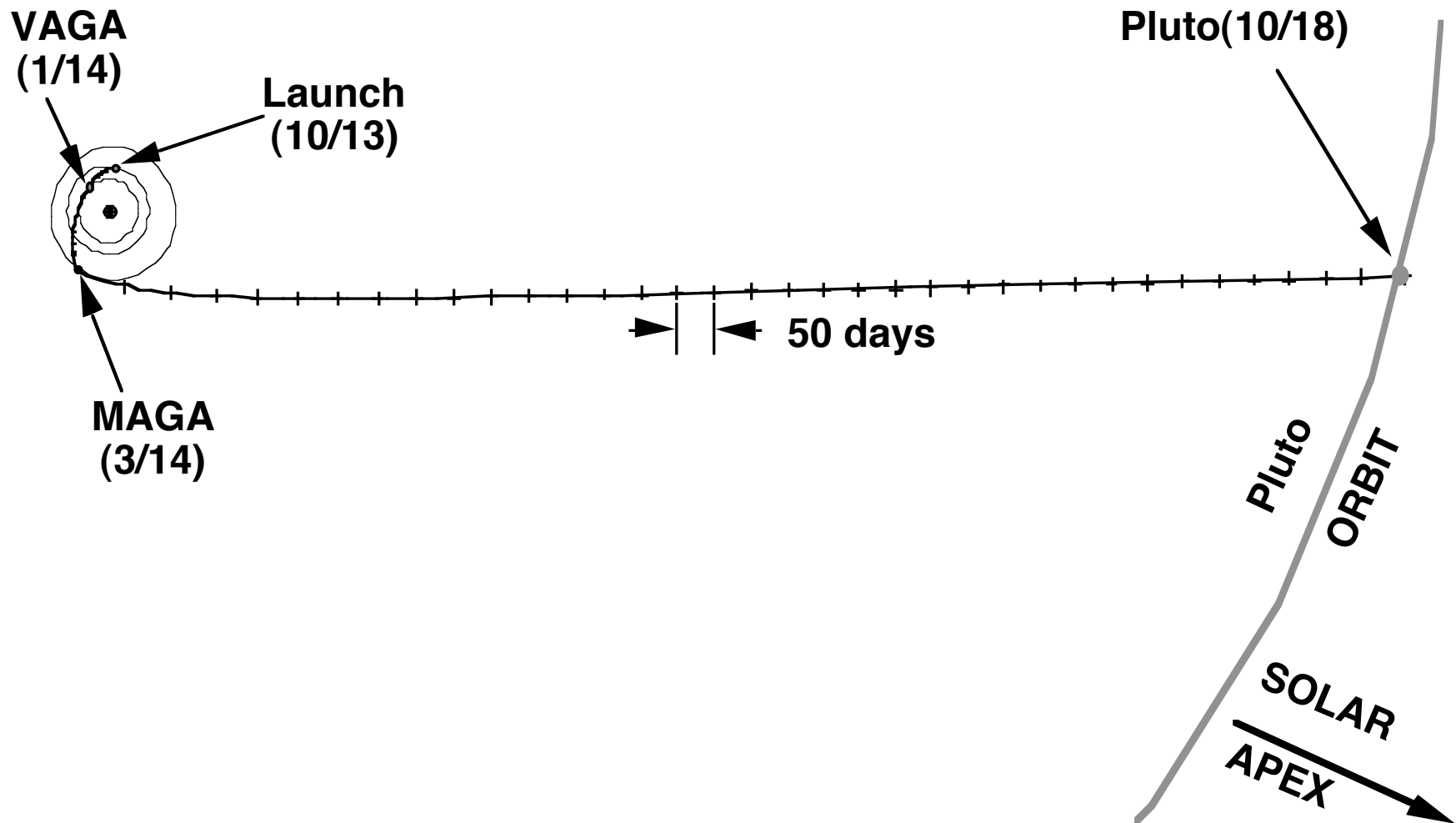
VENUS AGA Maneuver



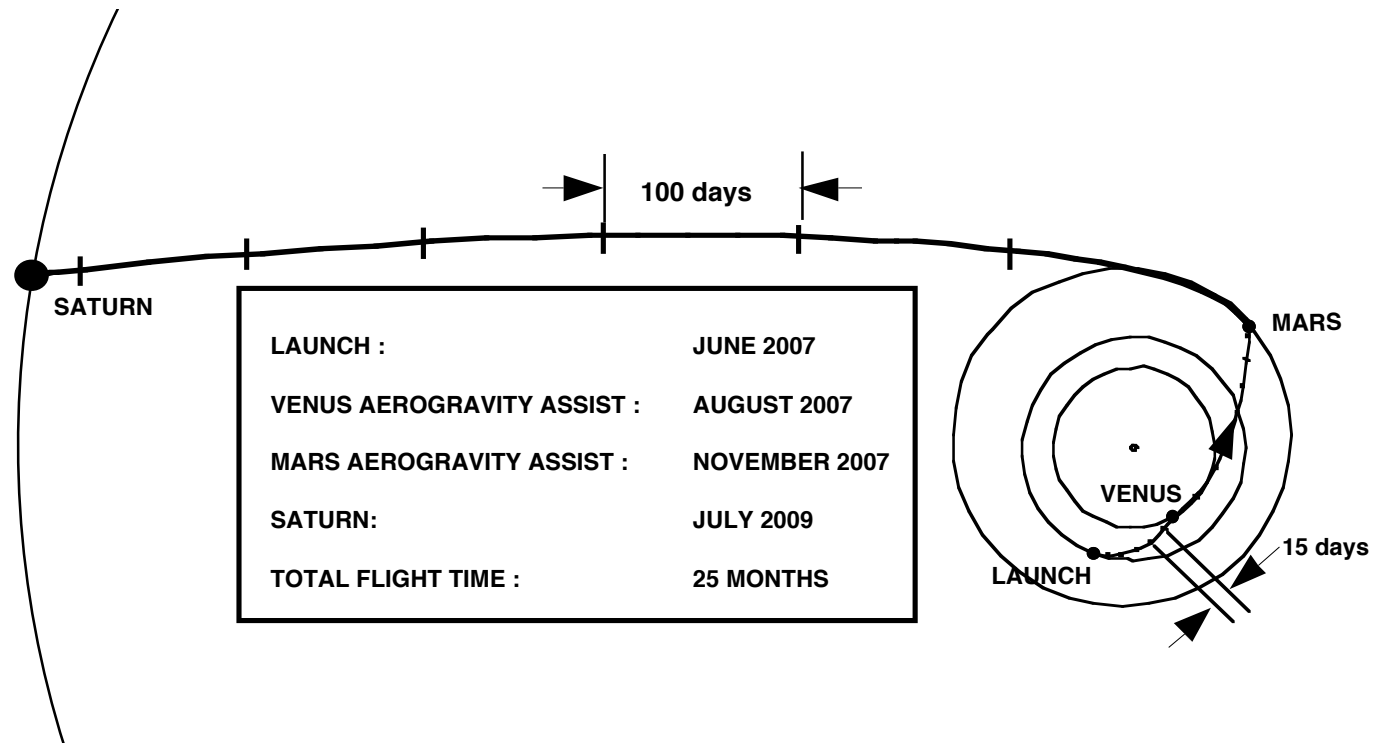
VENUS - MARS AGA TRAJECTORY TO THE SUN



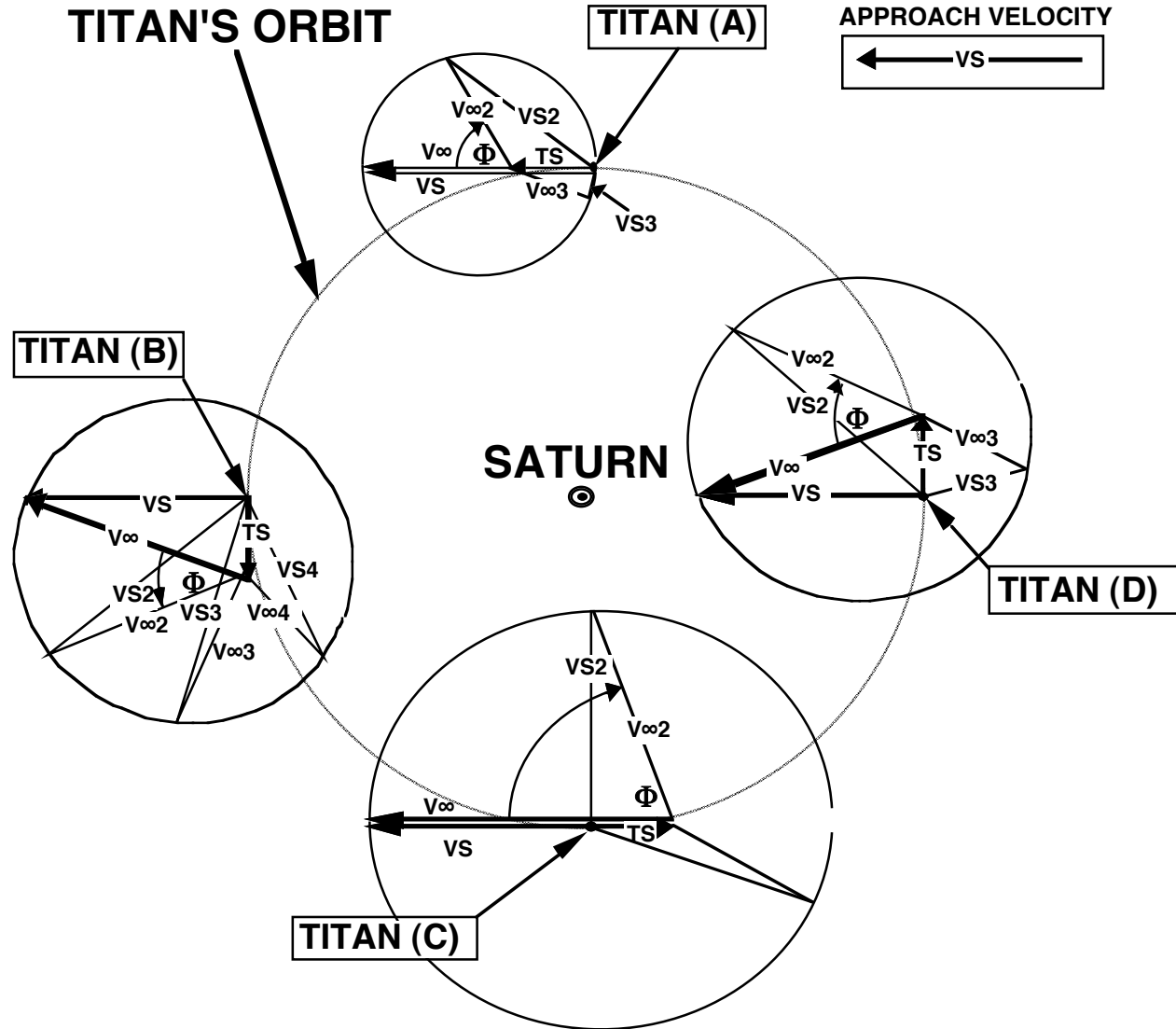
VAGAMAGA Trajectory to Pluto



VAGAMAGA Trajectory to Saturn



TITAN AGA OPTIONS



LEGEND

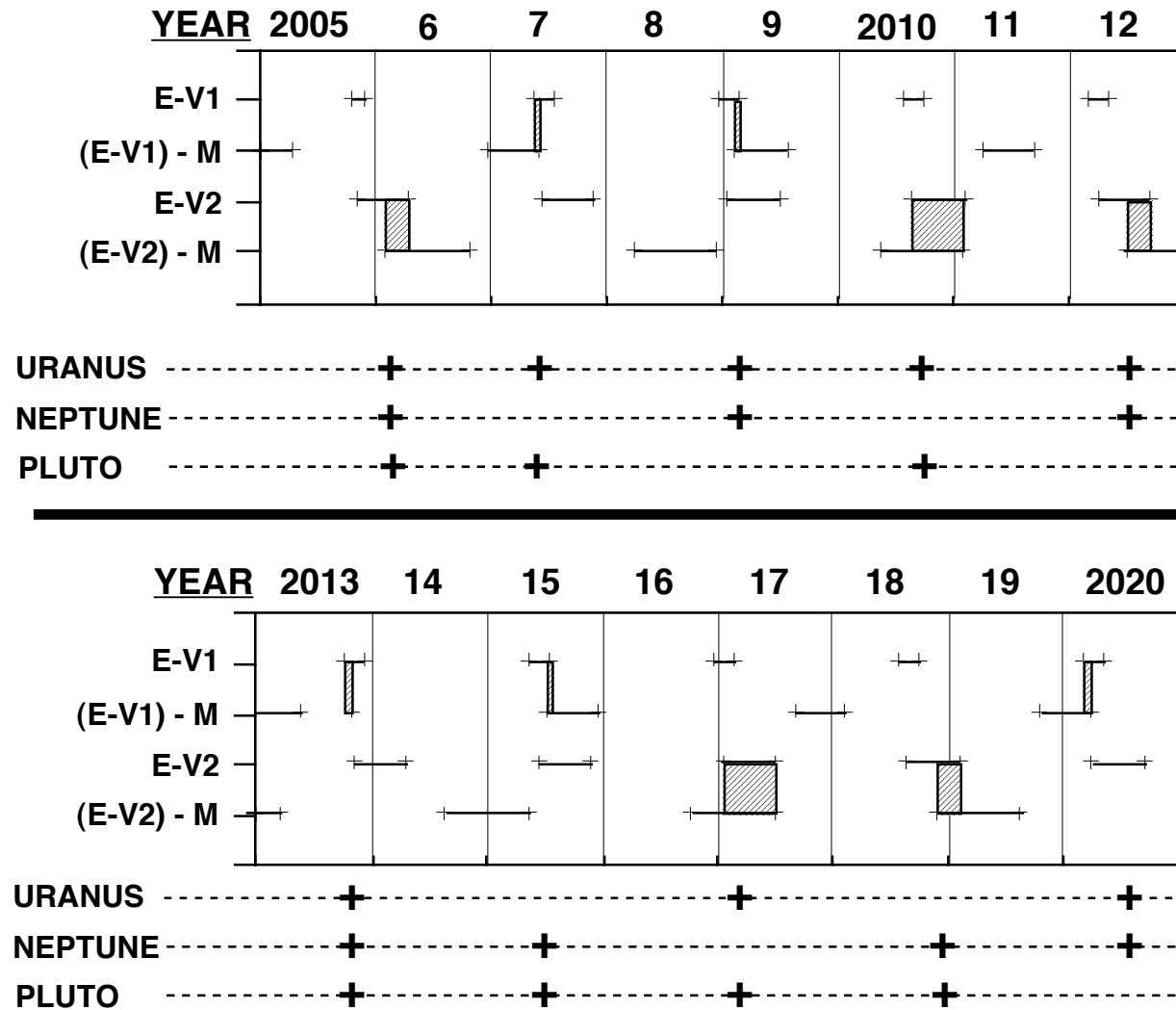
TITAN A:
Stop S/C, VS3 ~0

TITAN B:
Escape at “posigrade”
direction

TITAN C:

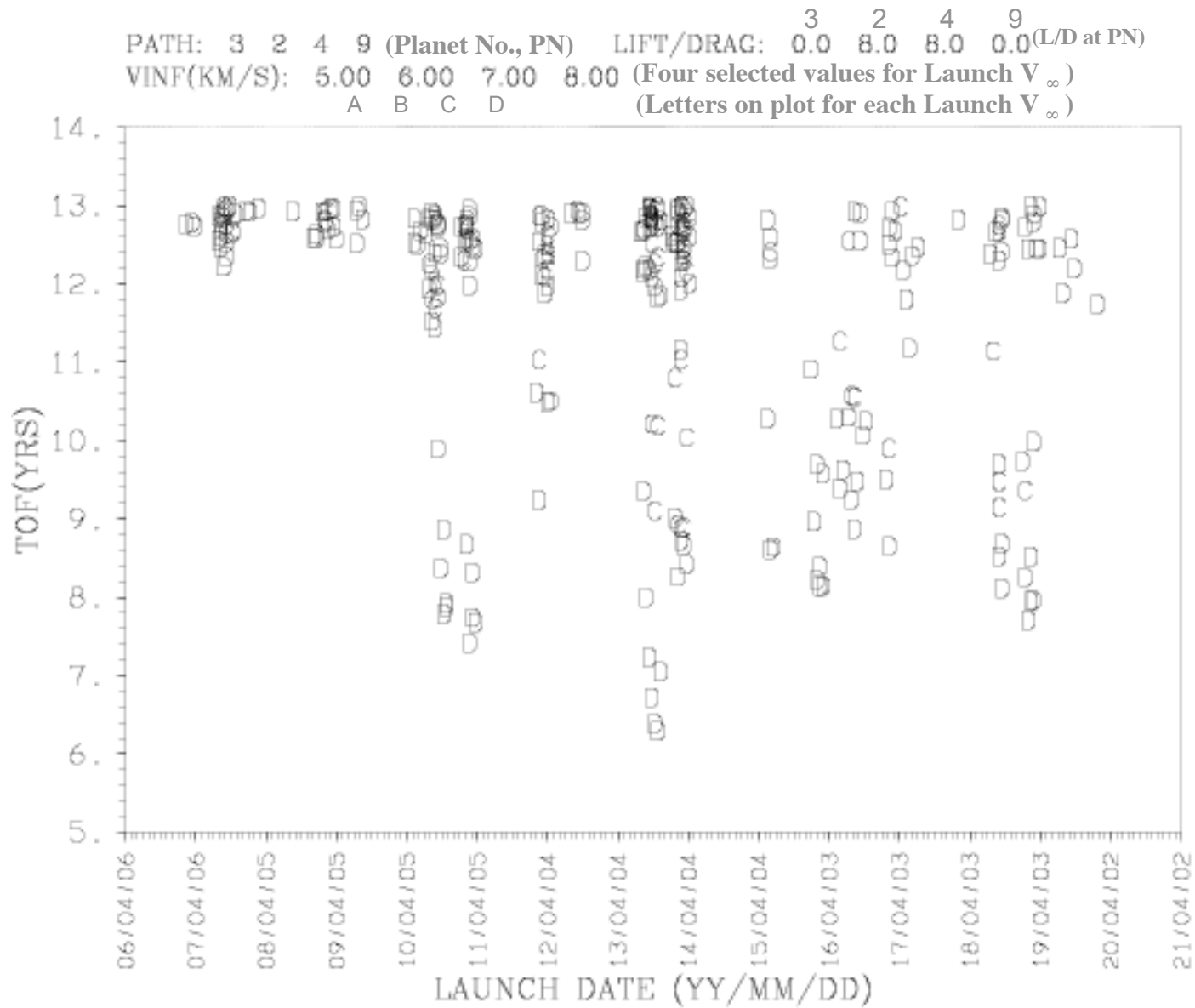
TITAN D:
Escape in retrograde
direction

Terrestrial Planets Trajectories and OP Launch opportunities from 2005 to 2020

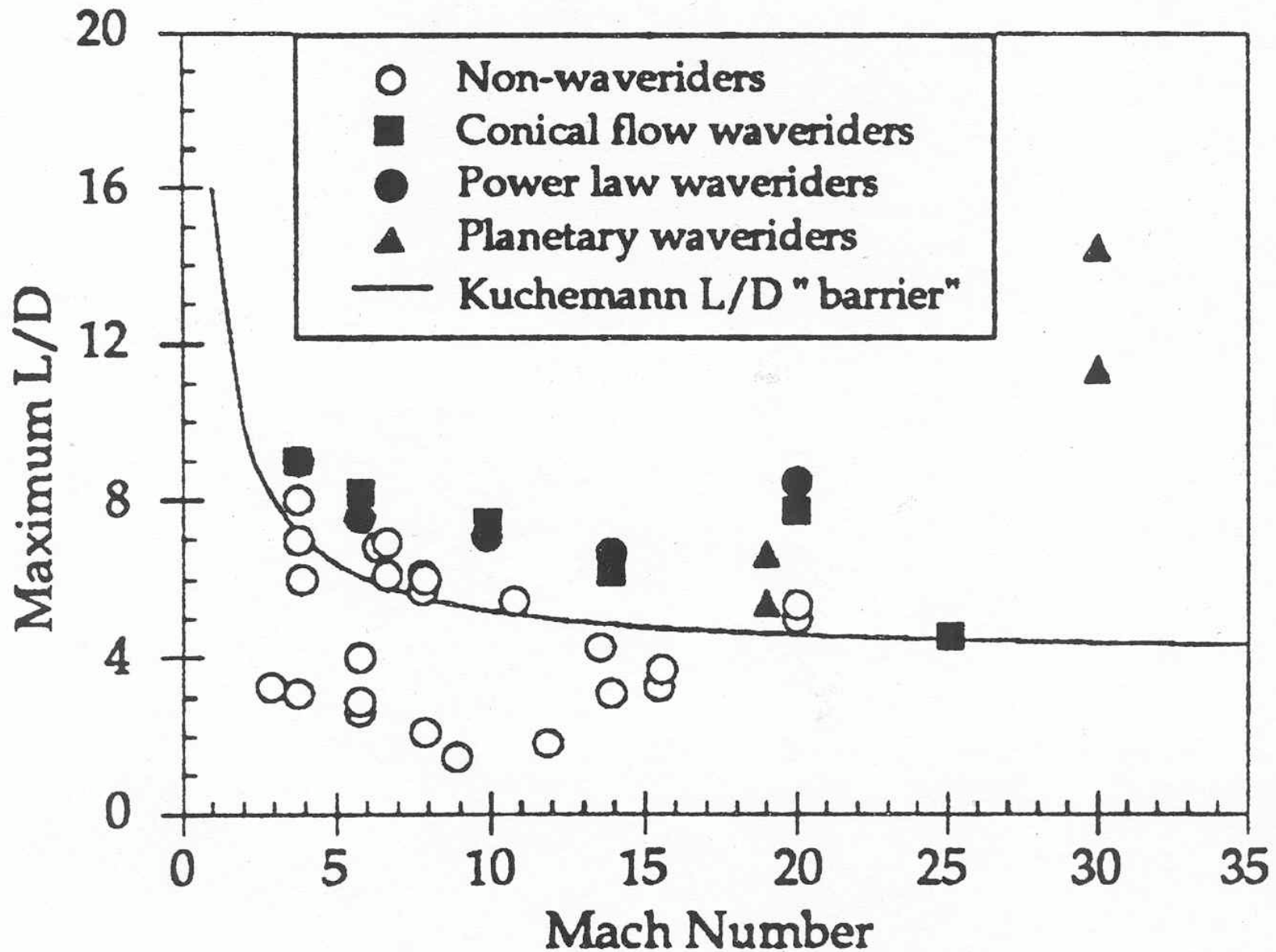


= Viable Opportunity to the Outer Planet Shown Below Box

Time of Flight for Pluto opportunities 2006 to 2020 **(using Venus and Mars AGA maneuvers)**

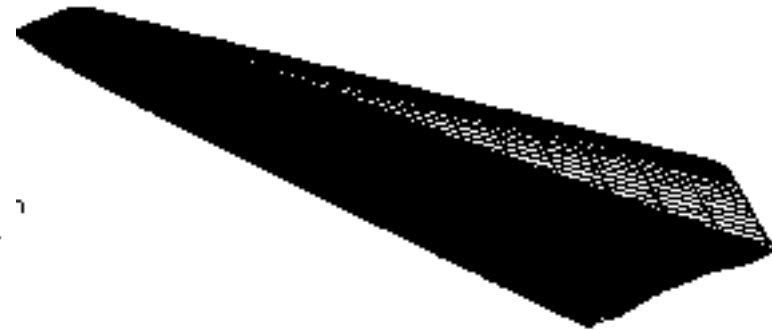
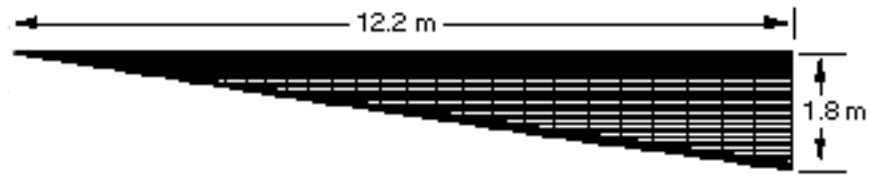


Planetary Waverider Performance Comparison*

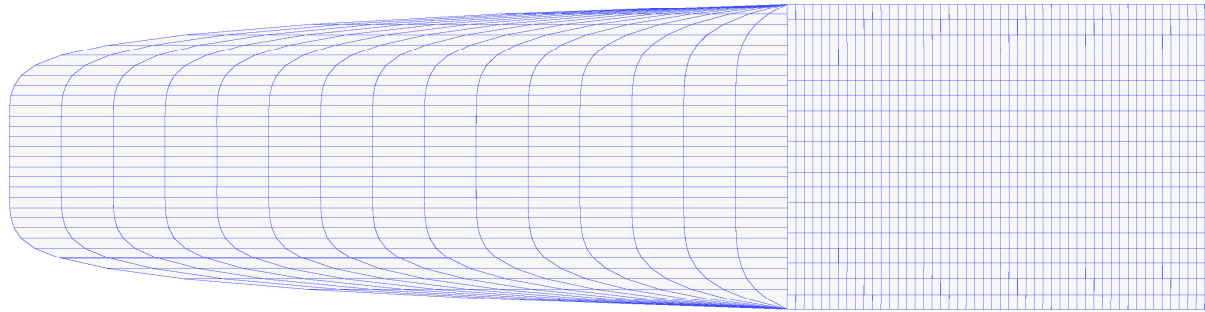


* From Lewis & McDonald, AIAA #91-0053, 1/7/91

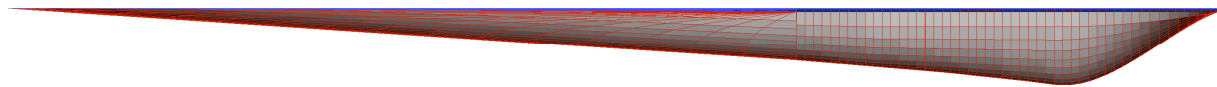
University of Maryland Waverider Concept



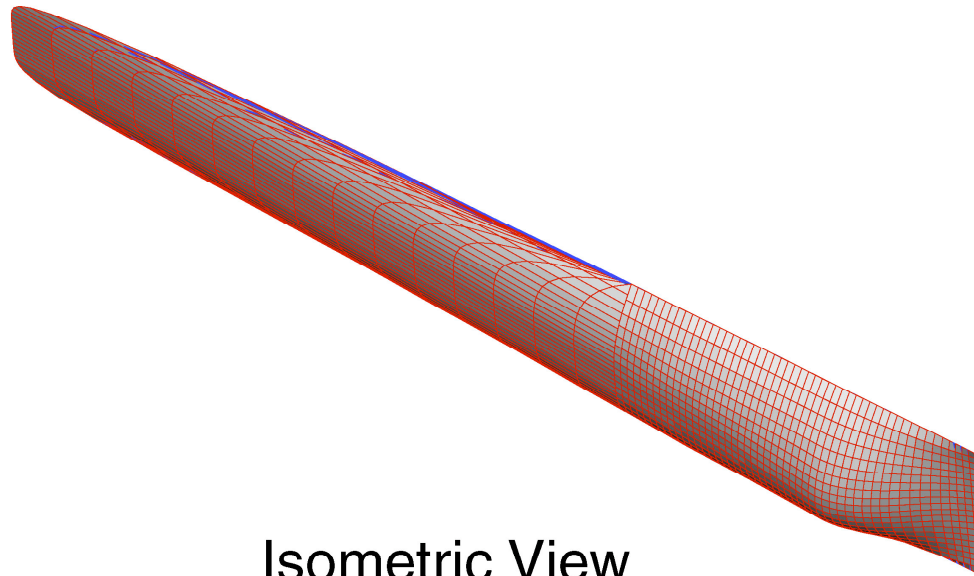
Waverider shape for a turbulent (CO₂) boundary layer (From the CVD design code at the U of Maryland)



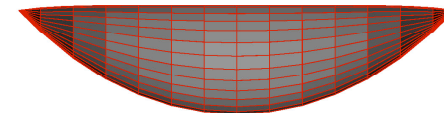
Planform View



Side View

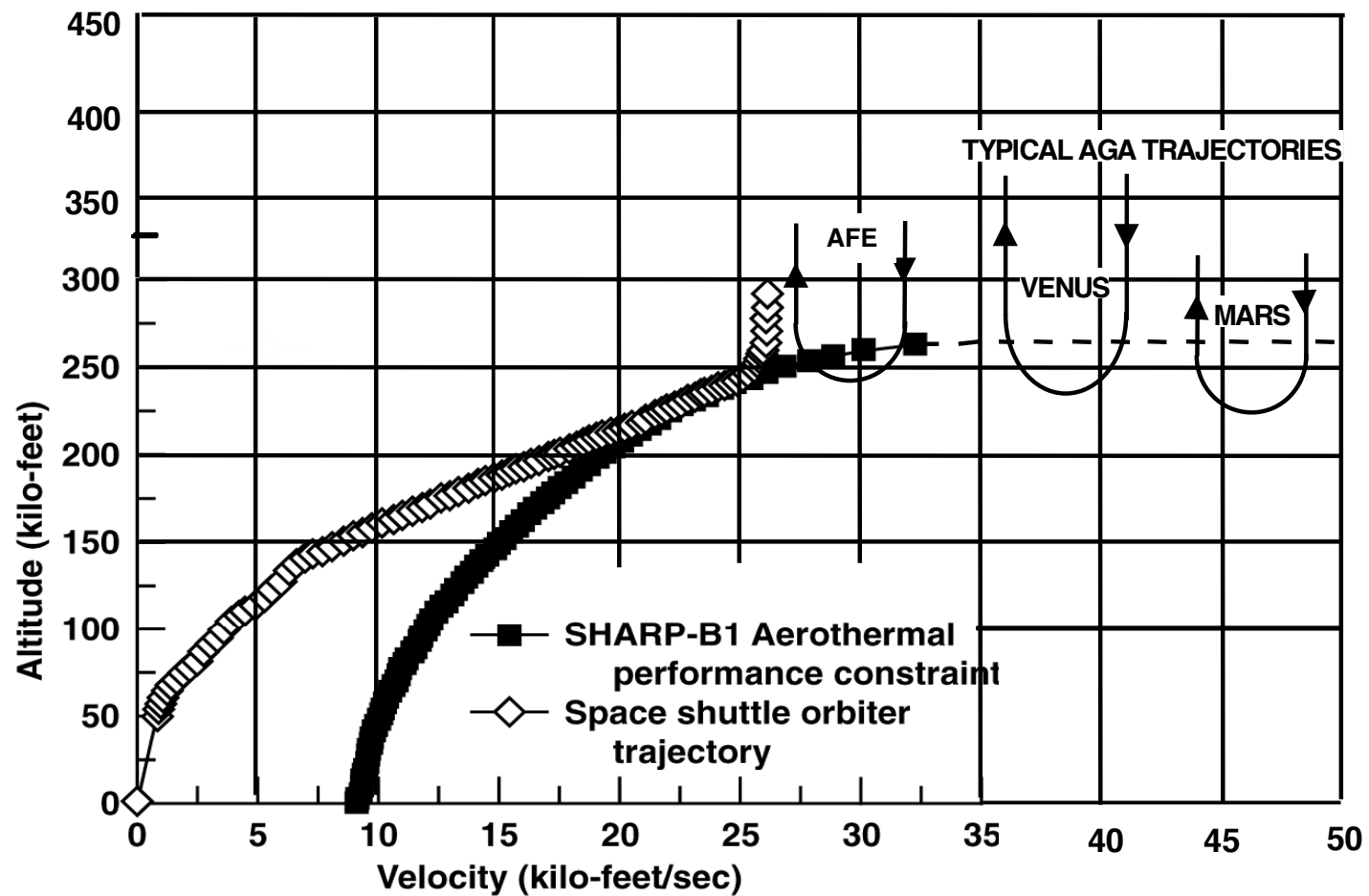


Isometric View



Base View

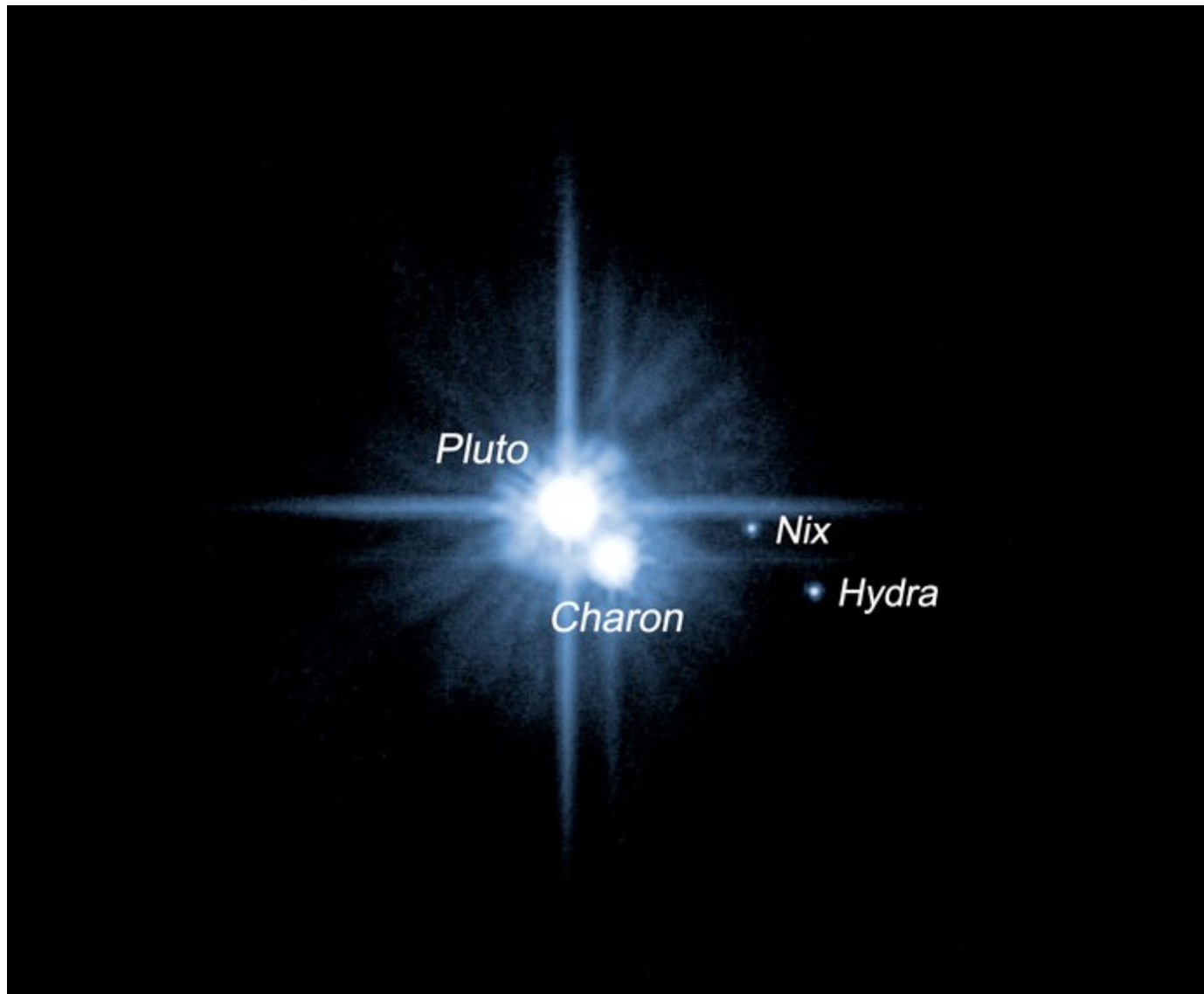
Aerothermal Performance Constraint (APC) Regimes*



* From Kolodziej, et al, NASA ARC

SOME WAVERIDER AGA ISSUES

- **ACTUAL L/D PERFORMANCE**
- **HEATING**
- **NAVIGATION ERRORS**
- **GUIDANCE AND CONTROL**
- **SCIENCE ACCOMMODATION**



References

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4. Longuski, J., "Can AGA through the Venusian Atmosphere Permit a Near Radial Trajectory into the Sun?", JPL Engineering Memorandum 312/82-133, December, 1982.
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6. Randolph, J. E., and McDonald, A. D., "Solar Probe Mission Status," *American Astronautical Society*, Paper 89-212, April 1989.
7. Lewis, M. J., "The Use of Hypersonic Waveriders for Aero-Assisted Orbital Maneuvering," *Proceedings of the 30th International Conference on Aviation and Space*, Tel Aviv, Israel, February 1990.
8. Lewis, M. J., and McDonald, A. D., "The Design of Hypersonic Waveriders for Aero-Assisted Interplanetary Trajectories," AIAA Paper 91-0053, January 1991.
9. McDonald, A. D., Randolph, J. E., "Hypersonic Maneuvering for Augmenting Planetary Gravity Assist," *AIAA Journal of Spacecraft and Rockets*, Vol. 29, No. 2, 1992.
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11. Gillum, M., Kammeyer, M., Burnett, D., "Wind Tunnel Results for a Mach 14 Waverider," AIAA Paper 94-0384, January 1994.