Patched Conics
...or...
let Gravity Assist you

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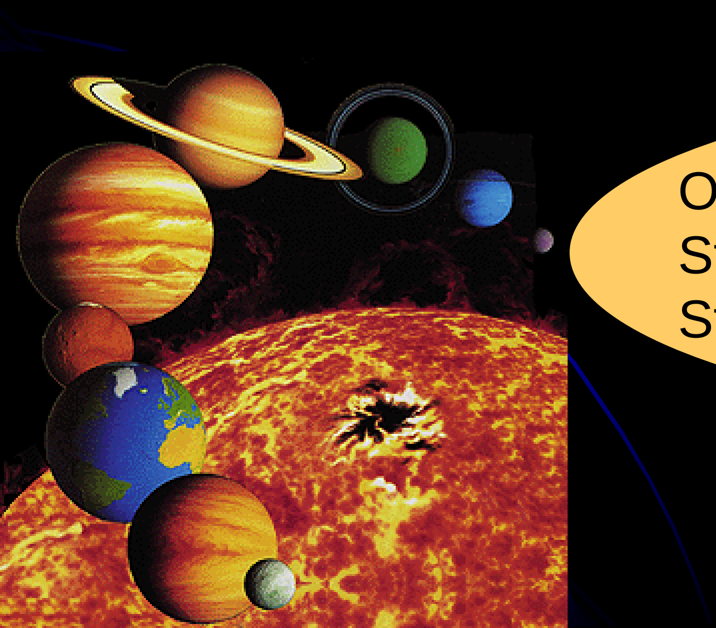
Trajectory design

Astrodynamics = part of Celestial Mechanics dealing with the design of s/c trajectory for space missions (geocentric, interplanetary)



Observation of planets and their satellites
Study of minor bodies (asteroids,comets)
Study of interplanetary environment, incl. the Sun

Building a trajectory means...

Fundamental ingredient is GRAVITY (n-body problem)

BUT

Design involves other parameters and constraints:
launcher capab., time of flight, number and size of orb. manouvres, phase angles, distances of closest approach, relative speed, ecc.

Preliminary Design

First step: feasibility study based on a simplified dynamical model: “restricted” two body problem (Sun-Planet, Sun-s/c)
and constraints.

Second step: optimization

Third step: full n-body model and other effects

Keplerian orbits

From N to 2 bodies…

The general solution of the N body problem requires 6N independent functions, one for each coordinate of position and velocity, with 6N constants of integration.

$$\vec{r}_i = \vec{r}_i(t, \vec{a})$$

$$\dot{\vec{r}} = \dot{\vec{r}}_i(t, \vec{a})$$

This is equivalent to finding 6N first integrals of the sytem, i.e., 6N independent functions of the dynamical variables (and time) which remain constant over the trajectory in phase space

$$f_j(\vec{r}_i, \dot{\vec{r}}_i, t) = c_j (j = 1, 2, \ldots, 6N)$$

We only know a total of 10 first integrals for any N>= 2

$$\sum_{i=1}^{N} m_i \ddot{\vec{r}}_i = 0 \Rightarrow \sum_{i=1}^{N} m_i \vec{r}_i = \vec{p}t + \vec{q}$$

$$\sum_{i=1}^{N} m_i \vec{r}_i \times \dot{\vec{r}}_i = \vec{h}$$

$$\frac{1}{2}\sum_{i=1}^{N} m_i \dot{\vec{r}}^{\,2} - G\sum_{i=1}^{N}\sum_{j=1}^{i-1} \frac{m_i m_j}{r_{ij}} = E$$

For N= 2 the general solution of the 6N differential equations ESISTS

It is related to the 3 Kepler's laws of planetary motion for which it provides a physical interpretation:

1) The orbit of every planet is an ellipse (planar curve) with the Sun at one focus

2) A line joining the planet and the Sun sweeps out equal areas during equal intervals of time

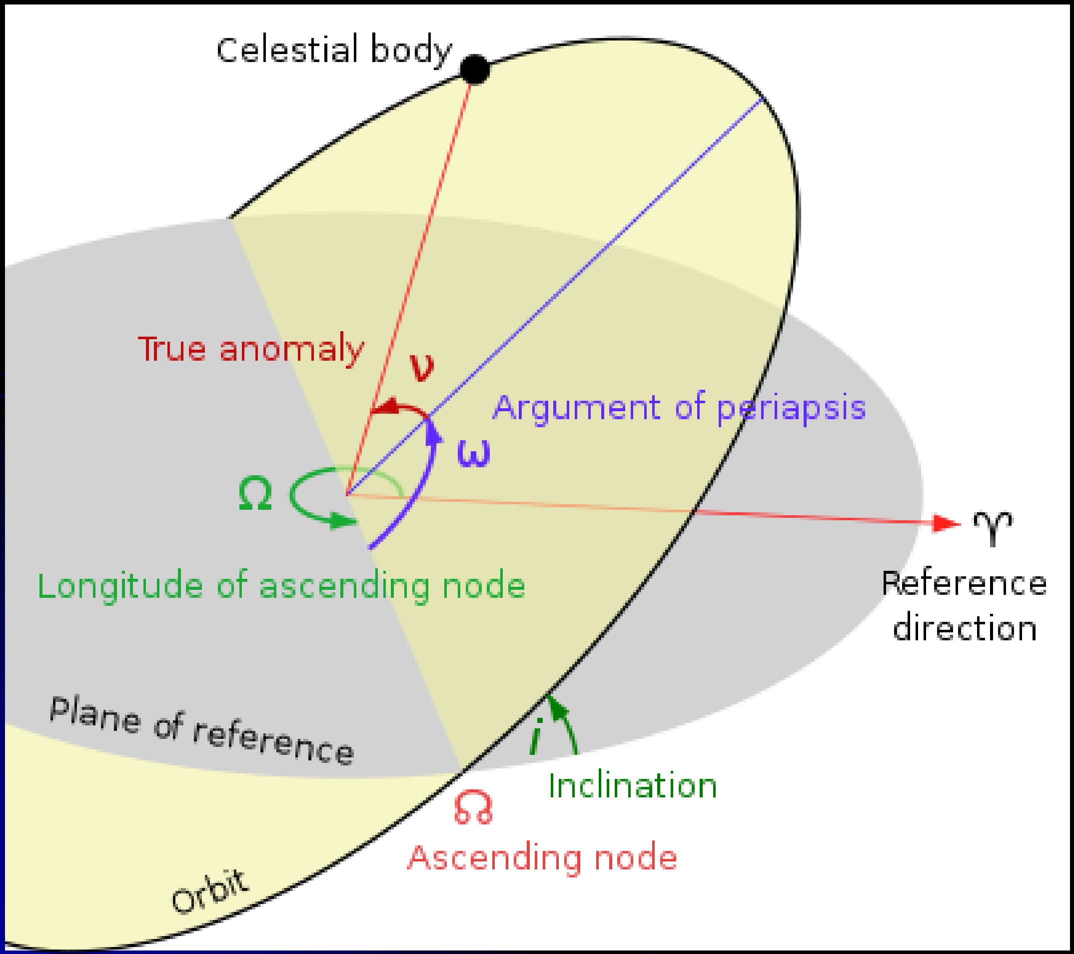
3) The square of the orbital period of a planet is directly proportional to the third power of the semi-major axis of its orbit. The constant of proportionality is the same for all the planets

Orbital elements on the elliptic orbit

a, e define the shape

τ gives time "origin"

Ω, ω, i define the orientation in space



$$\{a, e, i, \Omega, \omega, \tau\} + f$$

$$\updownarrow$$

$$\{\mathbf{r}, \mathbf{v}\} + t$$

From orbital elements to state vector

$$p = a(1 - e^2)$$

$$r = \frac{p}{1 + e\cos f}$$

Solution of
Kepler's equation

$$v_r = \sqrt{\frac{\mu}{p}} e \sin f$$

$$v_t = \sqrt{\frac{\mu}{p}} (1 + e\cos f)$$

$$b_x = \cos\Omega\cos(\omega + f) - \sin\Omega\sin(\omega + f)\cos i$$

$$b_y = \sin\Omega\cos(\omega + f) - \cos\Omega\sin(\omega + f)\cos i$$

$$b_z = \sin(\omega + f)\sin i$$

$$c_x = \cos\Omega\sin(\omega + f) + \sin\Omega\cos(\omega + f)\cos i$$

$$c_y = \sin\Omega\sin(\omega + f) - \cos\Omega\cos(\omega + f)\cos i$$

$$c_z = \cos(\omega + f)\sin i$$

$$x = r b_x$$

$$y = r b_y$$

$$z = r b_z$$

$$\dot{x} = v_r b_x - v_t c_x$$

$$\dot{y} = v_r b_y - v_t c_y$$

$$\dot{z} = v_r b_z - v_t c_z$$

From state vector to orbital elements

$$\vec{h} = \vec{r} \times \vec{v}$$

$$\frac{v^2}{2} - \frac{\mu}{r} = -\frac{\mu}{2a} \rightarrow a = \frac{r}{2 - \dfrac{rv^2}{\mu}}$$

$$\left.\begin{aligned} e\cos E &= 1 - \frac{r}{a} \\ e\sin E &= \frac{r\dot{r}}{\sqrt{\mu a}} \end{aligned}\right\} \rightarrow \left\{\begin{aligned} e &= \sqrt{(e\cos E)^2 + (e\sin E)^2} \\ E &= \tan^{-1}\left(\frac{e\sin E}{e\cos E}\right) \end{aligned}\right.$$

$$\Omega = \tan^{-1}\left(\frac{h_x}{-h_y}\right)$$

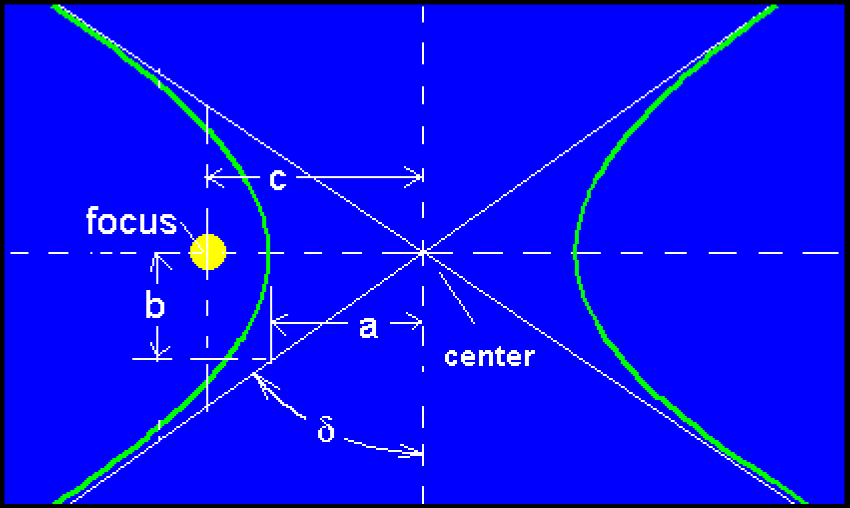
$$M = E - e\sin E \rightarrow \tau = t - \frac{M}{n}$$

$$i = \cos^{-1}\left(\frac{h_z}{h}\right)$$

$$f = 2\tan^{-1}\left(\sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2}\right)$$

$$\left.\begin{aligned} \cos(\omega + f) &= \frac{yh_x - xh_y}{hr\sin i} \\ \sin(\omega + f) &= \frac{z}{r\sin i} \end{aligned}\right\} \rightarrow \omega$$

Features and kinematical quantities of hyperbolas



$$f_\infty = \cos^{-1}\left(-\frac{1}{e}\right)$$

$$\cos\delta = \vec{v}_\infty^{+} \cdot \vec{v}_\infty^{-} \rightarrow \delta = \sin^{-1}\left(\frac{1}{e}\right)$$

$$v_\infty^2 = -\frac{\mu}{a}$$

$$e = 1 + \frac{r_p v_\infty^2}{\mu}$$

Types of transfers

- Direct transfer
- Multiple encounters trajectories

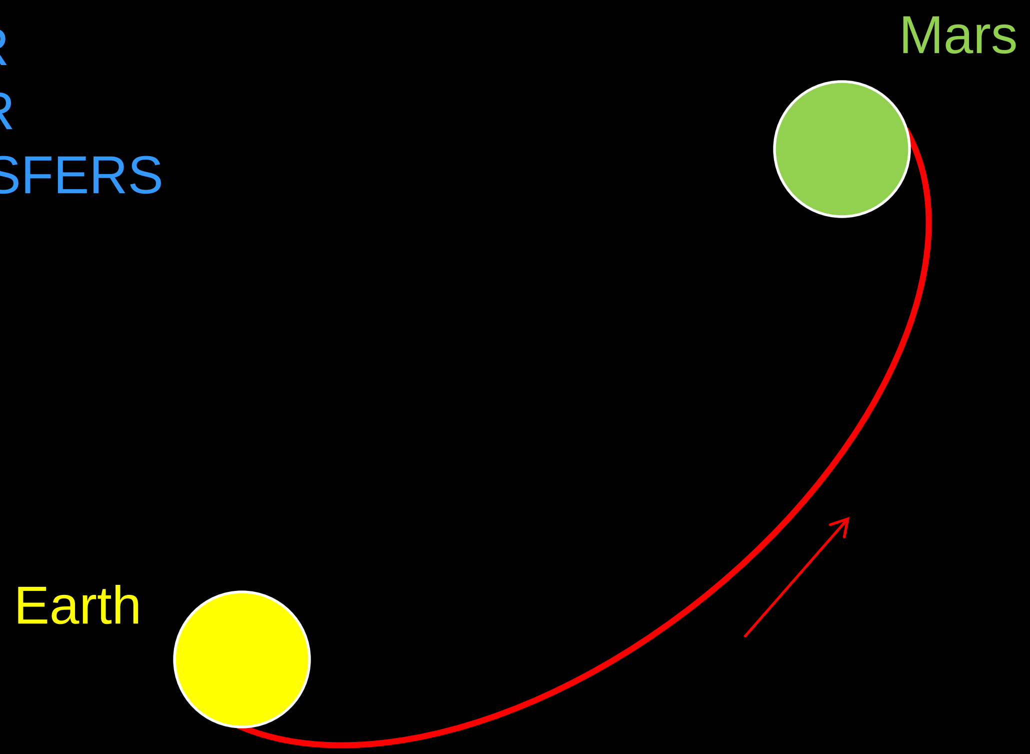
Powered

Ballistic

Direct transfers

Two point-masses orbiting the Sun on elliptic/circular orbits connected by one (or more) keplerian arc:

- HOHMANN TRANSFER
- BIELLIPTIC TRANSFER
- OUT-OF-PLANE TRANSFERS



Hohmann transfer

Transfer angle = 180 deg

Transfer time = $\pi\sqrt{\dfrac{a_H{}^3}{\mu_\odot}}$

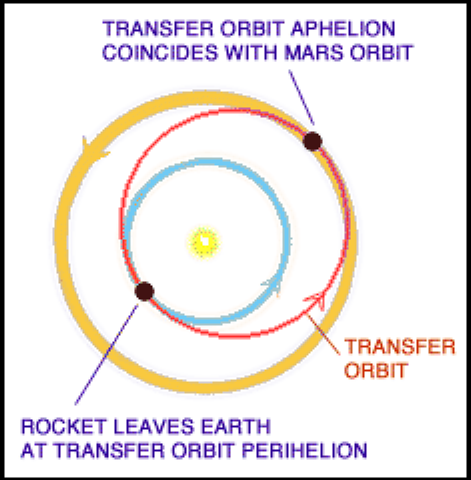
$$a_H = \frac{r_p + r_a}{2}$$

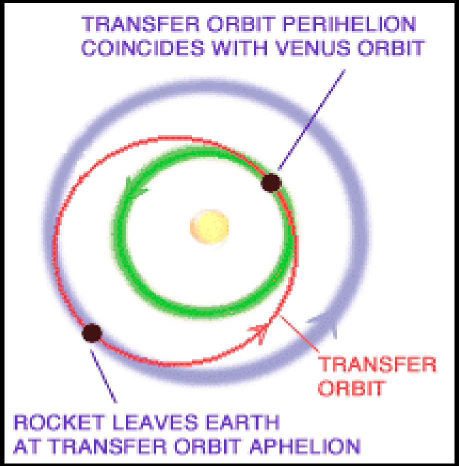
$$e_H = \frac{r_a - r_p}{r_p + r_a}$$

$$E_H = -\frac{\mu_\odot}{r_p + r_a}$$

$$\Delta v_p = \sqrt{\frac{\mu_\odot}{r_p}}\left[\sqrt{\frac{2r_a / r_p}{1 + r_a / r_p}} - 1\right]$$

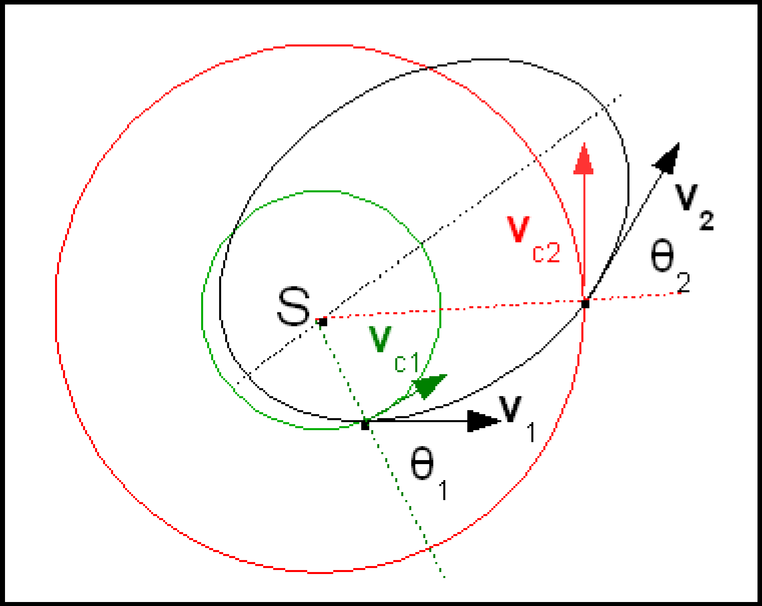
$$\Delta v_a = \sqrt{\frac{\mu_\odot}{r_a}}\left[1 - \sqrt{\frac{2}{1 + r_a / r_p}}\right]$$





Convenient only when ratio of planets radii ≤ 11.94

Optimality of Hohmann as a two-impulse transfer :



$$\vec{v}_1 : \begin{cases} v_{1t} = v_1 \sin\theta_1 \\ v_{1r} = v_1 \cos\theta_1 \end{cases}$$

$$\vec{v}_2 : \begin{cases} v_{2t} = v_2 \sin\theta_2 \\ v_{2r} = v_2 \cos\theta_2 \end{cases}$$

$$\Delta v = \Delta v_1 + \Delta v_2 = \sqrt{\left(v_1 \sin\theta_1\right)^2 + \left(v_1 \cos\theta_1 - v_{c1}\right)^2} + \sqrt{\left(v_2 \sin\theta_2\right)^2 + \left(v_2 \cos\theta_2 - v_{c2}\right)^2}$$

θ_1 and θ_2 that minimize Δv?

$$\frac{\partial \Delta v}{\partial \theta_1} = 0 \qquad \frac{\partial \Delta v}{\partial \theta_2} = 0$$

$$\theta_1 = \frac{\pi}{2}$$

This is Hohmann!!

$$\theta_2 = \frac{\pi}{2}$$

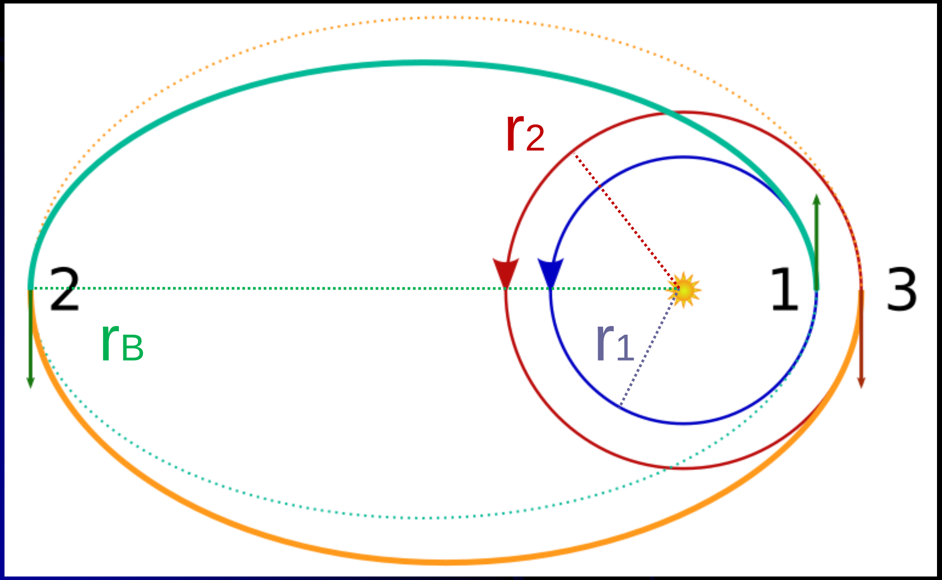
Bi-elliptic transfer

Three-impulse transfer between two circular orbits:

Outer: rB > r2
(Inner: rB < r2)

Trajectory consists of two half ellipses (1-2 and 2-3) :

$$a_1 = \frac{r_1 + r_B}{2} \qquad a_2 = \frac{r_2 + r_B}{2} \qquad T_B = T_1 + T_2 = \pi\sqrt{\frac{a_1^{\;3}}{\mu_\odot}} + \pi\sqrt{\frac{a_2^{\;3}}{\mu_\odot}}$$



$$\Delta v_1 = \sqrt{\frac{2\mu_\odot}{r_1} - \frac{\mu_\odot}{2a_1}} - \sqrt{\frac{\mu_\odot}{r_1}}$$

$$\Delta v_2 = \sqrt{\frac{2\mu_\odot}{r_B} - \frac{\mu_\odot}{2a_2}} - \sqrt{\frac{2\mu_\odot}{r_B} - \frac{\mu_\odot}{2a_1}}$$

$$\Delta v_3 = \sqrt{\frac{\mu_\odot}{r_2}} - \sqrt{\frac{2\mu_\odot}{r_2} - \frac{\mu_\odot}{2a_2}}$$

$$\Delta v_B = \Delta v_1 + \Delta v_2 - \Delta v_3$$

+ for inner
- for outer

$$y = \frac{r_b}{r_1} \qquad x = \frac{r_2}{r_1}$$

$$\Delta v_B(x,y) = \sqrt{\frac{\mu_\odot}{r_1}}\left[\sqrt{\frac{2y}{y+1}} - 1 + \sqrt{\frac{2}{x+y}}\sqrt{\frac{x}{y}} - \sqrt{\frac{2}{y(y+1)}} + \sqrt{\frac{2y}{x(x+y)}} \pm \frac{1}{\sqrt{x}}\right]$$

Outer bielliptic cheaper than inner bielliptic

$$\lim_{y\to\infty} \Delta v_B(x,y) = \sqrt{\frac{\mu_\odot}{r_1}}\left(\sqrt{2}-1\right)\left(1+\frac{1}{\sqrt{x}}\right)$$

(biparabolic transfer)

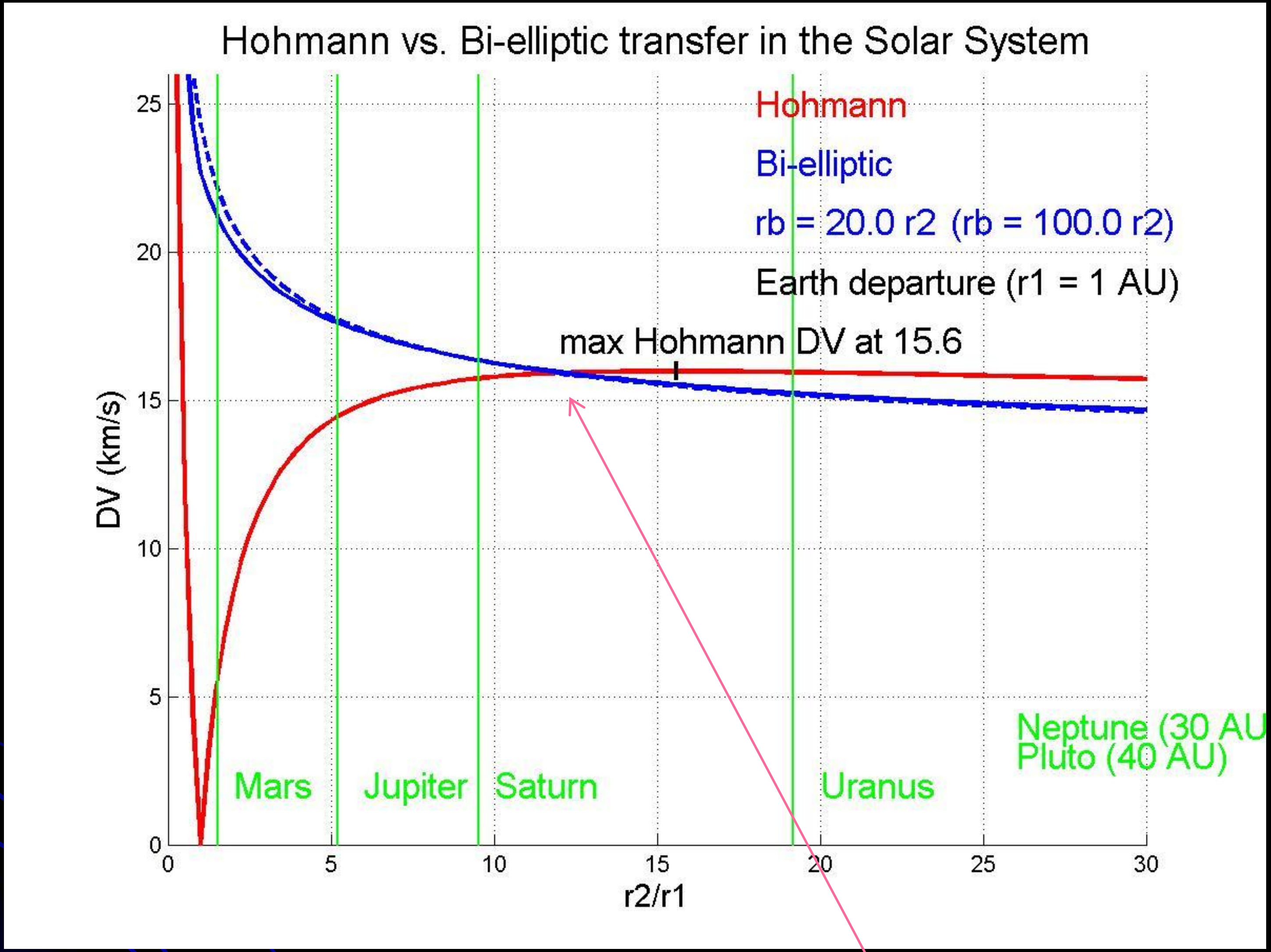
$$\Delta v_B(x,x) = \Delta v_H = \sqrt{\frac{\mu_\odot}{r_1}}\left[\sqrt{\frac{2x}{x+1}} - 1 - \sqrt{\frac{2}{x(x+1)}} + \sqrt{\frac{1}{x}}\right]$$

$$\Delta v_B(x, x+h) \simeq \Delta v_B(x,x) + \left.\frac{\partial \Delta v_B(x,y)}{\partial y}\right|_{y=x} \cdot h$$

Look for $\left.\frac{\partial \Delta v_B(x,y)}{\partial y}\right|_{y=x} < 0$

$$x > x_c \simeq 15.6$$

Bielliptic more efficient than Hohmann



$\Delta v_B(x,y) - \Delta v_H(x) = 0$ solve for x: $\boxed{\bar{x} = \bar{x}(y)}$

$$\lim_{y \to \infty} \bar{x}(y) = 11.94$$

To Mars:

Hohmann: $r_1 = 1$ AU; $r_2 = 1.52$ AU; $a_H = 1.26$ AU; t_H=258.9 d =8.6 m

$\Delta v = (2.95 + 2.65)$ km/s=5.6 km/s

Bielliptic: $r_b = 1.5 r_2$; $a_1 = 1.64$ AU; $a_2 = 1.91$ AU; t_1+t_2=864.76 d =28.8 m

$\Delta v = (5.35 + 2.25 + 2.30)$ km/s=9.9 km/s

To Venus:

Hohmann: $r_1 = 1$ AU; $r_2 = 0.72$ AU; $a_H = 0.86$ AU; t_H=146.0 d =4.9 m

$\Delta v = (2.50 + 2.71)$ km/s=5.21 km/s

Bielliptic: $r_b = 1.5 r_2$; $a_1 = 1.04$ AU; $a_2 = 0.90$ AU; t_1+t_2=351.21 d =11.7 m

$\Delta v = (0.60 + 2.43 + 3.34)$ km/s=6.38 km/s

To Uranus:

Hohmann: $r_1 = 1$ AU; $r_2 = 19.18$ AU; $a_H = 10.09$ AU; t_H=16.2 y

$\Delta v = (11.28 + 4.66)$ km/s=15.94 km/s

Bielliptic: $r_b = 1.5 r_2$; $a_1 = 14.89$ AU; $a_2 = 23.98$ AU; t_1+t_2=88.7 y

$\Delta v = (11.62 + 3.53 + 0.65)$ km/s=15.80 km/s

To the planets with Hohmann

Planet	Orbital radius	Orbital period	Synodical Period	a_H	t_H	ΔV
Mercury	0.390	87.96	0.32	0.70	0.29	16.99
Venus	0.723	224.68	1.60	0.86	0.40	5.21
Mars	1.524	686.98	2.14	1.26	0.71	5.60
Jupiter	5.203	11.86	1.09	3.10	2.73	14.44
Saturn	9.539	29.46	1.04	5.27	6.05	15.73
Uranus	19.180	84.07	1.01	10.09	16.02	15.94
Neptune	30.060	164.81	1.01	15.53	30.60	15.71
Pluto	39.530	247.70	1.00	20.27	45.61	15.50
units	AU	days/ years	years	AU	years	Km/sec

Transfer time: Lambert problem

Two-Point Boundary Value Problem

Sun + s/c: given P1 and P2, find the trajectory corresponding to a given transfer time

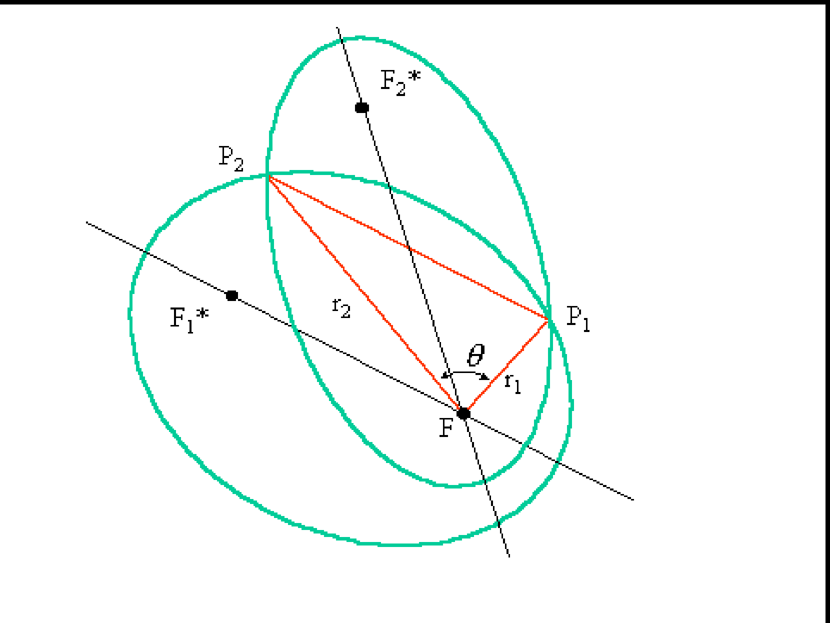
Lamber theorem:
$\Delta t = \Delta t\ (a, r_1 + r_2, c)$

↓

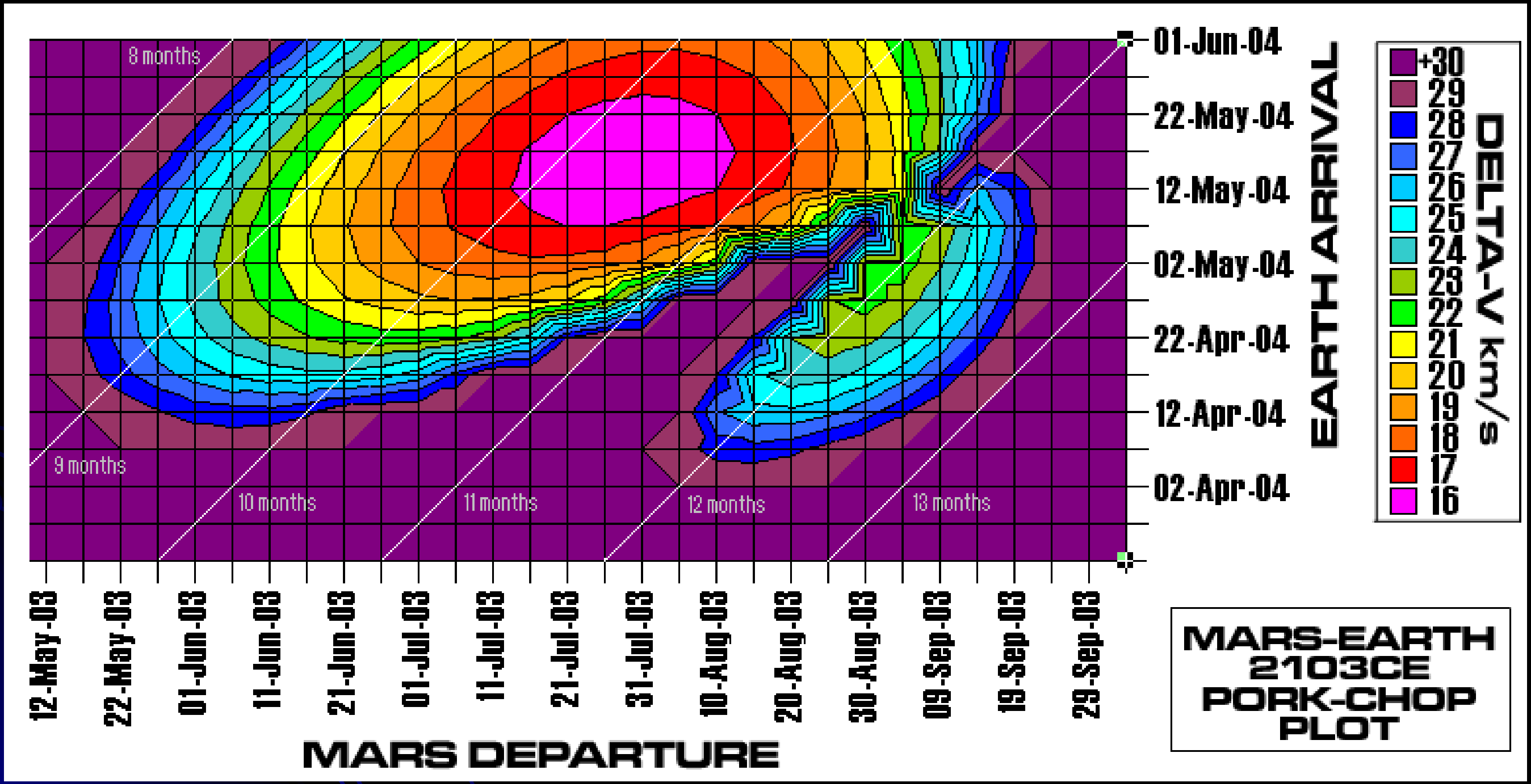
Transcendent equation

↓

Iterative solution



Launch opportunities



Designing interplanetary transfers involves a trade-off between FUEL (Δv) and TIME

Journeys to the nearest planets, Mars and Venus, can use Hohmann requiring very nearly the smallest possible amount of fuel, but slow (8 months from Earth to Mars)
-- RTBP libration point orbits use even less fuel, but are much slower--

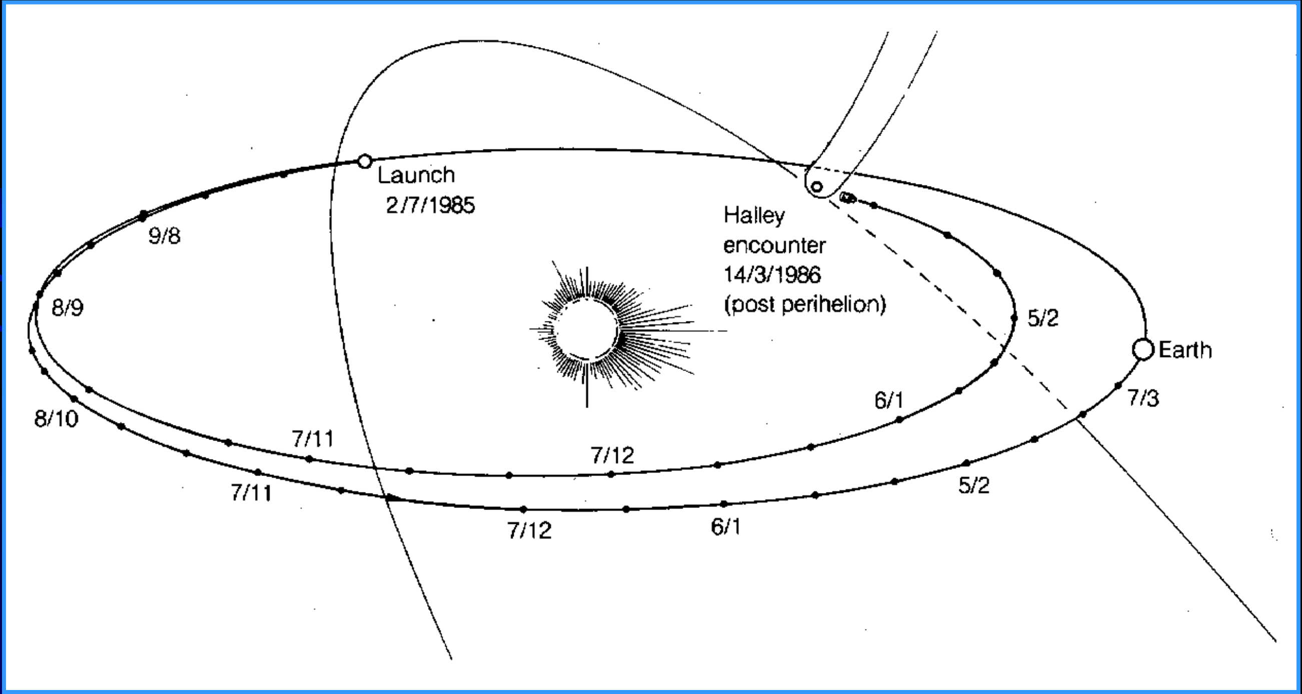
It might take decades for a spaceship to travel to the outer planets (Jupiter, Saturn, Uranus, etc.) using Hohmann and would still require far too much fuel

Gravitational slingshots offer a way to gain speed without using any fuel, and all missions to the outer planets have used it.

Types of encounter (1/3)

- FLYBY: with minor body, no grav. interaction, fast or with planet but fast and grav. interaction irrelevant

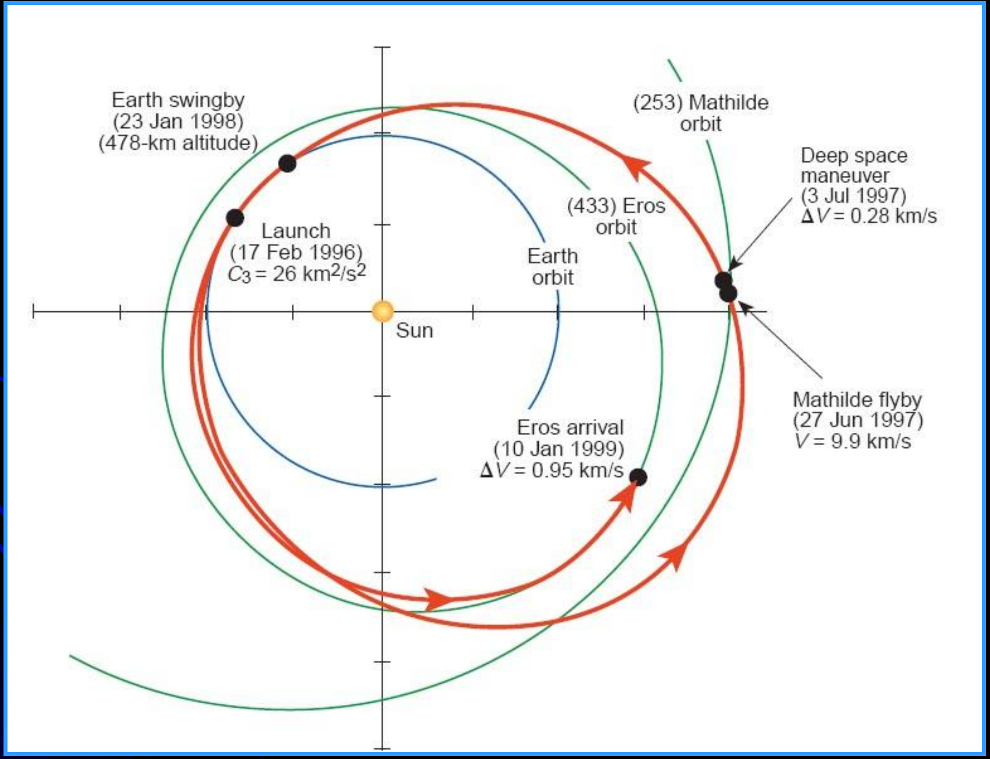
e.g., Giotto encounter with comet Halley in 1986
Relative speed 70 km/s at closest approach (600 km)



Types of encounter (2/3)

- RENDEZVOUS: with minor body, no interaction, slow, similar orbit as target body

e.g., NEAR (Near Earth Asteroid Rendezvous) with asteroid EROS in 1999



Types of encounter (3/3)

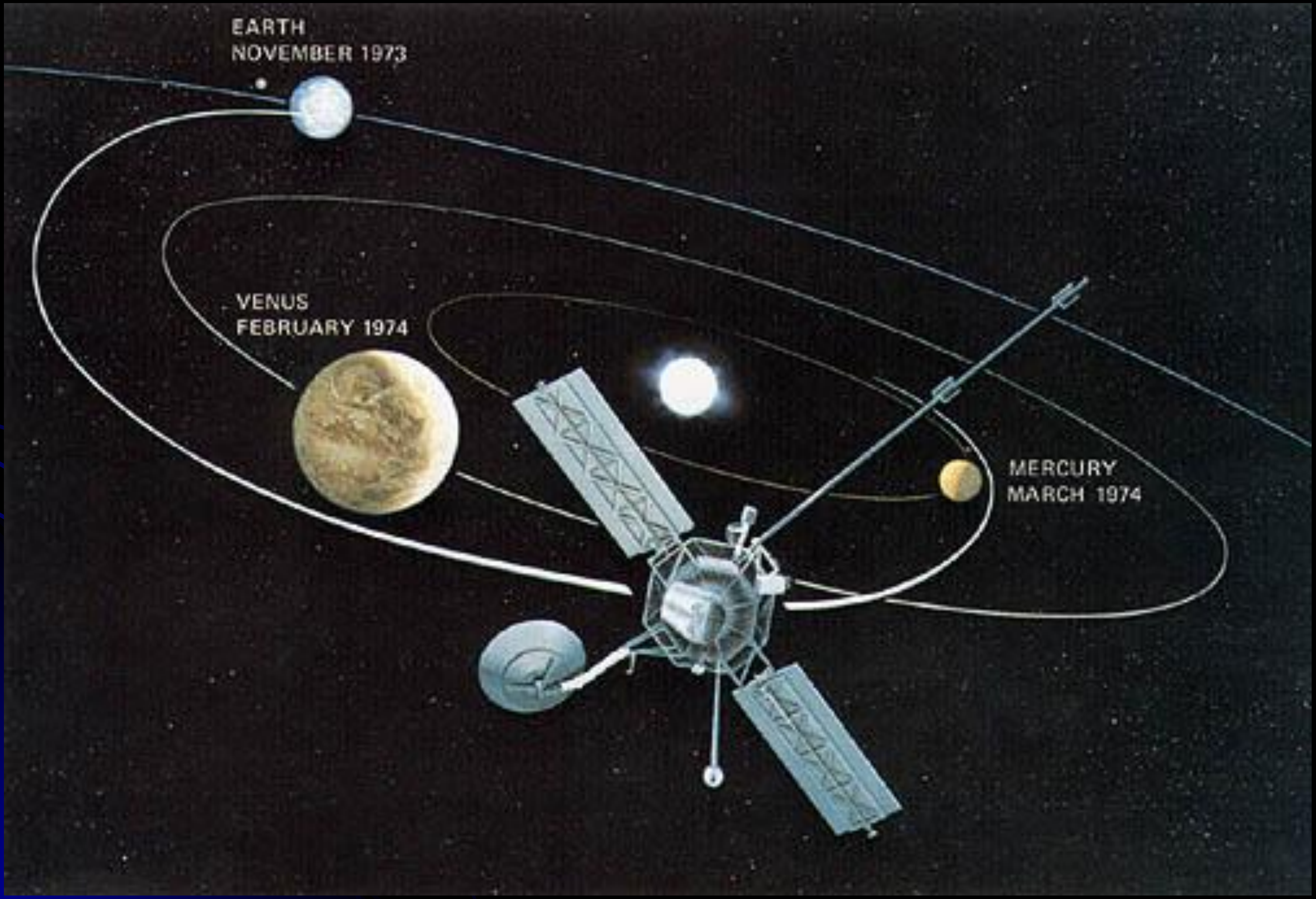
- SWINGBY = GRAVITY ASSIST = GRAVITATIONAL SLINGSHOT: with massive body (=planet), strong gravitational interaction which significantly perturbs the s/c orbit.

Exploits the relative movement between s/c and planet and the gravity of the planet to alter the path and speed of the s/c typically in order to save fuel and time.

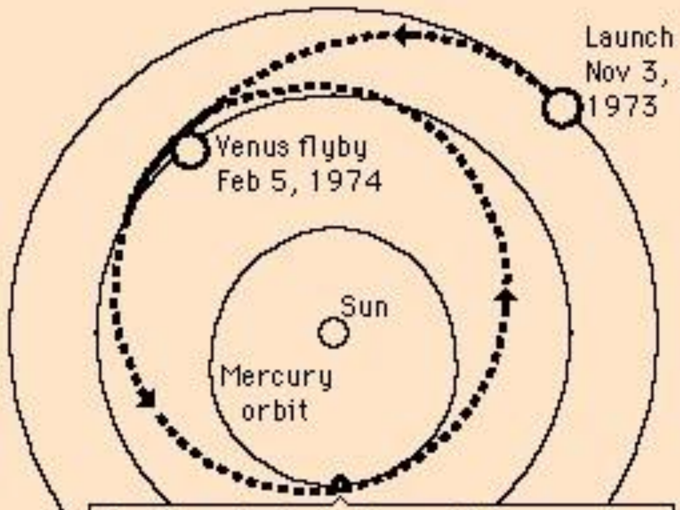
Gravity assists can be used to decelerate or accelerate the s/c

A BIT OF HISTORY and SOME EXAMPLES

- Mariner 10 & Giuseppe Colombo



Mariner 10 Slingshots

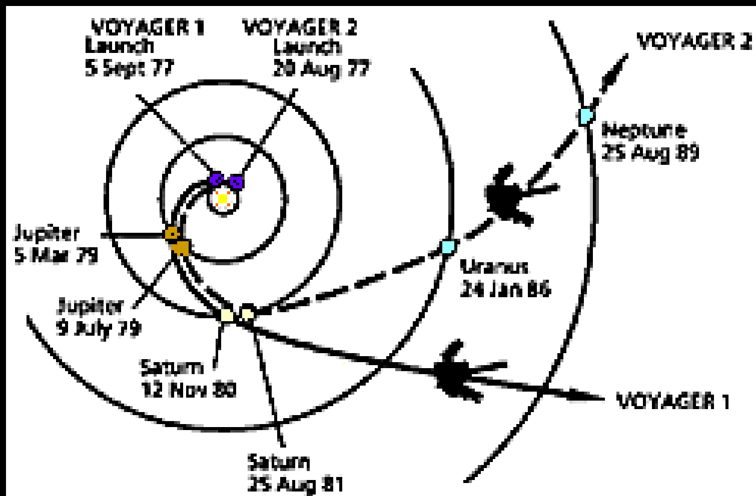


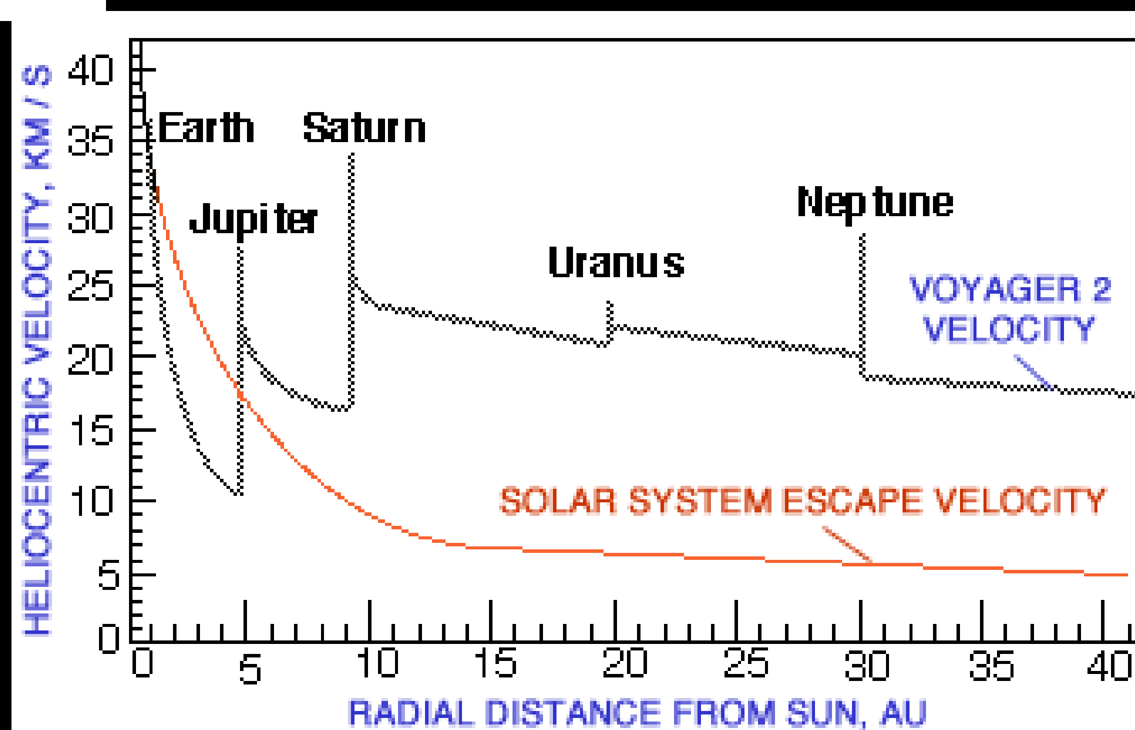
Synchronized gravity-assist maneuvers looped Mariner 10 past Venus and back to Mercury for flybys on Mar 29, 1974, Sep 21, 1974, and Mar 16, 1975. It is still executing the loops, but ran out of fuel to stabilize the craft after three loops.

When Mariner 10 passed by Venus on February 5, 1974 at a distance of 5770 km, it gained energy from the collision in what is called a slingshot maneuver. This was a particularly favorable maneuver, because the project directors discovered that the orbit could be fine tuned to loop around Mercury and back to Venus in twice Mercury's orbital period, so that it could loop back to look at Mercury again every second orbit. So instead of one look at Mercury, the Mariner craft got three flybys before its fuel ran out.

A great success wrt to the initially planned direct transfer to Mercury considered risky due to high-precision requirements of targeting

- Voyager 2 (Launch Sept. 1977, Neptune Aug. 1989)



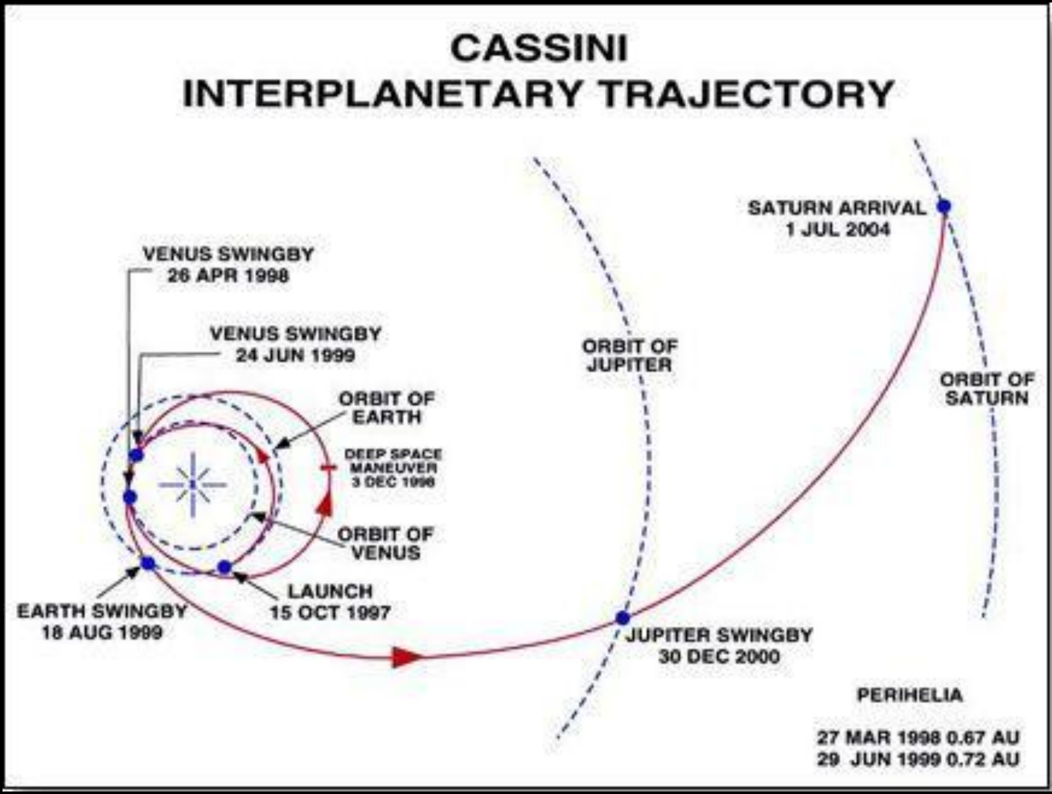


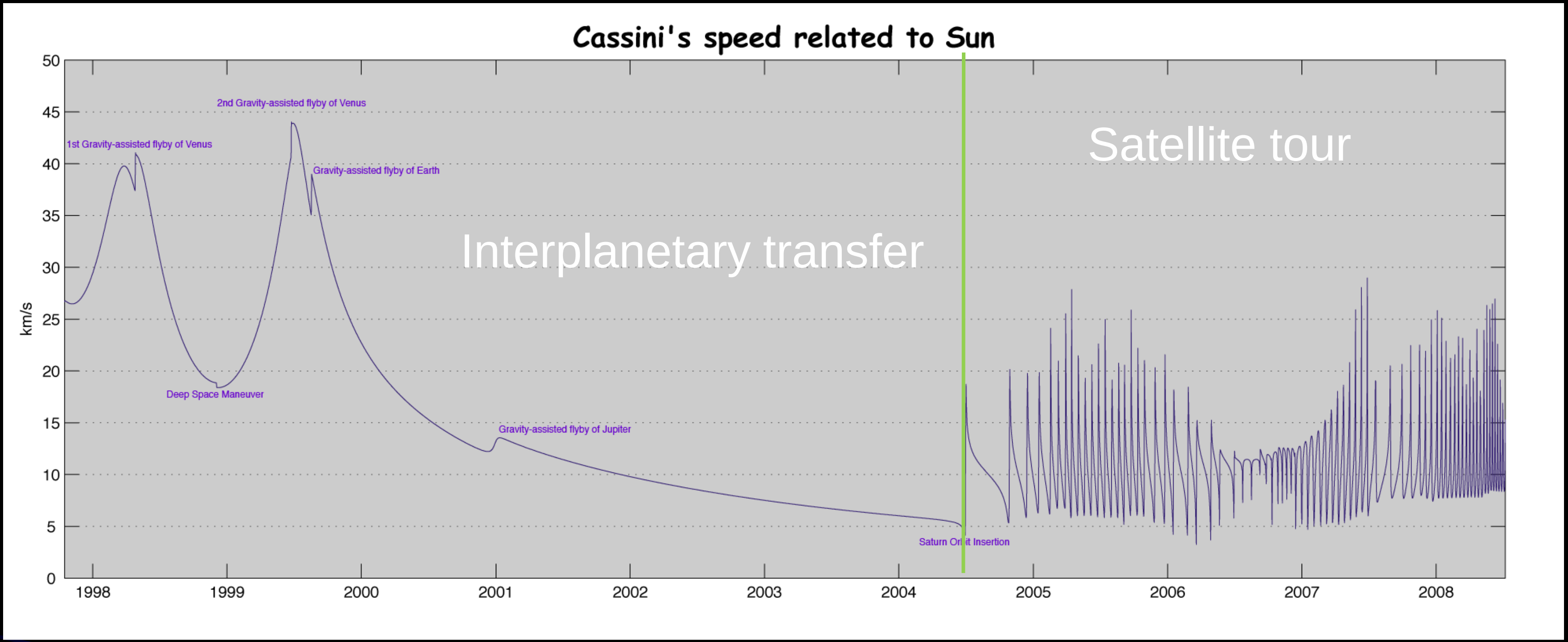
- Rosetta: a "date" with Comet 67P/Churyumov-Gerasimenko

Launch: 2 March 2004
First Earth swing-by: 4 March 2005
Mars swing-by: 25 February 2007
Second Earth swing-by: 13 November 2007
Steins fly-by: 5 September 2008
Third Earth swing-by 13 November 2009
Lutetia fly-by: 10 June 2010
Comet rendezvous manoeuvres: 22 May 2014 (@ 5.25AU)
Lander delivery: 10 November 2014
Escorting the comet around the Sun: November 2014 - December 2015
End of mission: December 2015

- Cassini-Huygens: to Saturn and its moons

Launch:15 October 1997,
Venus swing-by: 26 April 1998
Venus swing-by: 21 June 1999
Earth swingby: 18 August 1999
Jupiter swingby : 30 December 2000
Saturn arrival:1 July 2004,
followed by a four-year
orbital tour of the Saturn system.



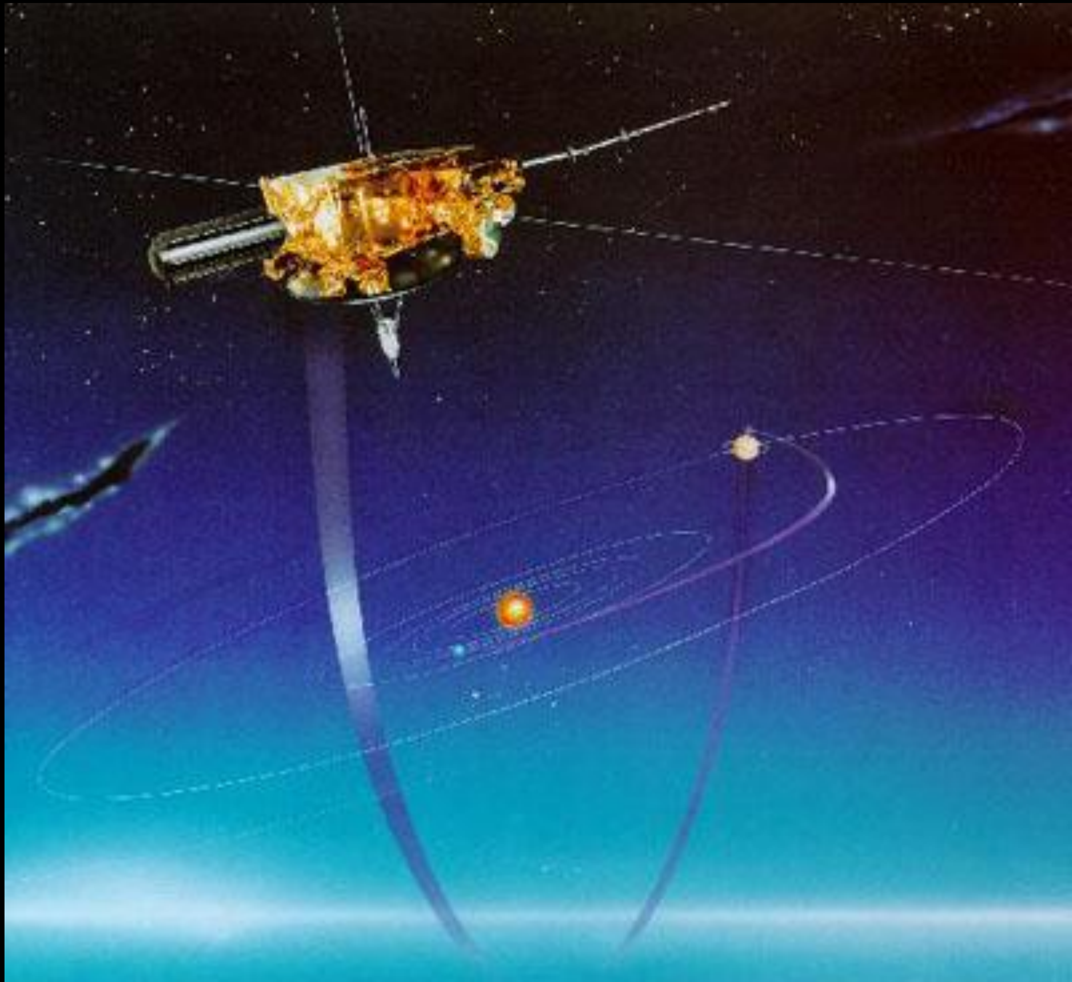


With the use of the VVEJGA (Venus-Venus-Earth-Jupiter Gravity Assist) trajectory, it takes 6.7 years to reach Saturn and total Δv=2 km/sec

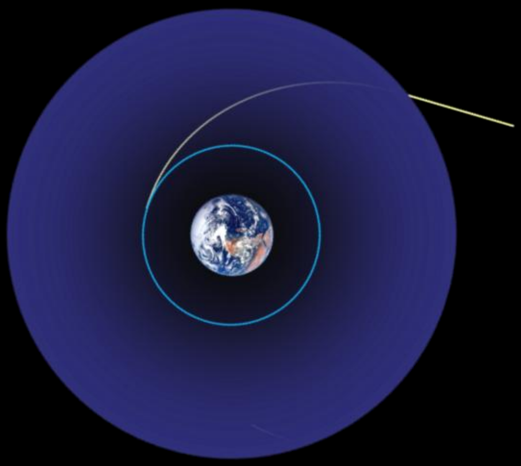
Hohmann requires less time (6 years) but a Δv of 15.7 km/sec

- Ulysses: in the 3D Solar System

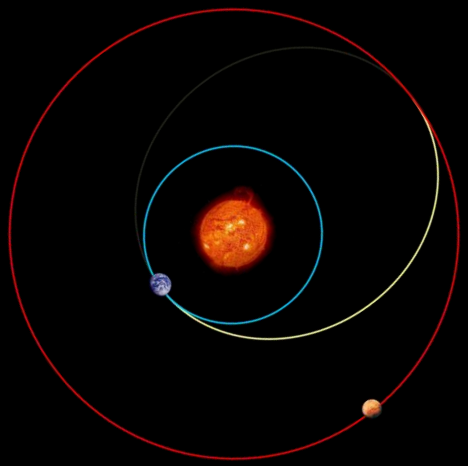
Launch**:** 6 October 1990
Jupiter swingby: February 1992
Sun's south pole: 1994
Sun's north pole: 1995
Sun's south pole: 2000
Sun's north pole: 2001
Head back to Jupiter



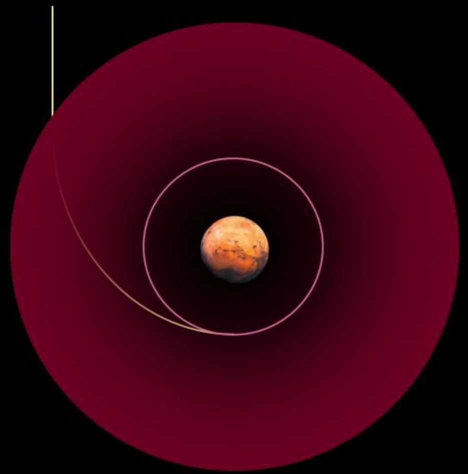
Patching conics



Geo: Hyperbolic escape

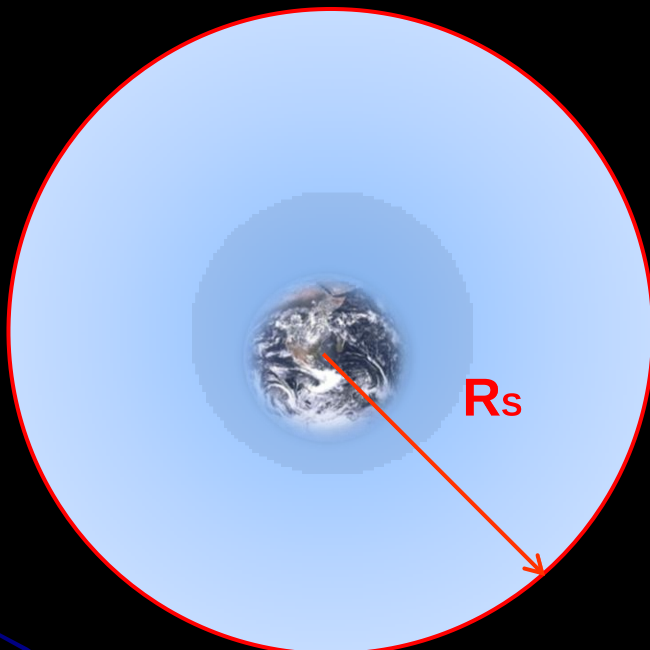


Helio: Elliptical transfer



Target: Hyperbolic arrival

Sphere of Influence (SOI)

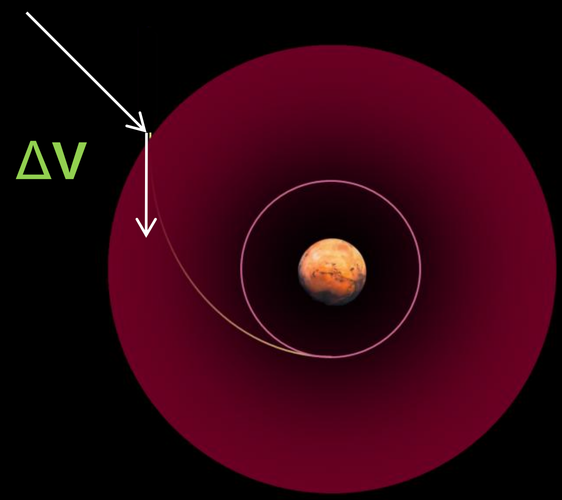


$$R_S = \left(\frac{m}{3M}\right)^{1/3} r$$

Mercury	0.22	10^6 km
Venus	1.01	
Earth	1.50	
Mars	1.09	
Jupiter	53.13	
Saturn	65.32	
Uranus	70.14	
Neptun	115.26	
Pluto	28.95	

Patching at the SOI

Patching at the sphere of influence = passing from one keplerian arc to the next imposing continuity in position and (possibly) allowing for discontinuity in velocity (ΔV) at the patch point (=on the sphere of influence)
(ΔV may be eliminated by subsequent optimization)



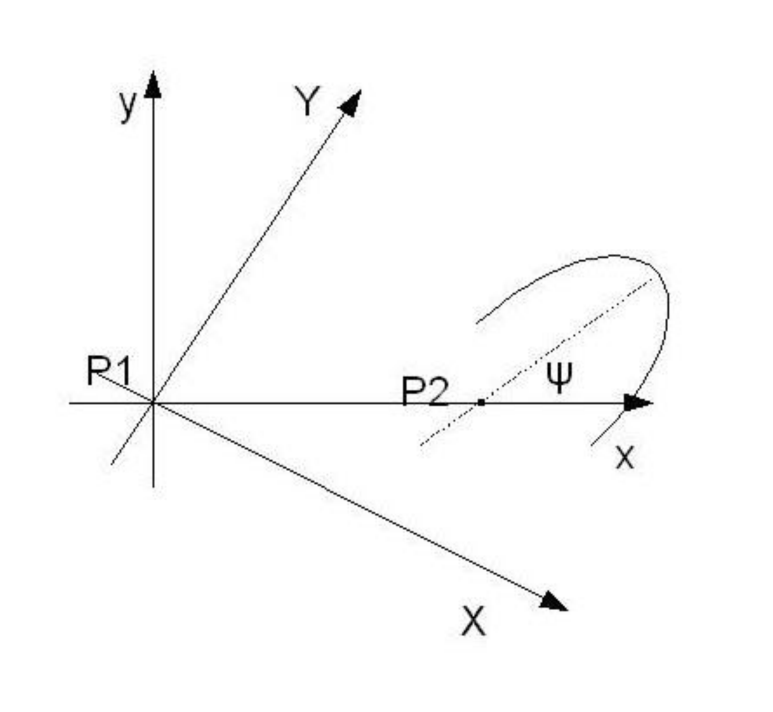
Broucke,1984

The physics of GA (1/4)

The mechanism of GA well known for >150 years: capture & escape of comets due to Jupiter action (Leverrier 1847)

Basic assumptions:
2D case + CR3BP:
P1 (m1) and P2 (m2 << m1) on circular orbits, P3 (m3 = 0)
d(P1-P2) = d, ω(P2) = ω
Jacobi constant of P3 is conserved throughout close encounter

Statement of the problem:
P3 moves on a keplerian (elliptic) orbit around P1
Study the perturbations/modification of such orbit when P3 encounters P2



The physics of GA (2/4)

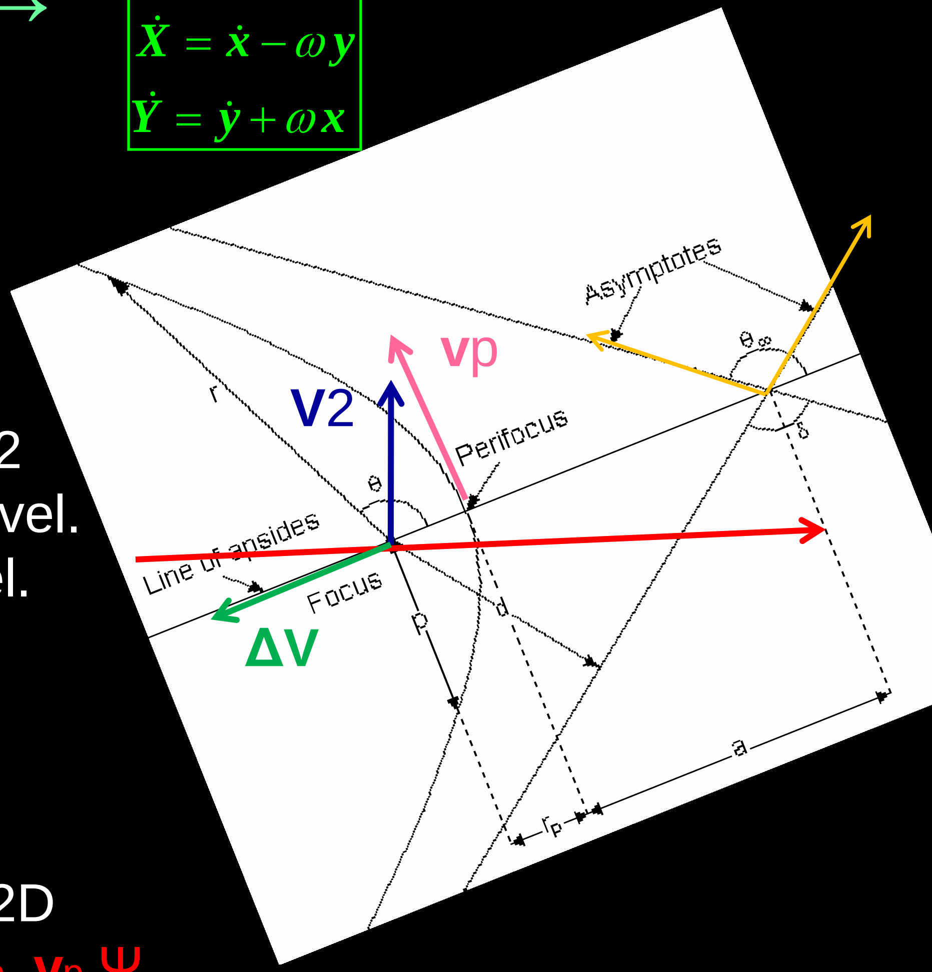
$$X = x\cos\omega t - y\sin\omega t$$
$$Y = x\sin\omega t + y\cos\omega t$$
$$\dot{X} = (\dot{x} - \omega y)\cos\omega t - (\dot{y} + \omega x)\sin\omega t$$
$$\dot{Y} = (\dot{x} - \omega y)\sin\omega t + (\dot{y} + \omega x)\cos\omega t$$

$\longrightarrow$

$$X = x$$
$$Y = y$$
$$\dot{X} = \dot{x} - \omega y$$
$$\dot{Y} = \dot{y} + \omega x$$

V2 = vel. vector of P2 in (OXY)
Ψ = orientation of hyperbola wrt x
r_p= periapsis distance
v$_p$= periapsis velocity relative to P2
V$_i$, **V**$_o$ = incoming,outgoing inertial vel.
v$^-_\infty$,**v**$^+_\infty$ = incoming,outgoing rel. vel.
2δ = deflection angle

$$\sin 2\delta = \left(1 + \frac{r_p v_\infty^2}{G m_2}\right)^{-1}$$



$\longrightarrow$ The close approach orbit in 2D depends on 3 parameters: r_p, **v**$_p$, Ψ

The physics of GA (3/4)

$$\vec{V}_i = \vec{v}_\infty^- + \vec{V}_2$$

$$\vec{V}_o = \vec{v}_\infty^+ + \vec{V}_2$$

$$\Delta\vec{V} = \vec{V}_o - \vec{V}_i = \vec{v}_\infty^+ - \vec{v}_\infty^- = (\Delta\dot{X}, \Delta\dot{Y}) = (\Delta\dot{x}, \Delta\dot{y}) = (-\Delta v \cos\psi, \Delta v \sin\psi)$$

$$\left|\Delta\vec{V}\right| = 2\left|\vec{v}_\infty\right| \sin\delta \Rightarrow (\Delta\dot{x}, \Delta\dot{y}) = (-2v_\infty \cos\psi \sin\delta, -2v_\infty \sin\psi \sin\delta)$$

Effect on angular momentum:

$$C = X\dot{Y} - Y\dot{X}$$

$$\Delta C \simeq X\Delta\dot{Y} - Y\Delta\dot{X}$$

$$t = 0 : \Delta C = d\Delta\dot{Y} \Rightarrow \Delta h = \omega d\Delta\dot{Y} = -2\omega d v_\infty \sin\delta \sin\psi$$

X,Y almost constant

Effect on energy:

$$E = K + U$$

$$\Delta E \simeq \Delta K \leftarrow \Delta U \simeq 0$$

$$\Delta K = -2v_\infty V_2 \sin\delta \sin\psi \leftarrow \dot{X} \simeq \dot{x}, \dot{Y} = \dot{y} + V_2$$

$$\Delta E = \Delta K = \vec{V}_2 \cdot \Delta\vec{V}$$

The physics of GA (4/4)

Effect on semimajor axis:

$$E = -\frac{Gm_1}{2a}$$

$$\Delta a = -\,4a^2 v_\infty V_2 \sin\delta \sin\psi \Big/ Gm_1$$

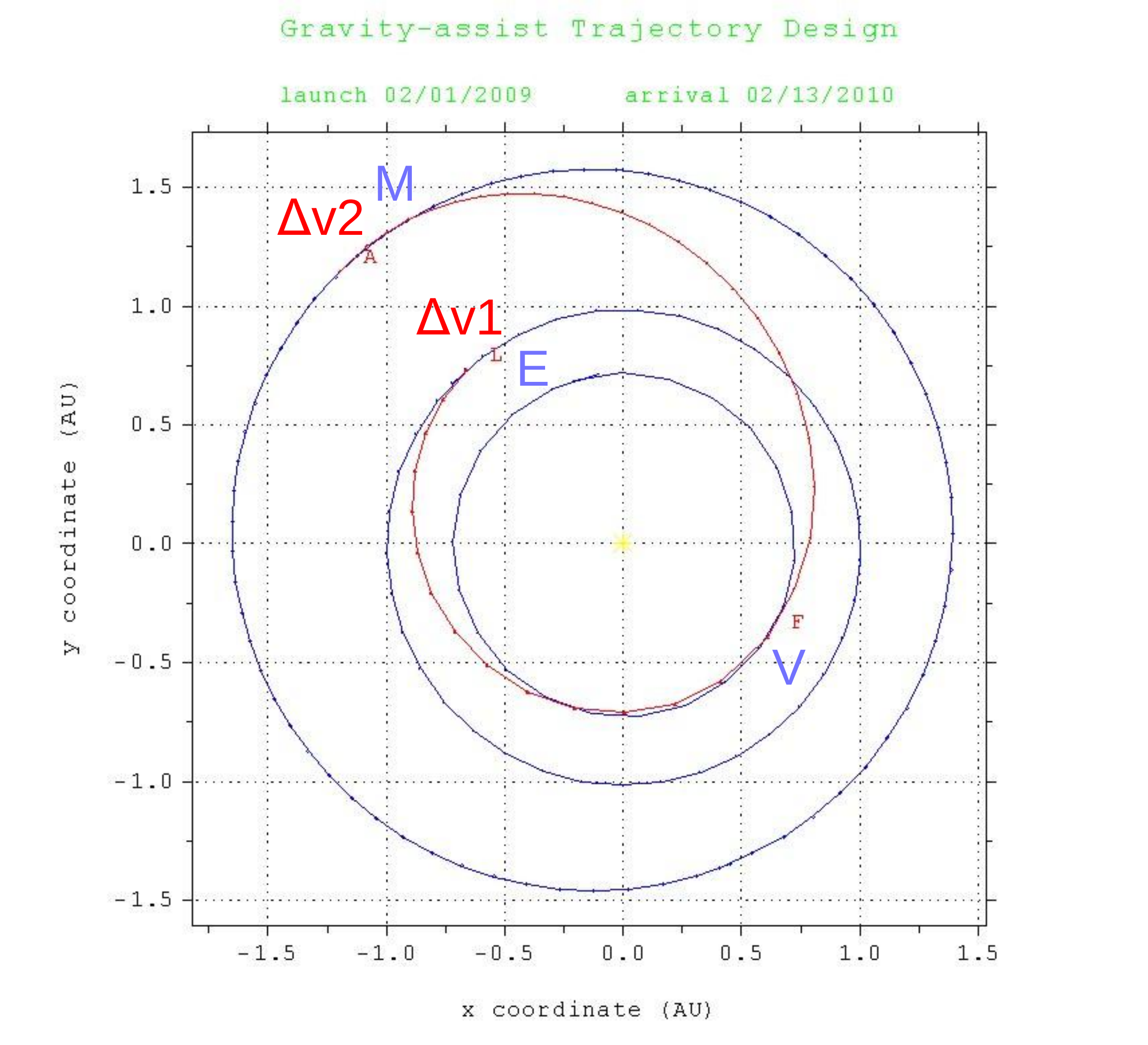
Max energy decrease occurs when the swing-by is in front of planet
Max energy increase occurs when the swing-by is behind planet

Optimum v_∞ (for max ΔV) = $v_c = \sqrt{\frac{Gm_2}{r_p}} \Rightarrow \Delta V = v_c; v_p = \sqrt{3} v_c$

Being a good accelerator depends on value of circular vel at the surface

Optimum 2δ = 60 degrees

Example: from Earth to Mars through a Venus GA



computed with Numerit Pro (flyby.exe)

$\Delta v1 + \Delta v2 = 6.95$ km/sec

TOF=1 year

a1=0.85 AU

a2=1.19 AU

h=5000 km

$v_\infty = 7.73$ km/sec

But this is not the whole story…

- Powered gravity assisted trajectories
- Optimization

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