



Orbital Dynamics at Binary Asteroid Systems: Opportunities, Challenges and Constraints

Acknowledgements:

Dr. Scheeres, University of Colorado at Boulder.

Dr. Ostro and group, JPL +

Study of 1999 KW4, Science 314, 2006

Dr. Yano, JSPEC

Students and PIs/Co-PIs at Summer internship at Ames (S4P)

summer 2008

Didymos explorer mission concept, DEX

The ESA Workshop on GNC for Small Body Missions

January 15, 2009



1999 KW4

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Motivation

- From current estimates: 15% of Near-Earth Asteroids are thought to be binaries.
- Interest in Binary Asteroids:
 - Two asteroids instead of one.
 - If formed through fission, a binary may directly show its internal structure.
 - System dynamics may tell more about formation and evolution of planetary systems.
 - Rendezvous to a small body may reveal a multiple body system
- Challenges in having vehicles in orbit about a binary system
 - Motion resembles a “mini” 3 body problem
 - Imagine the Earth and Moon separated by a few km.
 - The time scale of motion around these systems are on the order of 10's of hours
 - The motion is strongly perturbed by the system itself, close approaches to other bodies, and solar effects.
 - Must account for non-spherical asteroid shapes
 - Gravitational model and orbit propagation in proximity operations are more complex
 - Need to design for low gravity environment, 10^{-4} g – same as for single asteroids
 - Any stable orbits, semi-stable orbits, or long term orbits are associated with possible dust hazards.



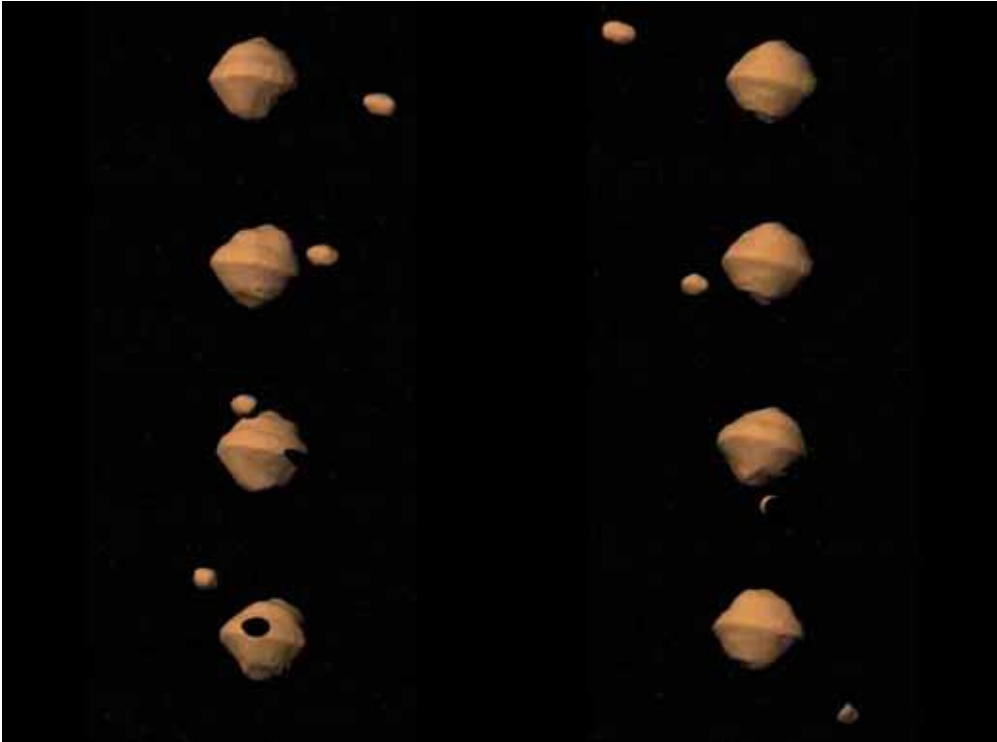
A few known Binaries

Binary	ΔV (<i>km/s</i>)	P_1 (<i>hr</i>)	P_2 (<i>hr</i>)	P_{mut} (<i>hr</i>)	D_2/D_1	D_1 (<i>km</i>)	D_2 (<i>km</i>)	r_b (<i>km</i>)
→ Didymos (1996GT)	5.102	2.26	11.9	11.9	0.22	0.75	0.165	1.1
2000 DP107	5.97	2.77	42.20	42.20	0.41	0.8	0.328	2.6
1999 DJ4	6.04	2.51	17.73	17.73	0.5	0.35	0.175	0.8
1991 VH	6.37	2.62	NA	32.69	0.4	1.1	0.44	3.2
→ 1996 FG3	6.61	3.59	16.15	16.14	0.31	1.5	0.465	2.6
1998 PG	6.66	2.52	14.01	NA	0.3	0.9	0.27	1.5
Dionysus (1984KD)	6.75	2.71	NA	27.74	0.2	1.5	0.3	3.8
2000 UG11	6.88	4.44	NA	18.4	0.6	0.26	0.156	0.4
Hermes (937UB)	7.78	13.89	13.89	NA	0.9	0.6	0.54	NA
2001 SL9	9.32	2.4	NA	16.4	0.28	0.8	0.224	1.4
1994 AW1	10.25	2.52	NA	22.3	0.49	1.0	0.49	2.3
1999 HF1	13.03	2.32	NA	14.03	0.23	NA	NA	7.0
2002 CE26	14.08	3.29	NA	16	0.07	3	0.21	5.1
2003 YT1	16.47	2.34	< 6	30	0.18	1.0	0.18	2.7
1998 RO1	19.4	2.49	14.52	14.54	> 0.4	NA	NA	1.4
→ 1999 KW4	21.3	2.765	17.45	17.44	[0.3,0.4]	1.5	0.57	2.54

Some well-known NEA binary asteroid systems (Pravec, Harris, Deschamps, Marchis, Richardson)



1999 KW4 System



1999 KW4 (see Science 314, 2006, Ostro et al.)

Approximated as an
ellipsoid-sphere system

Primary: Alpha

Secondary: Beta

System parameters:

$r = 2.54$ km

Total mass: $2.472E^{12}$ kg

Mass fraction: 0.9457

Ellipsoid: [1:0.8:0.6]

Alpha spin rate: 2.8 hrs

ω , orbit rate: 17.458 hrs

Note: 1996 FG3 has about the
same characteristics.



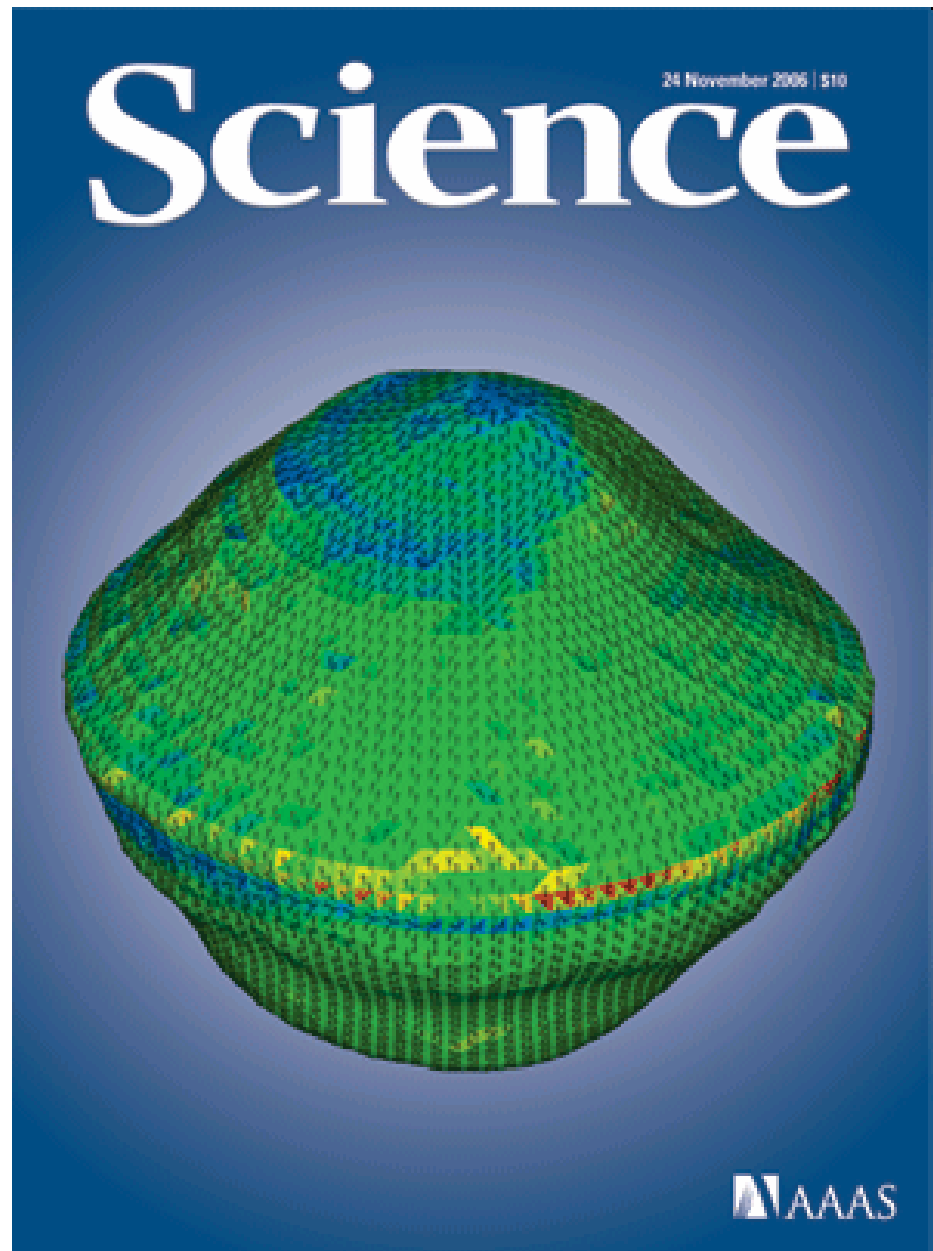
Primary of 1999 KW4

Primary spins fast,
~ 3 hrs period.

Loose particles tend to fall
towards the equator – may
not have easily accessible
core samples.

Secondary is locked
with respect to the primary.

**If secondary was detached
from the primary, sample
of secondary may be good
enough.**





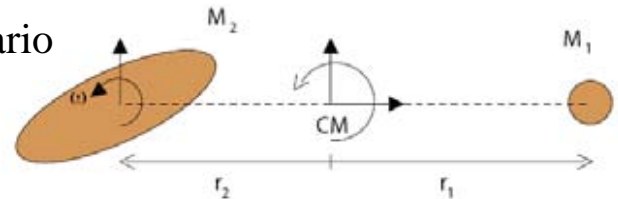
Overview

- Introduction/Motivation
- Brief overview of Dynamics of Binary Asteroid Systems
- Spacecraft/particles dynamics near Binary Asteroids
 - Energy constraints and comparison with the known R3BP.
 - Transition paths between the two asteroid bodies
 - In-plane and out-of-plane dynamics
- Mission Case Studies
 - 1999 KW4
 - Didymos Explorer
- Discussion



On the Dynamics of Binary Systems

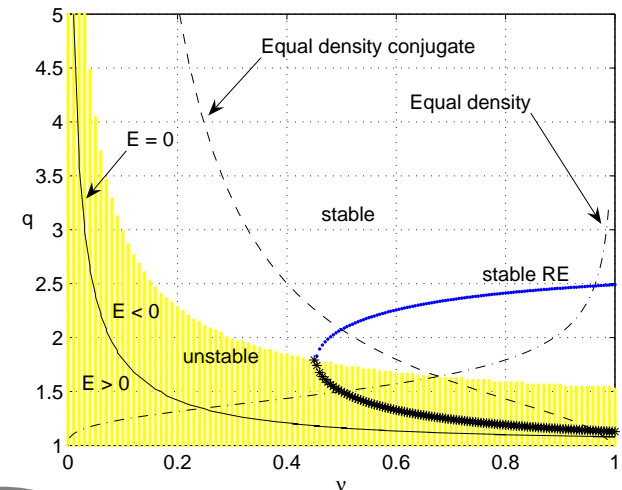
- The Two Body Problem has been extensively investigated.
- General formulation of the F2BP is possible, but computationally hard (Maciejewski, Danby)
 - mutual potential expressions, methods of reduction, and equilibrium solutions were derived.
- Using one body as a sphere reduces complexity.
 - The conditions for relative equilibria and their stability for a binary with one body having an arbitrary shape was derived (Scheeres).
- An ellipsoid-sphere system was further investigated, with extension to spacecraft application (Scheeres, Bellerose, Marsden).
 - Fits preliminary observations data.
 - Gives overall dynamics – possibly worst case scenario for dust hazards.
- More accurate/complex methods, for example:
 - Use of polyhedral mutual potential and potential derivatives, use of Lie group Variational Integrator (Fahnestock & Scheeres, Teawong & McClamroch)





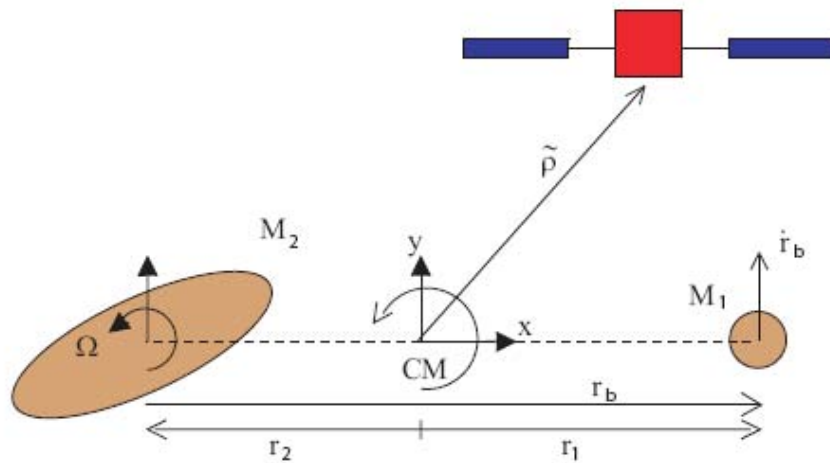
Fundamental Properties: Observations and Analytical Methods

- Binary systems can be in locked configuration or not (or relative equilibrium or not).
 - If the system is close to an ellipsoid-sphere system, bodies can be aligned along their long or short axis, but...
 - The long axis configuration is the only one that can be energetically stable.
 - Corresponds to families of gravity gradient orientations up to a massive sphere
 - Can be stable or unstable depending on parameters.
 - A number of binary systems have been observed to be in such a locked configuration.
- Relative equilibria (RE) can be solved for and mapped.
 - The energy indicates the possibility for the system to escape.
 - It can be shown that under constant angular momentum, two solutions exist associated with opposite stability properties (C-shape curve).
 - If energy dissipation occurs, a system may go from an unstable to a stable state.

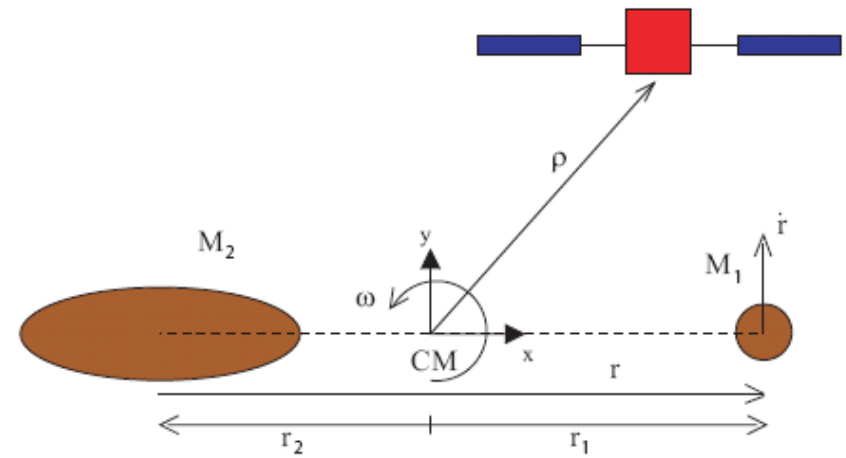




Dynamics of Spacecraft/Particle in Orbit about a Binary System



General approach

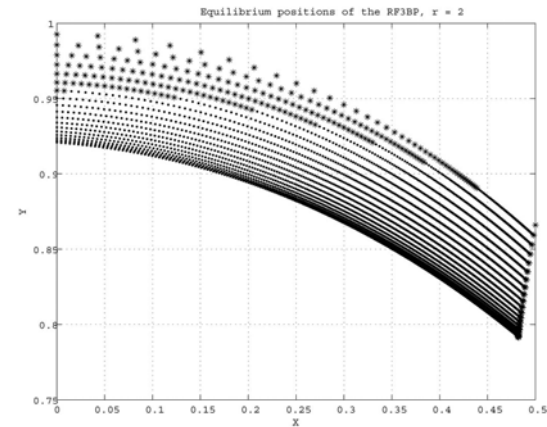
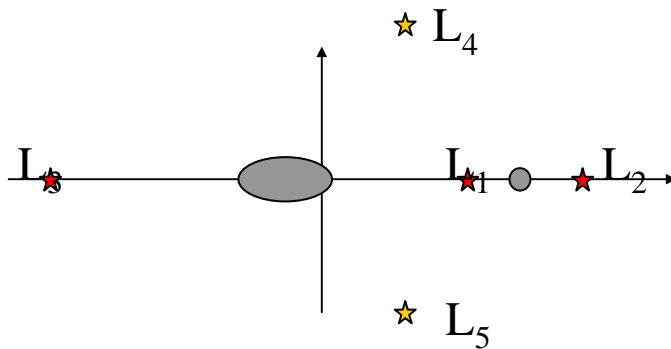


Under relative equilibrium
for the binary itself



Analogue to the Restricted Three Body Problem

- Solve for equilibrium solutions.
 - The spin rate is found from solving the binary system equations of motion.
 - We find the “analogue” Lagrangian points and their stability
 - The free parameters are the mass ratio, shape parameters, and the distance between the bodies.

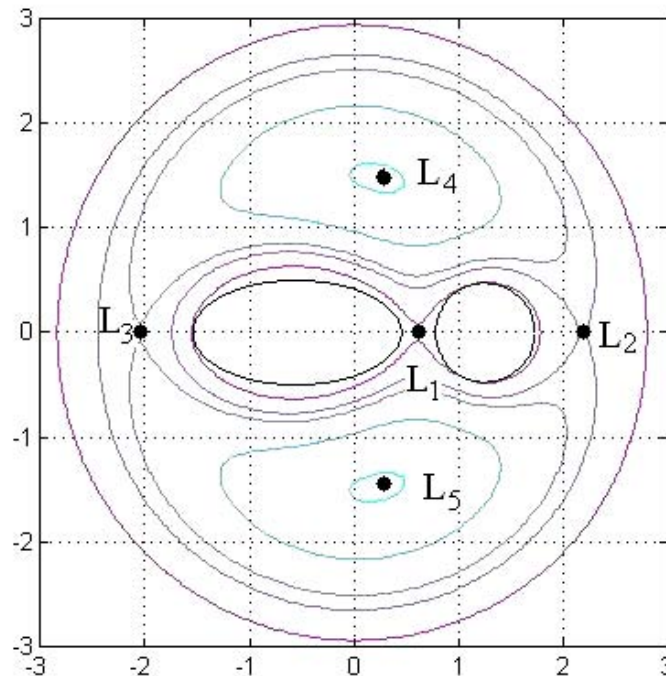


- Stability regions can be mapped
- The presence of the ellipsoid body reduces the stability as compared to the R3BP, although there are some exceptions.



Particles Dynamics for a Binary System – Energy Constraints

- If the system configuration is locked, it has one conserved quantity - the Jacobi integral. We can investigate the energy constraints.

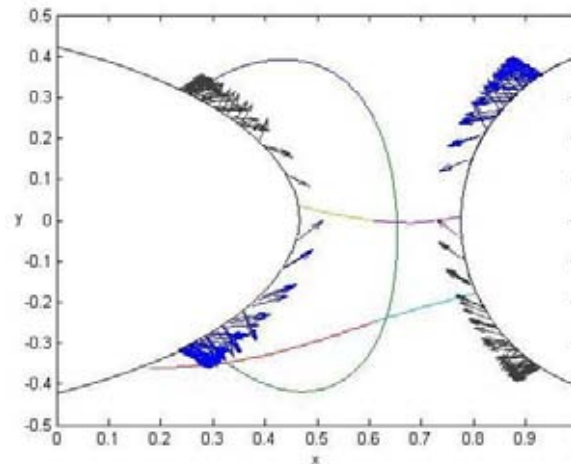


Zero-velocity curves in the x, y coordinate frame for an ellipsoid-sphere system with distance between the bodies of $r = 1.8$, ellipsoid parameters, $a = 1$, $\beta = \gamma = 0.5$, and mass ratio of $\nu = 0.3$. The black lines represent the bodies themselves.



In-plane Dynamics

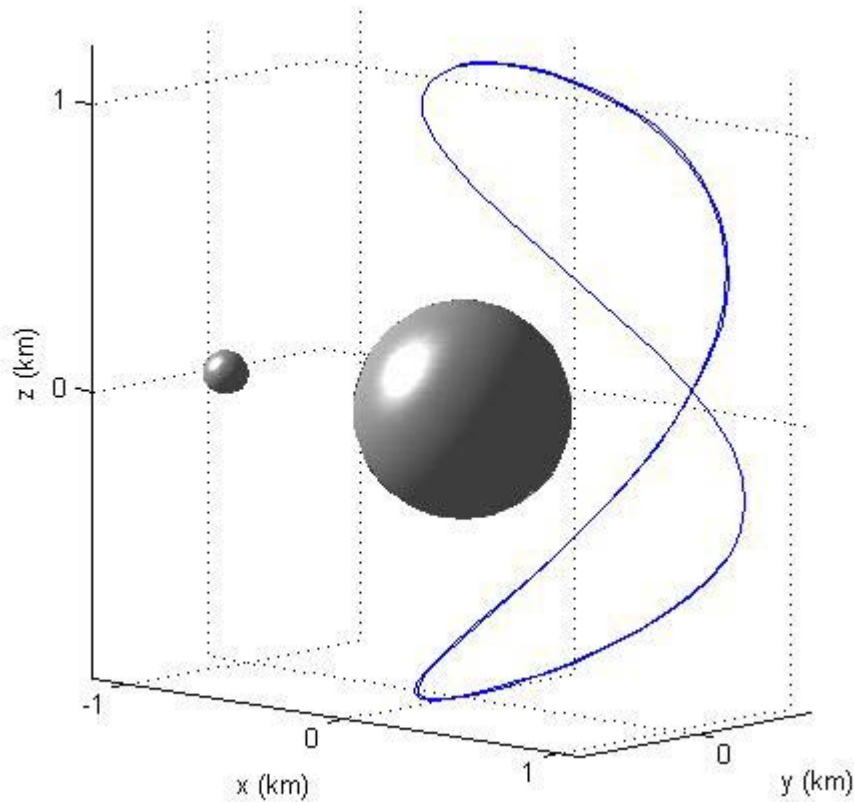
- We can compute orbits encircling both bodies, as well as orbits bound to each body.
- We can find transfer trajectories between the two asteroids using linearization at L_1 and orbit propagation.



Transit and non-transit trajectories for a binary system with $r = 1.8$, $\nu = 0.3$ and ellipsoid parameters $\beta = \gamma = 0.5$. The arrows are initial and final conditions on the surface of the bodies leading to non-transit trajectories.



Out-of-plane Dynamics



Unstable periodic orbits exist, for a variety of systems, and orbit eccentricities.

At the primary, terminator orbits may be used.

These may be wanted for landing at the poles.

However, due to perturbations, out-of-plane dynamics may cost more than simply hovering.

The s/c configuration needs to be designed to account for such geometry.

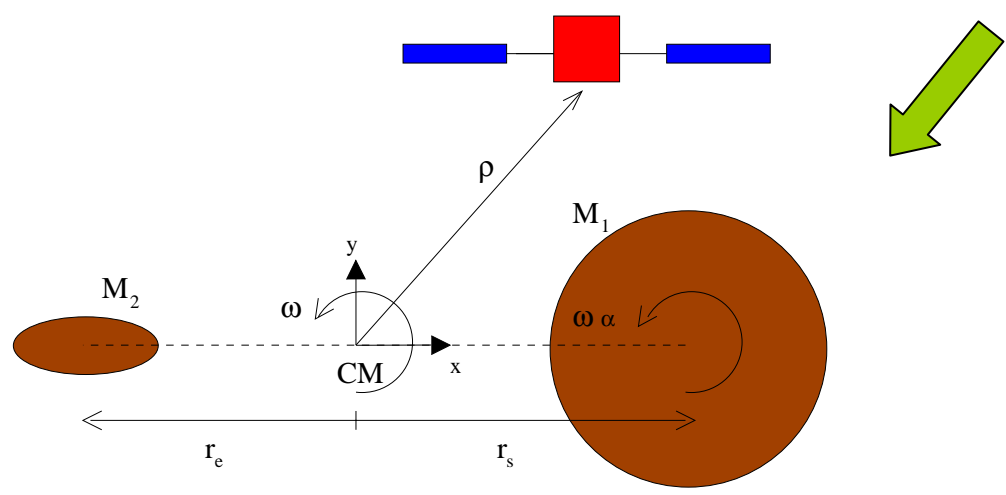
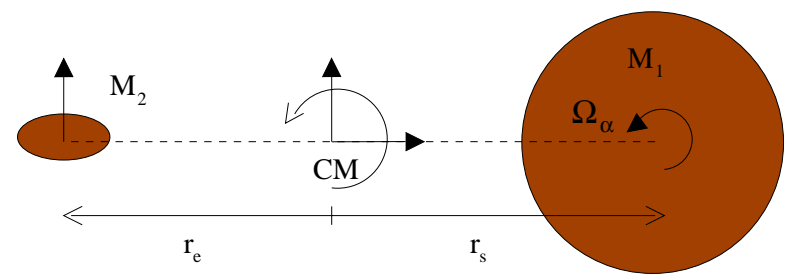


Models for Systems like KW4

Asteroid 1999 KW4

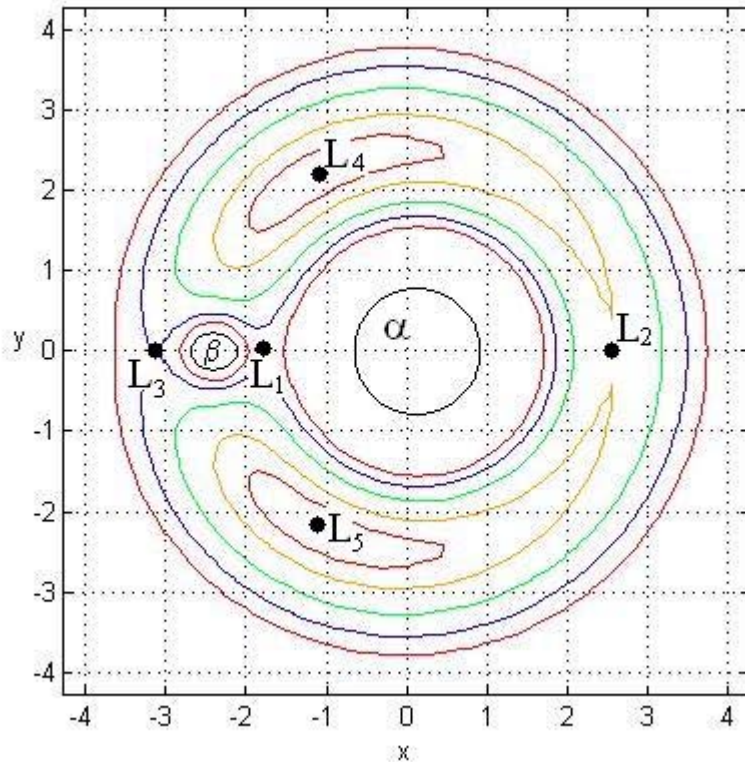


Simplified Full Two-Body Problem for 1999 KW4





Energy Constraints for 1999 KW4



Zero-velocity curve plot for 1999 KW4 with $r = 2.54$ km. The black lines represent the bodies.

Lagrangian points:

L_1 : -1.7773 km, L_2 : 2.594 km

L_3 : -3.14 km, $L_{4,5}$: -1.13, ± 2.2 km

Order in which they appear from the Jacobi integral values:

$$C_1 < C_3 < C_2 < C_4 = C_5$$

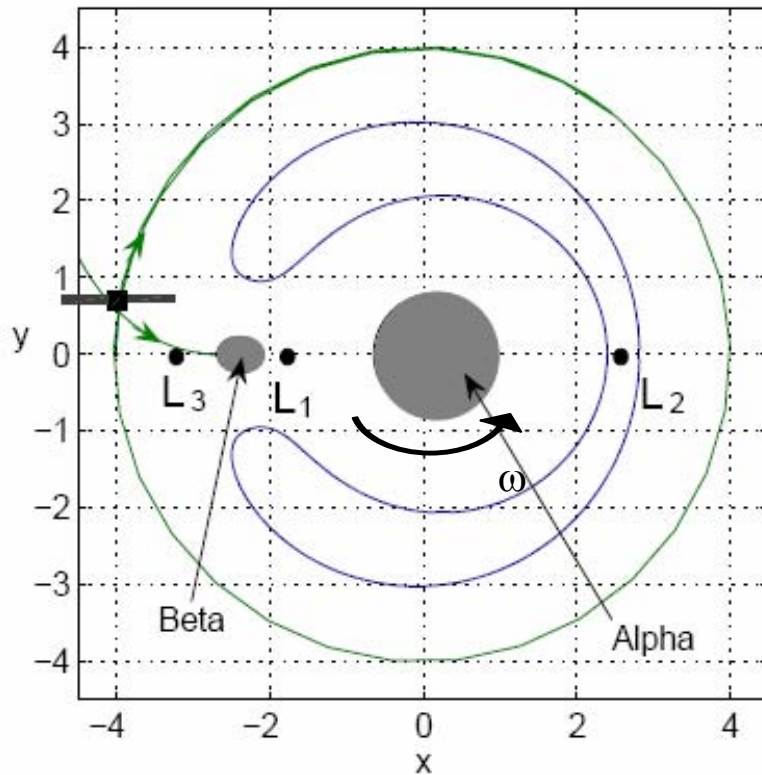
→ L_3 opens up before L_2

Mission design:

A missions could approach KW4 from L_3 without possibility of escaping.

→ $L_{4,5}$ are unstable for KW4

Approach to Secondary Body First



L_3 is the only entrance/exit region.
Surface packages are ejected from
the back of the spacecraft.
The spacecraft stays on its
retrograde orbit for communication.

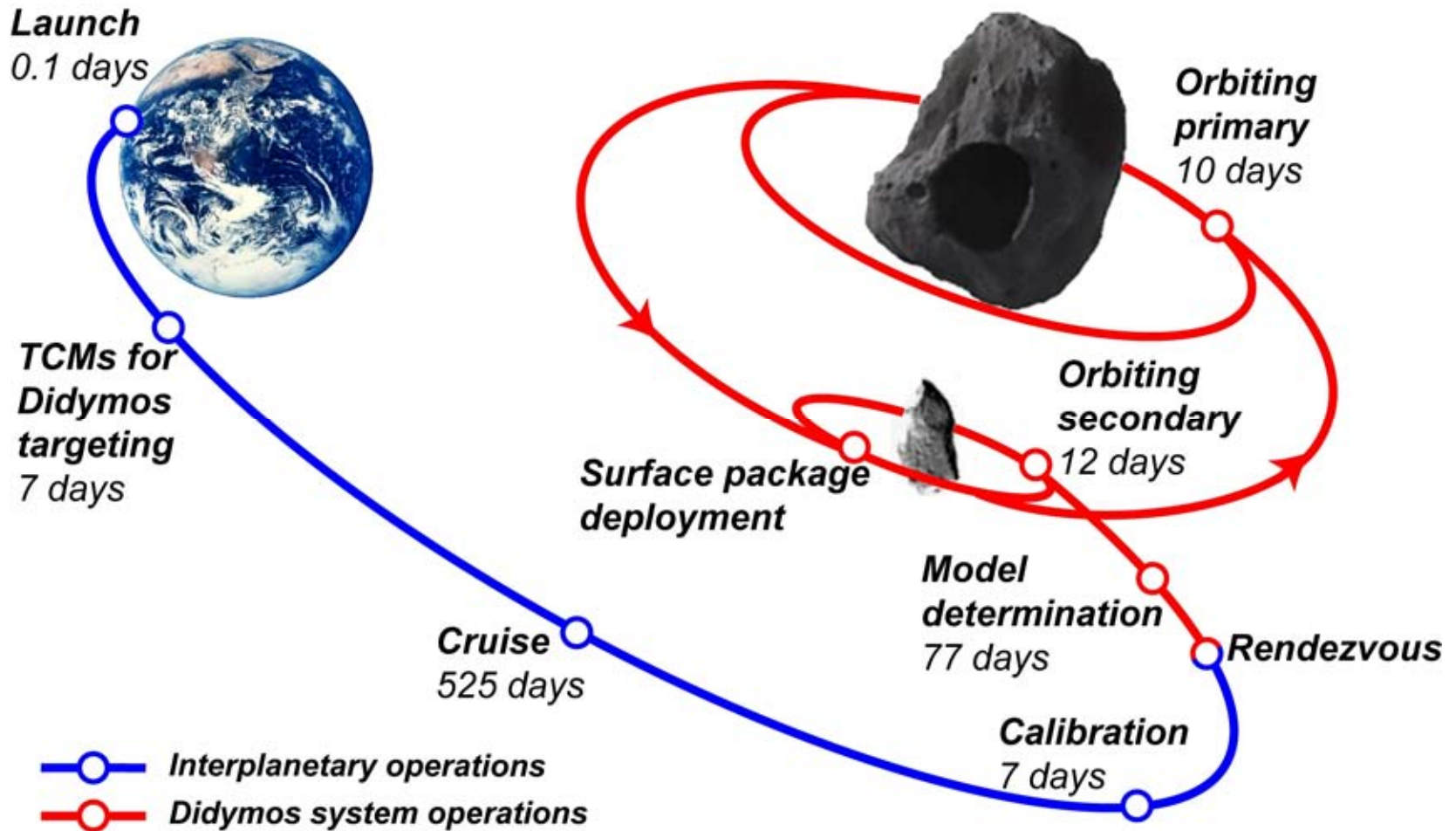
The ejection speed less than 1 m/s
at 85° from the binary x axis.

The landing speed on Beta is less than
0.2 m/s.



Didymos Explorer: DEx

(S4P at NASA AMES, summer 08)



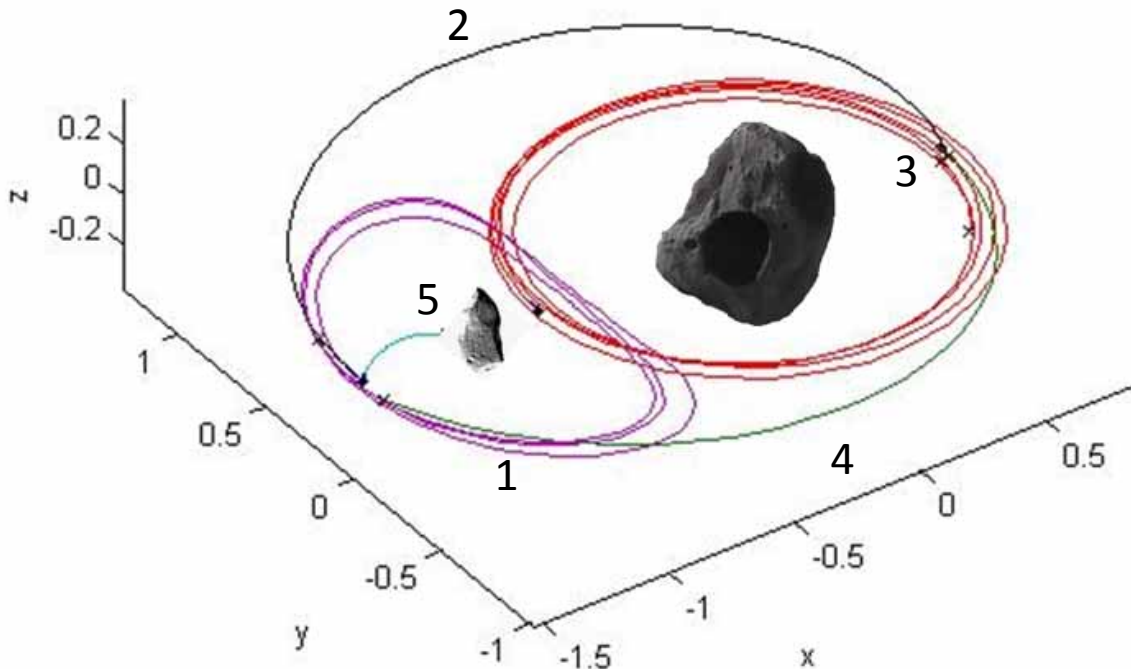
Mission Scenario at Didymos (1/2)

Objectives at target...

- Allow for precise shape determination and gravity model

Flybys at 5 km and 3 km closest approach

- Perform close approach for detailed composition and thermal imagery
- Prepare for package deployment



1: Binary orbit (using 2,4), 10 days

2: Transfer to primary

3: Orbit the primary, 14 days

4: Transfer to secondary

5: Eject surface package,

continue observe

lander, 5 days

End of mission

- DEX lands on secondary



Mission Scenario at Didymos (2/2)

- Approach
 - Although orbiting the secondary may be possible, its mapping can efficiently be done from a reconnaissance orbit around the whole system.
- Risk Items/mitigation
 - Need to cut communication during shadow time
 - In-plane orbits involve eclipse time of 30-35 min
 - If presence of 3rd body
 - Need to account for extra perturbations
 - Can still get shape determination, gravity model
 - Hovering and landing on third or secondary body may still be possible.
- Mission Parameters
 - Total fuel needed at target (large contingencies and margins) is about 100 m/s
 - Proximity operations last about 140 days



Discussion

- The unique environment of binary asteroid systems opens up to discoveries and new exploration techniques.
- We can apply fundamental analytical tools to investigate energy constraints for a spacecraft in orbit, or periodic orbits and stability of orbits, also linked to dust hazards.
- Case studies of 1999 KW4 and Didymos.
 - Approach through the secondary is more suitable
 - Naturally more stable environment
 - Lower cost
 - In-plane dynamics used for better stability and fuel savings: **hover or orbit?**
 - May be possible to orbit the secondary depending on body size
 - Solar radiation pressure may be damped or averaged from orbiting in the plane
 - Orbiting depends on s/c configuration
 - Need to cut communication with Earth, and may lead to long shadow time.
 - Need a more robust GNC capability for orbiting
 - Out-of-plane dynamics
 - Usual stable orbits for single asteroids are most likely perturbed by secondary
 - May lead to higher fuel expenditure