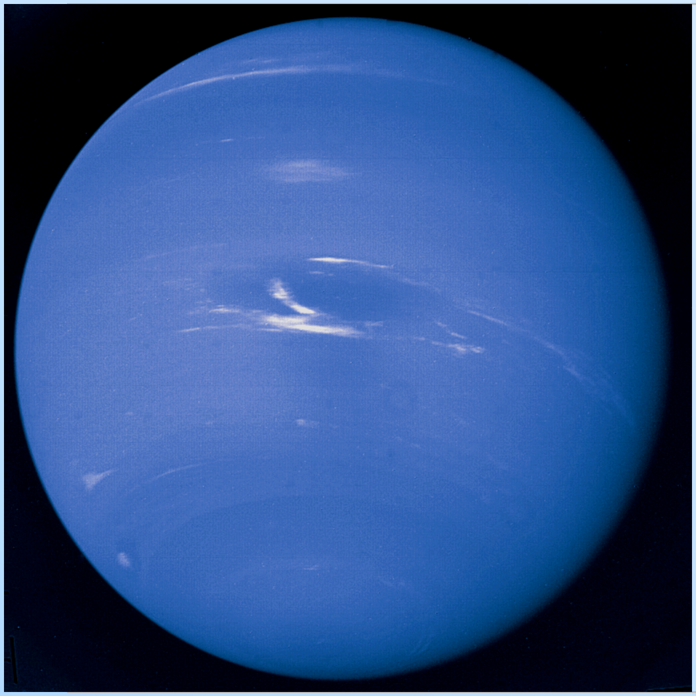
JPL Advanced MISSION STUDIES

Mission Design Aspects of Planetary Entry Probe Missions



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Organization

- The Technical Trade Space
- Entry Flight Path Angle and Speed
- Entry Probe Orbital Mechanics
- Interplanetary Transfer
- Cost of Changing Approach Parameters to Change Entry Location
- Summary

The Technical Trade Space

Science

- Descent Location & Visibility
- Data Return

Destination

- Location in Solar System
- Size & Shape
- Gravity Field (Mostly mass)
- Atmosphere Characteristics
  - Depth
  - Composition
  - Scale height
  - Rotation & Circulation (Winds)

$$H = \frac{RT}{\mathcal{M}g}$$

Orbital Mechanics

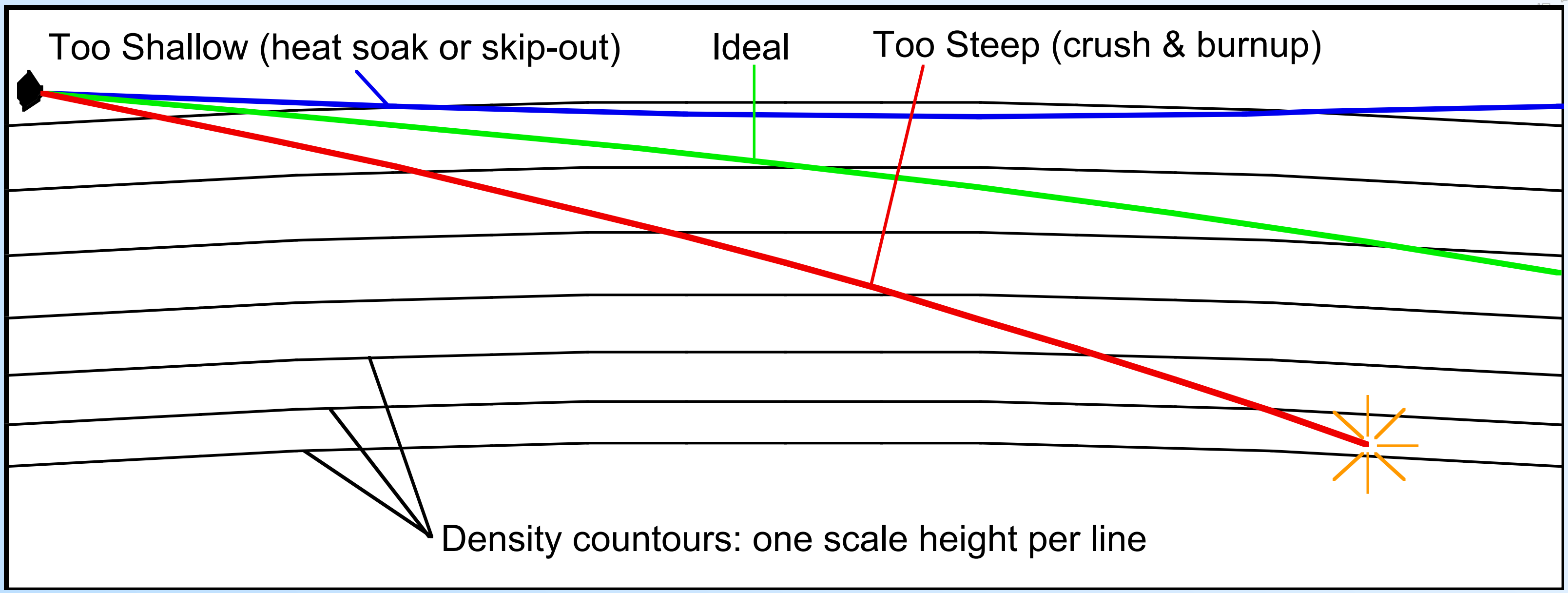
- "Rules of the Road": Physics
- "If you start *here*, here's where you *will* go and how you'll arrive"
- "If you start *here* and *do this*, here's where you *can* go and how you'll arrive"

Technology

- Sets the envelope of tolerable conditions
- Many-dimensional envelope
  - T, P, composition, Mach number, deceleration rate, duration, etc.
- Gives system requirements for tolerating conditions
  - Mass, geometry, control, power

Entry Flight Path Angle and Speed

Proper Entry Flight Path Angle



$$F = \frac{1}{2} C_D A \rho V^2 \qquad a = \frac{F}{m} = \frac{1}{2} \frac{C_D A \rho V^2}{m} \qquad P = F V \text{ (Power } \alpha \text{ heat rate)}$$

- Entering at much too shallow an angle causes skip-out; slightly too shallow results in greatly increased descent location error and longer heat pulse
- Entering too steeply causes large ρ to be encountered while V is still too high -- results in large inertial forces and high heating rates
- Proper entry angle is a function of entry speed, atmosphere composition, vertical density profile (scale height), ballistic coefficient, and heat shield capabilities

Proper Entry Flight Path Angle

For a given entry probe, destination, and approach trajectory, the range of survivable entry flight path angles is called the *entry corridor*.

Generalizations about entry corridors

The more demanding the entry, the narrower the entry corridor

- What makes an entry more demanding? Three primary culprits:
  - High entry speed
  - Small atmospheric scale height
  - Encounter a solid surface at relatively low atmospheric densities

Overbuilding the heatshield (and probe structure) expands the entry corridor

- Can survive the greater heating rate and higher inertial loads of steeper entry
- Can insulate against the longer-duration heat soak of shallower entry

However ...

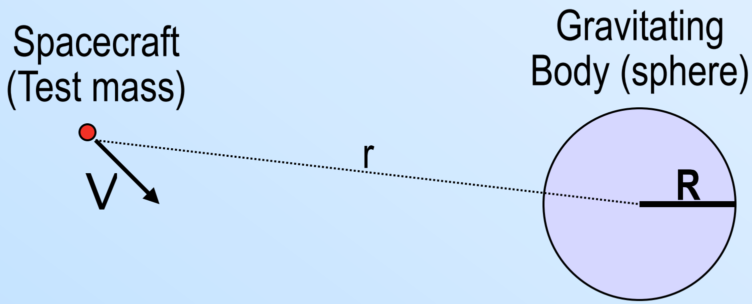
The more demanding the entry, the less extra entry corridor overbuilding buys!

Destinations with wide feasible entry corridors: Venus, Titan

Destinations with narrow feasible entry corridors: Mars, giant planets

Probe Orbital Mechanics

Motion in a Central Force Field



$$\mu = G \cdot M$$

Specific Potential Energy = $\dfrac{E_p}{m} = -\dfrac{\mu}{r}$

Specific Kinetic Energy = $\dfrac{E_k}{m} = \dfrac{|V|^2}{2}$

Specific Mechanical Energy **:**

$$\boxed{E_b = \frac{E_k}{m} + \frac{E_p}{m} = \frac{|V|^2}{2} - \frac{\mu}{r}}$$

E_b is *a constant of the orbit*

If $E_b > 0$, the orbit is hyperbolic (unbound); = 0, the orbit is parabolic (unbound);
< 0, the orbit is elliptical or circular (bound)

Knowing E_b allows calculation of the test mass's speed for any r:

$$\boxed{V(r) = \sqrt{2\left(E_b + \frac{\mu}{r}\right)}}$$

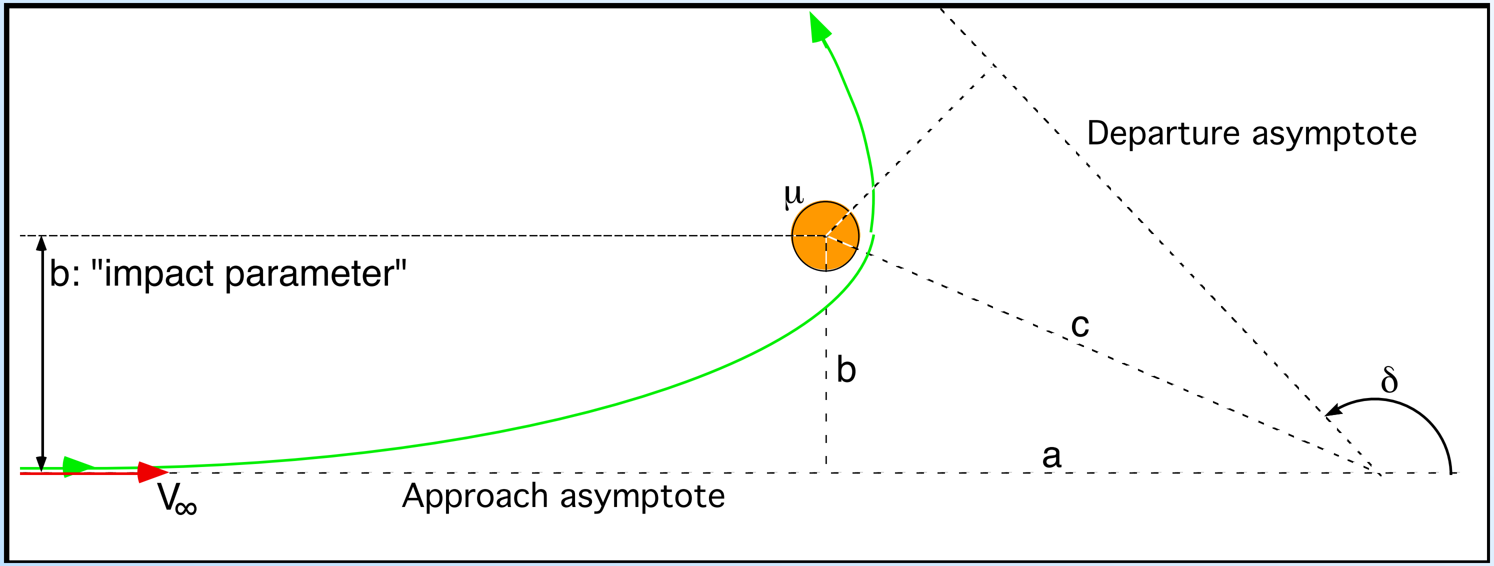
When r is sufficiently large that

$$\frac{\mu}{r} <<< \frac{|V|^2}{2}$$

the central object's gravity is not affecting the test mass's velocity significantly, and the velocity vector is the test mass's *V-infinity*, or V_∞, and E_b is just

$$E_b = \frac{|V_\infty|^2}{2} \quad \text{so} \quad \boxed{V(r) = \sqrt{V_\infty^2 + \frac{2\mu}{r}}}$$

Motion in a Central Force Field: Hyperbola



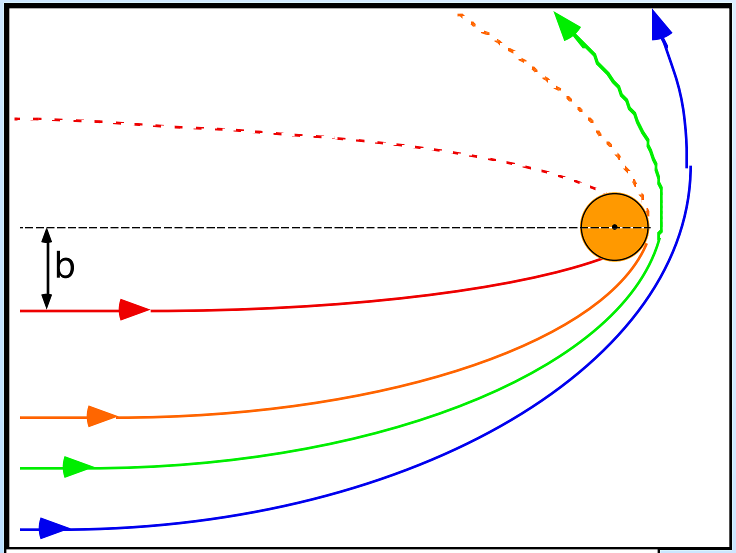
An hyperbola in a plane is defined by three characteristics: shape, size, and orientation

- Shape is specified by the eccentricity e, which is larger than unity; it sets *bending angle* δ
- Size is specified by any of the dimensions a, b, or c
- Orientation is specified by the direction of one of the asymptotes

V_∞, b, and μ completely define an hyperbolic trajectory

$$a = \frac{\mu}{V_\infty^2} \qquad e = \sqrt{1 + \left(\frac{V_\infty^2 b}{\mu}\right)^2}$$

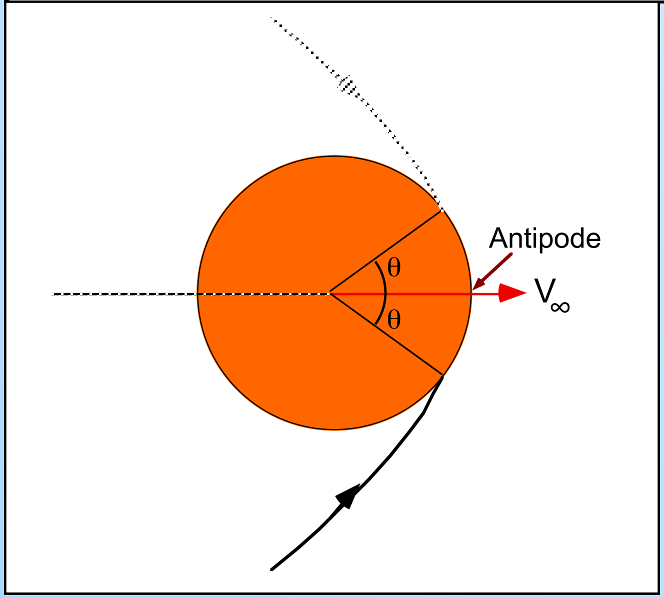
Motion in a Central Force Field: Hyperbola



For a given destination, and for a given magnitude and direction of V_∞, changing b changes the eccentricity of the resulting hyperbolic trajectory.

For larger values of b, the trajectories do not impinge on the planet's atmosphere. For smaller b they do, and the value of b sets the entry flight path angle.

A narrow range of b targets the proper entry corridor.

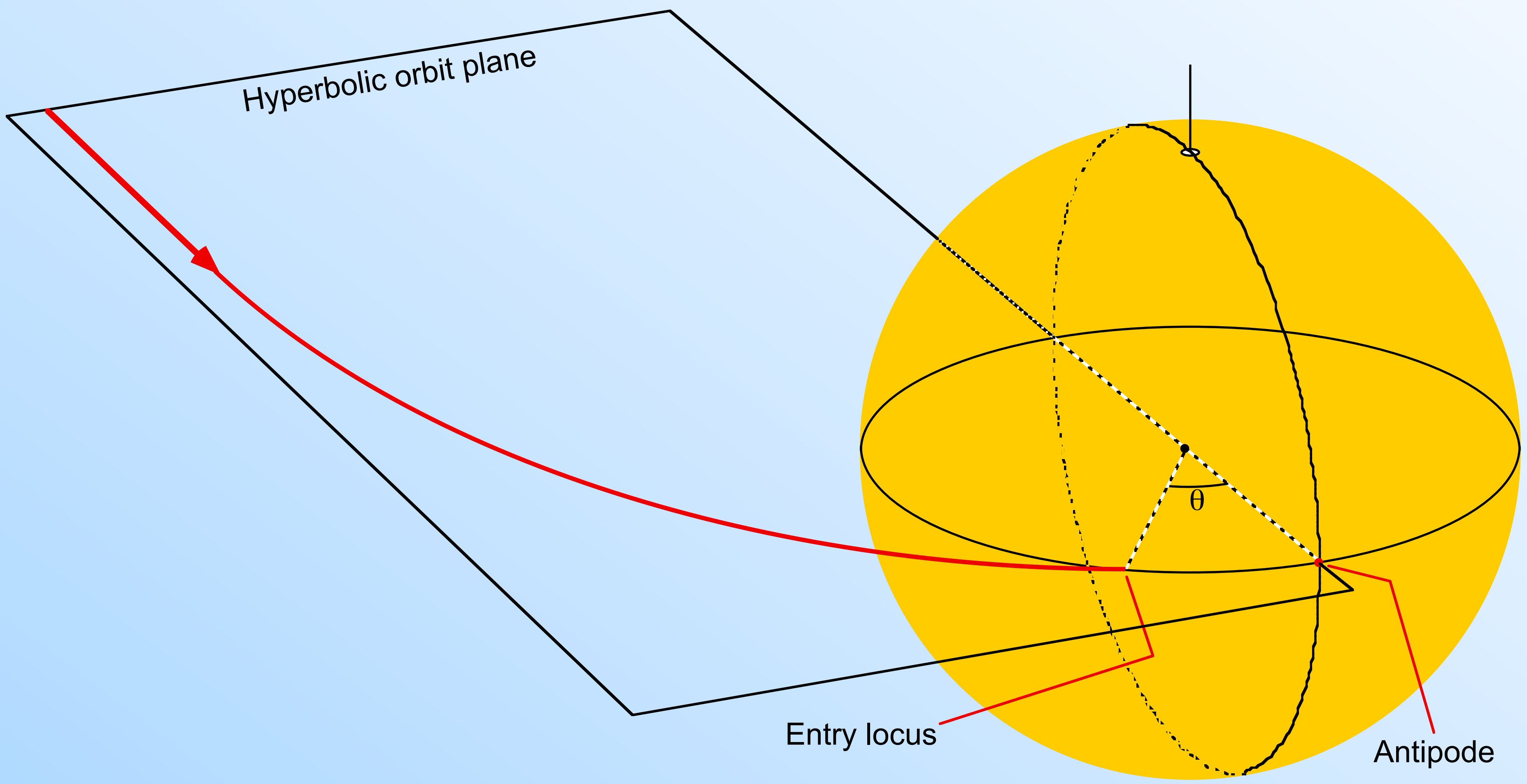


A V_∞ vector parallel-transported to the planet's center intersects the planet's "surface" at a point called the *antipode*.

As seen from the planet's center, the entry locus is offset from the antipode by the angle θ. This geometry is symmetrical about the line through the V_∞ vector.

$$\theta = \frac{1}{2}(\pi - \delta)$$

Motion in a Central Force Field: Hyperbola



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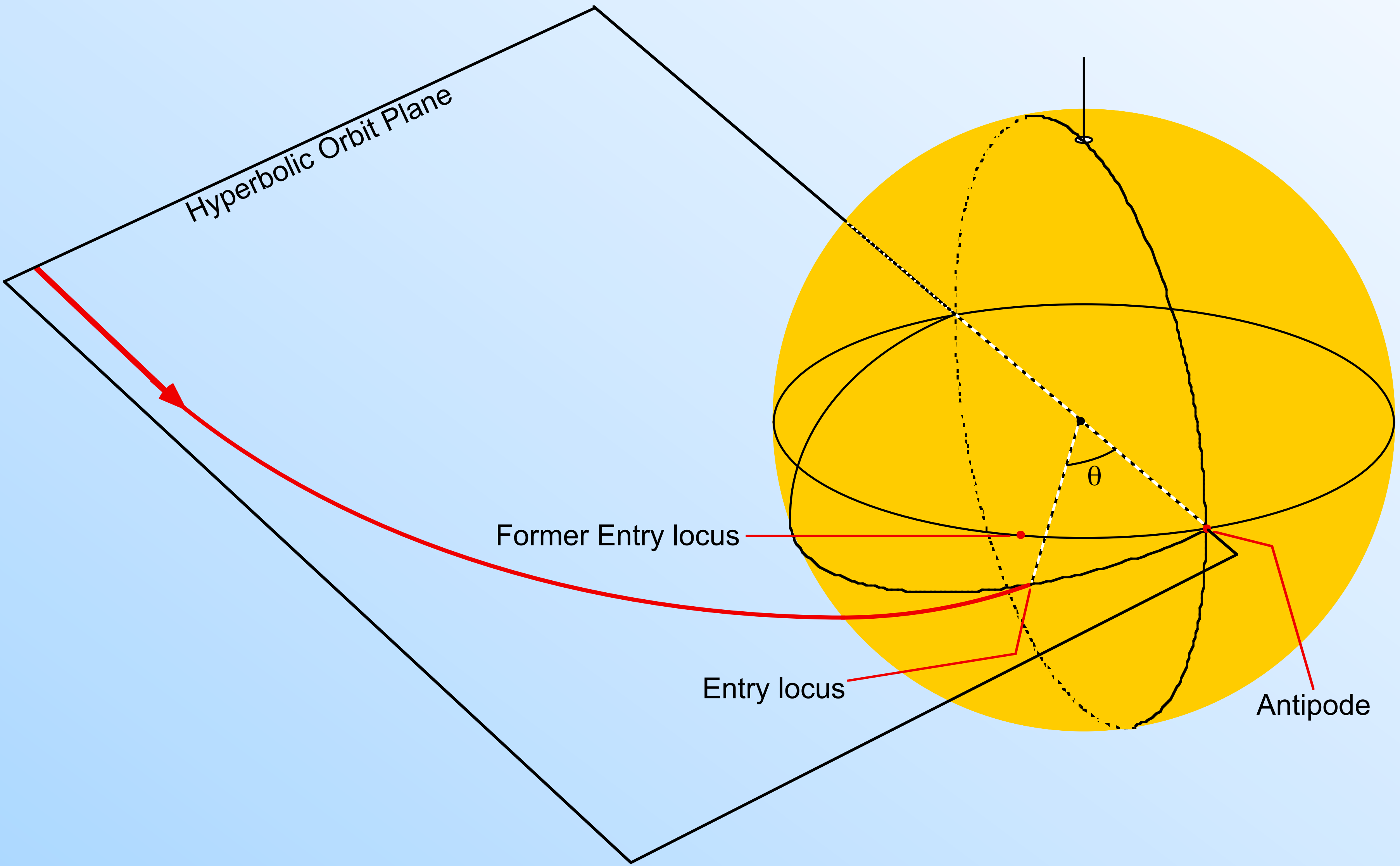

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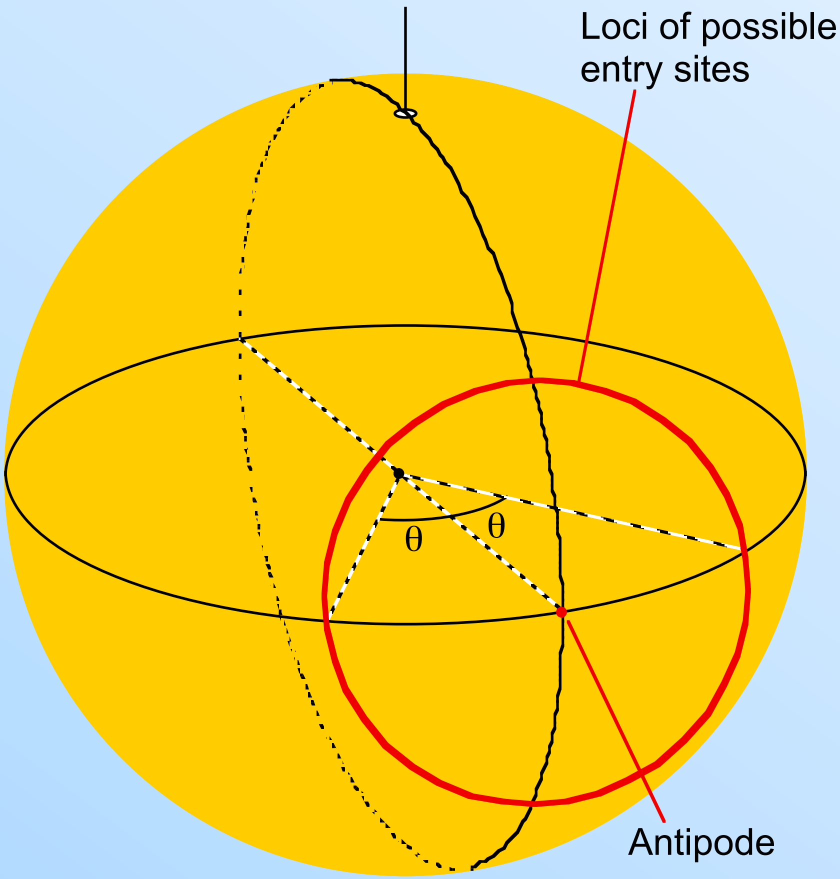


The loci of entry sites with the proper entry flight path angle define (roughly) a circle centered on the antipode with central angle θ.

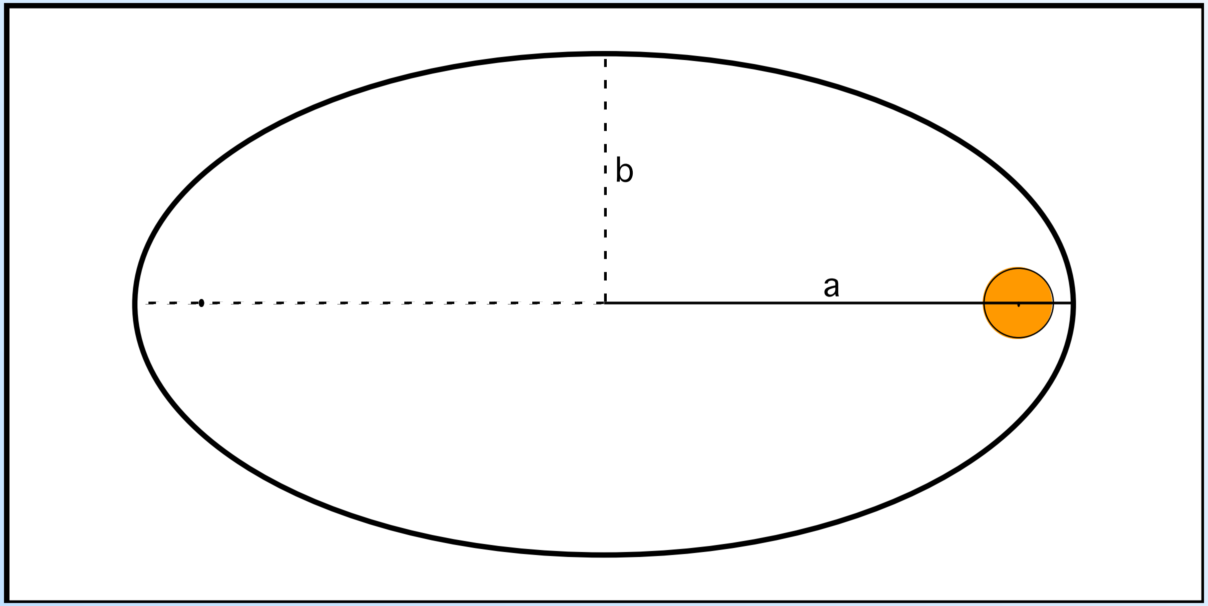
Various characteristics of the planet cause deviations of this set of loci from circular

- Planetary rotation
- Planetary shape

Planetary rotation can cause some or most of the circle to be unusable due to high entry speeds.

In general, the antipode will *not* be at the planet’s equator.

Motion in a Central Force Field: Bound Orbits



A bound orbit around a spherically symmetrical primary is either an ellipse or a circle, which is a degenerate case of an ellipse. The primary is at one focus of the ellipse.

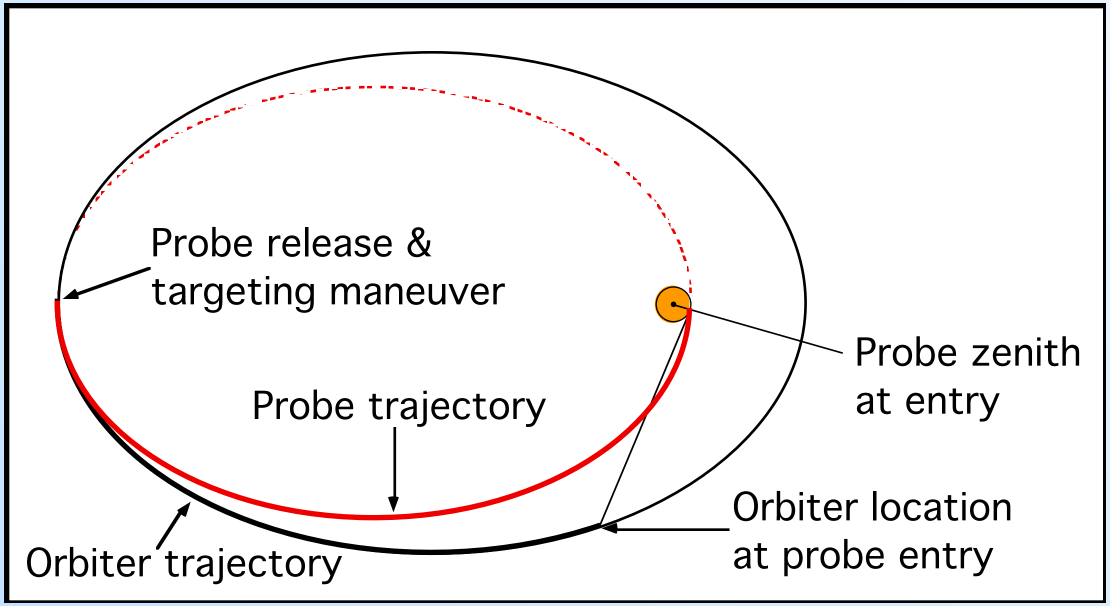
Like the hyperbola, the shape parameter is eccentricity, ranging from 0 to 1.

The principal size parameter is the semi-latus rectum, *a*.

The parameter *a* determines the orbit period, *independent of shape*:

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

Motion in a Central Force Field: Bound Orbits



Assume an orbiter, carrying an entry probe, in an eccentric orbit. To enter the atmosphere, the probe must decrease one of its orbit dimensions to bring it into the atmosphere; this is easiest done at periapse, by slowing the probe at apoapse

But in doing so, the probe's new orbit has *a* smaller than the orbiter's, and thus has a shorter period.

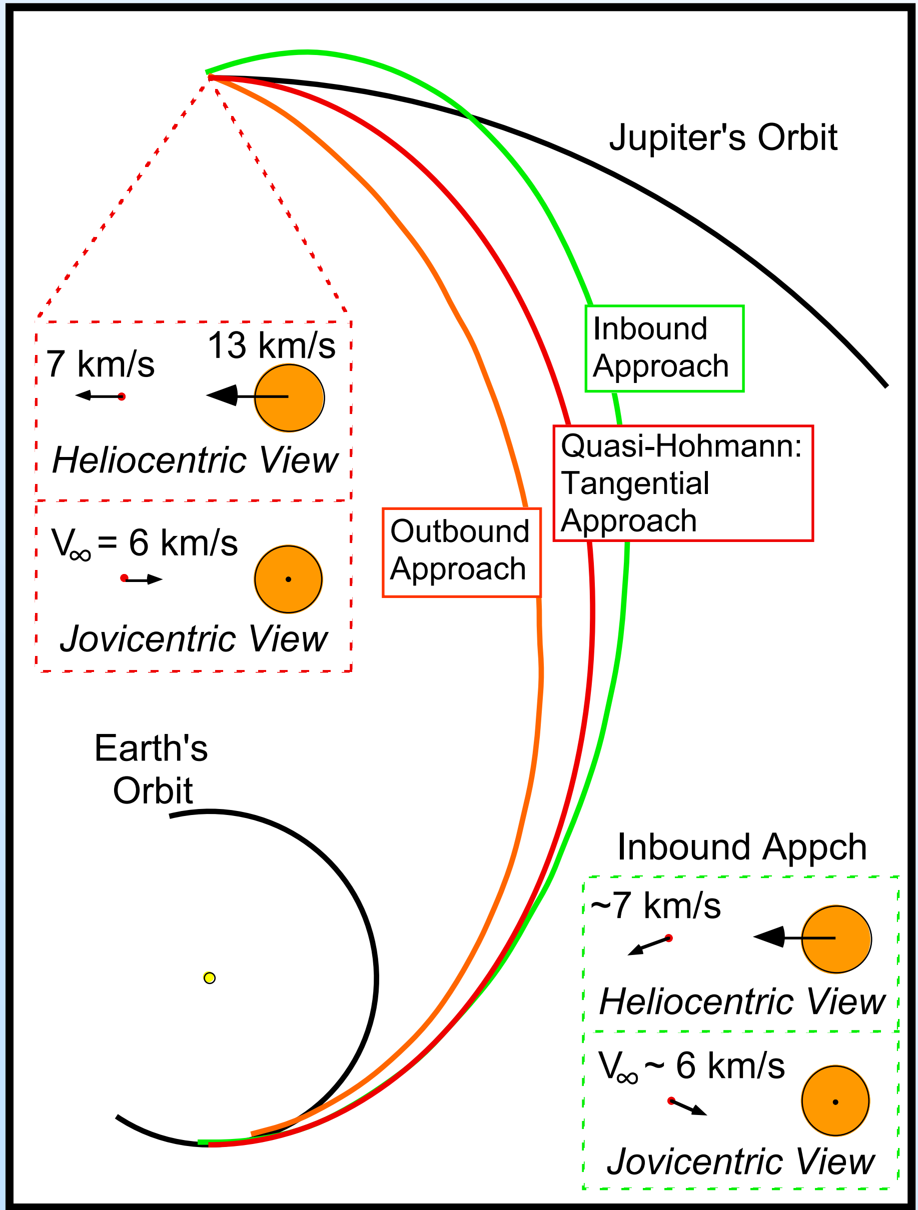
When the probe reaches the atmosphere, essentially half a period after deboost, the orbiter has traversed considerably less than half a period. By being closer to the primary, the probe accelerates faster than the orbiter.

If the orbiter's apoapse is sufficiently high, the probe can't see the orbiter at entry!

Interplanetary Transfer

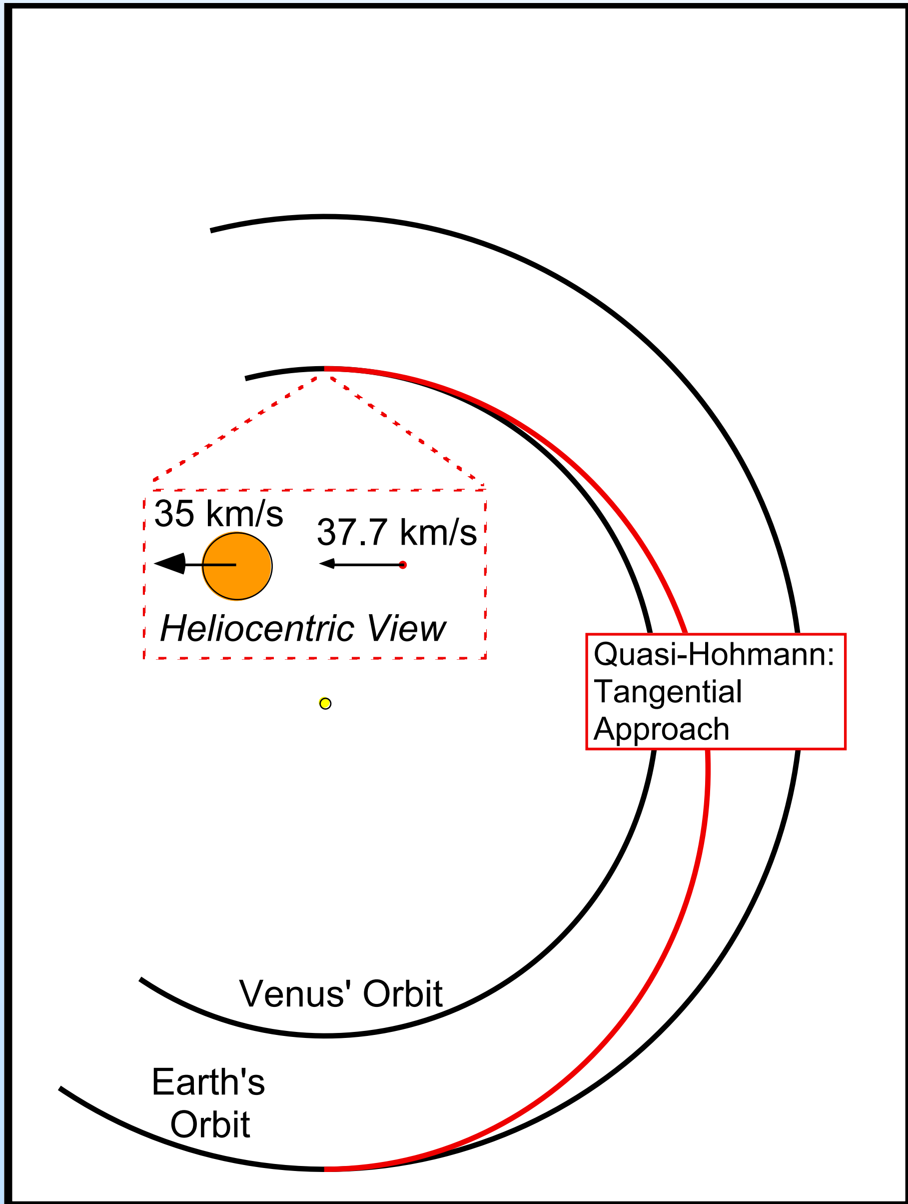
Interplanetary Transfer: Outward

- An Earth-to-Jupiter trip serves as an outward transfer example
- Transfer orbits' perihelia are near the Sun (~1 AU in this diagram) because, near Jupiter, the S/C are moving slower than Jupiter
- Jupiter *overtakes* the S/C; in the tangential approach case it appears to approach Jupiter from the direc-tion Jupiter is heading (dawn side)
- An outbound approach turns the approach V_∞ outward slightly; likewise for an inbound approach
- Outbound takes less time than the tangential; inbound takes more
- This general description holds for all planets farther from the Sun than Earth



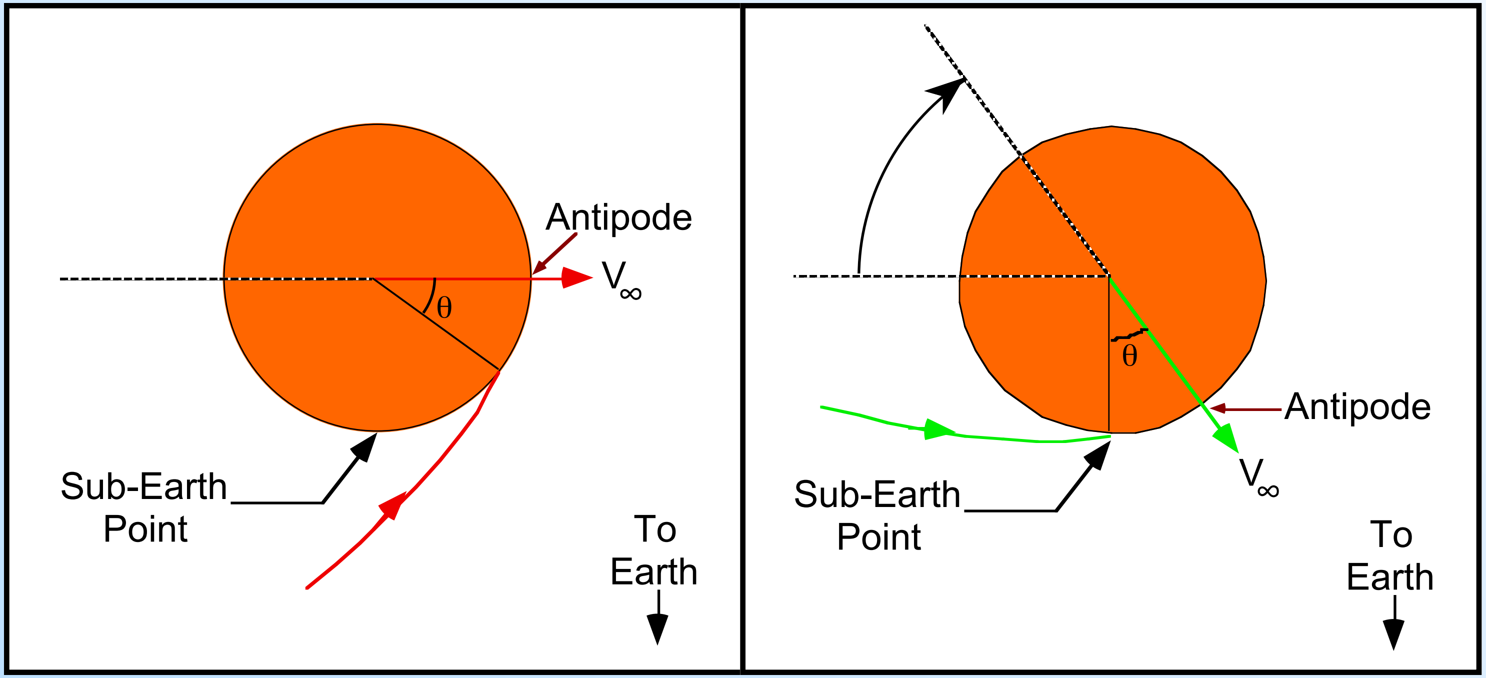
Interplanetary Transfer: Inward

- An Earth-to-Venus trip is the only useful example of inward transfer
- Transfer orbit's aphelion is ~1 AU because, near Venus, the S/C is moving faster than Venus
- The S/C overtakes Venus; it approaches Venus from opposite the direction Venus is heading (dusk side)
- Desirable probe entry location for DTE data communications uses a very steep entry



Cost of Changing Approach Parameters

Cost of Changing Approach Parameters



Consider the delta-V cost of moving a Jupiter entry location to the sub-Earth point for DTE communications.

The left panel shows the minimum-energy transfer and resultant entry point. The right panel shows rotating that approach trajectory to yield a sub-Earth entry. Since q is ~30 deg, the rotation is ~60 deg. Rotating V_∞ 60 deg is a *6 km/s delta-V!*

Using an inbound approach can reduce the required rotation by ~15 deg, but the required delta-V is still ~4 km/s, *more than a single bipropellant stage delivers!*

Summary

- For a standard hyperbolic approach to probe entry, the V_∞ vector largely determines feasible entry sites
  - Venus and Titan offer much more flexibility than Mars or the giant planets
- The interplanetary transfer trajectory determines the unmodified (by propulsive maneuver) approach V_∞ vector
- Changing the approach V_∞ vector via a propulsive maneuver requires large, often prohibitive, delta-V
- Delivering probes from an orbiting vehicle involves problems with view geometry
  - Solving the view geometry problem usually involves large delta-V

Questions?