AEROSPACE ENGINEERING
UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Insights on Interplanetary Aerodynamic Environments for Small Spacecraft

First Interplanetary Small Satellite Conference

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Spacecraft and Aerodynamics

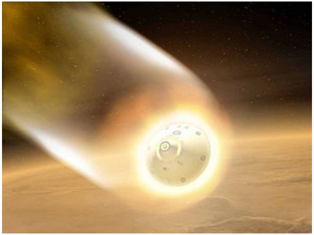
And why these examples aren't too important for small spacecraft

Launch:

Air-launched space access, this from the launch of Space Technology 5

Launch of STS-120

Atmospheric Entry:



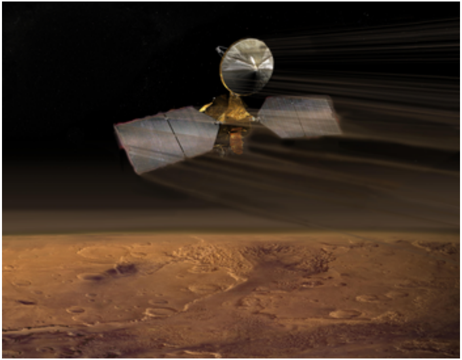
Mars Exploration Rover entry

Recovery/Landing:

Practice recovery of Genesis asteroid sample return capsule

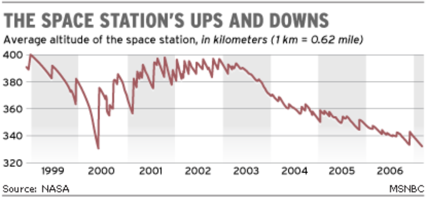
Spacecraft and Aerodynamics

Examples that are a little more relevant



←Aerobraking

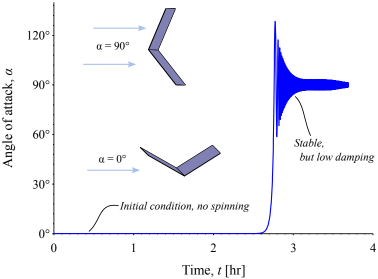
(No picture?)
(Very) low-altitude orbits
See Mike Mullane's account of STS-36
Riding Rockets: The Outrageous Tales of a Space Shuttle Astronaut

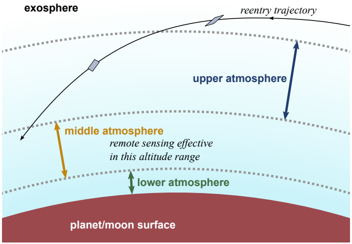


Orbital decay

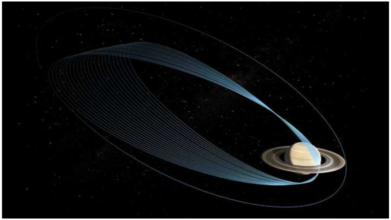
Unique SmallSat Aerodynamic Environments

Low-Heating Atmospheric Entry:

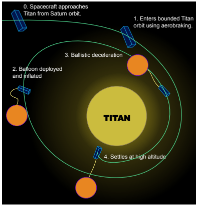




Ring Exploration:

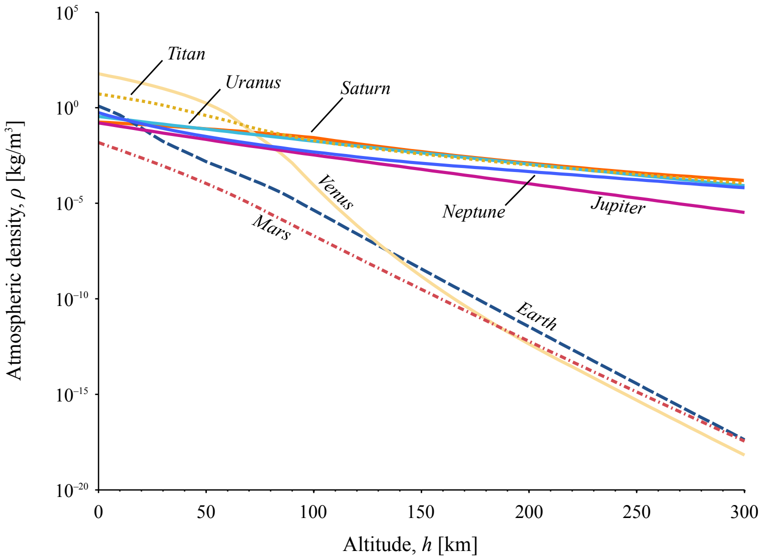


Transition to Floating Flight:

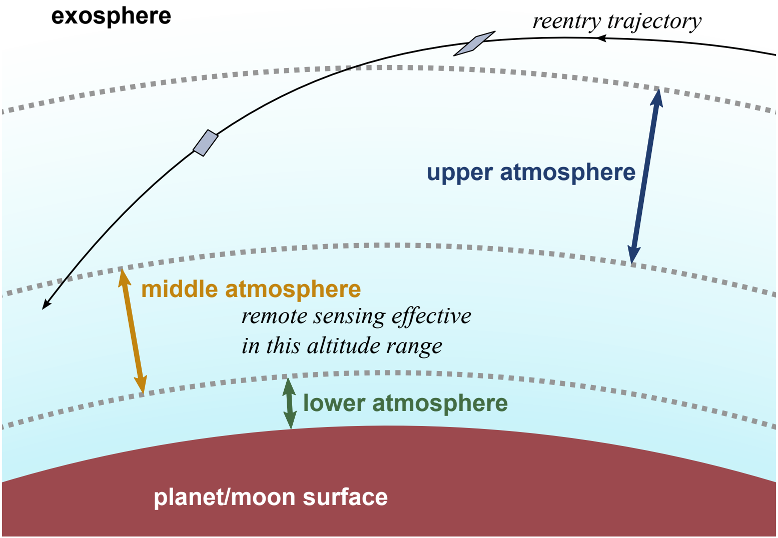


Atmospheres of the Solar System

Thank you, Voyager 2! Lindal, G. F. et al. "The Atmosphere of X: Analysis of Voyager Radio Occultation Measurements." 1981-19992



What can you do with small satellites in the upper atmosphere? Can you enter?



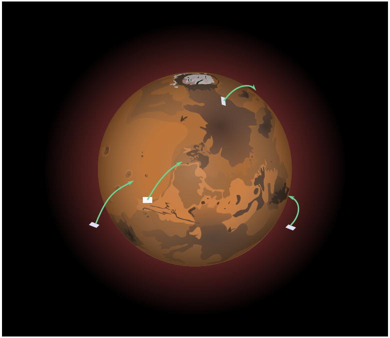
Alternatives for getting upper atmosphere data

Some favorable aspects of chip-scale atmospheric sensors

Spacecraft with “air-breathing” electric propulsion, balloons, remote sensing, larger entry probes

Advantages of chip-scale atmospheric entry sensors:

- Cheap and light; easy to get to other planets/moons
- Distributed *in situ* atmospheric measurements
- Greater risk tolerance: higher degree of failure may be allowable
- Provide indirect data just from their trajectory



What does entry look like for small (small == thin) spacecraft?

Small mass like $O(10\ \mathrm{mg})$

Acceleration at max heating (a_{max}) stays about constant

$$m_{sc} a_{max} = \frac{1}{2} \rho_{atm} V^2 A_{sc} C_D$$

(sc = spacecraft, atm = atmospheric)

That means the atmospheric density (ρ_{atm}) at which maximum heating occurs is proportional to the mass of the spacecraft.

The mass is about $m_{sc} = \rho_{sc} A_{sc} t_{sc}$ where t_{sc} is the thickness.

Max heating:

$$\dot{q}_{max} \propto \rho_{atm} V^3 \propto t_{sc}$$

Heating is proportional to spacecraft thickness.

Furthermore, it occurs at very low densities, $O(10^{-8}\ \mathrm{kg/m^3})$

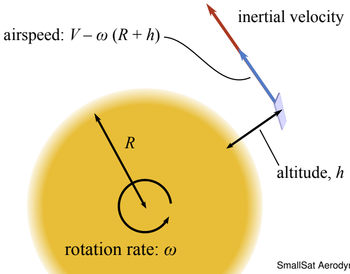
What makes an atmosphere hard (or easy) to enter?

You might think that a thick atmosphere is helpful, but really that just means that everything happens at a higher altitude.

Initial velocity is the most important driver:

$$V_{orbit} = R_{planet}\sqrt{\frac{g_{surface}}{R_{planet}+h}}$$

Why does velocity mater so much for heating? $\dot{q} \propto \rho_{atm} V^3$

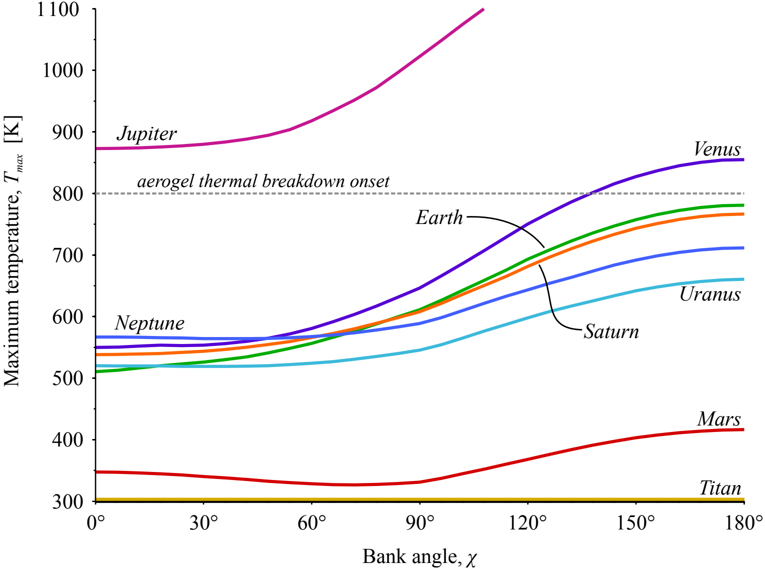


A planet's rotation can also be very important.

Especially for the gas planets (which rotate really fast, ∼once per 10 hrs)

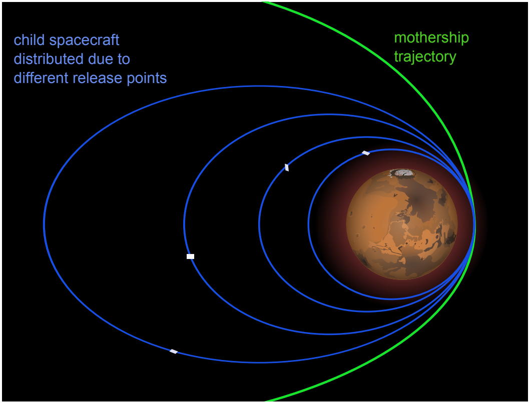
Results: chip-scale (1cm × 1cm × 0.032mm)

Bank angle = 180° $\Longrightarrow$ lift force points down



Aerobraking

Not particularly different from full-size spacecraft



Child spacecraft are more affected by aerobraking than motherships (usually)

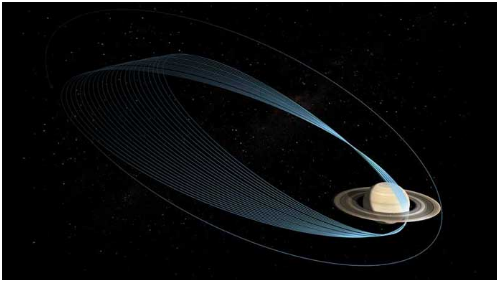
One deployed earlier will slow down more

A single mother ship can deploy to a wide range of orbits during a single aerobraking pass

The SmallSats have little control over their orbits, which will decay rapidly without a maneuver to raise the periapsis.

Ring Exploration

Unusual coupling between orbital mechanics and aerodynamics



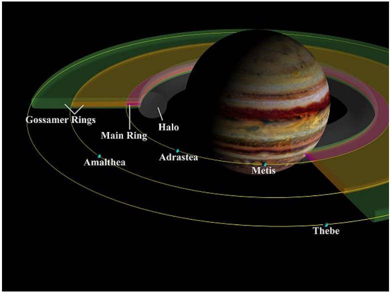
Cassini will fly between Saturn and its innermost ring near the end of its life around 2017.

Using a polar orbit because an equatorial orbit would require the spacecraft to fly *through* the rings

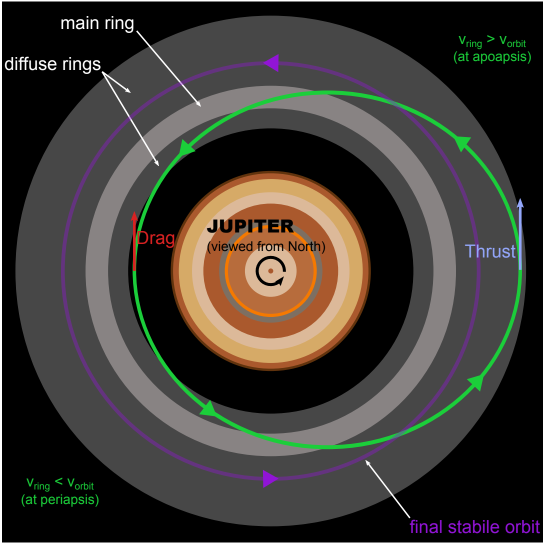
Saturn's rings are not ideal for such a maneuver.

Jupiter has rings that are not quite as interesting, but they may be safe to fly through.

Notwithstanding the radiation environment



Effects of Rings on Orbits



Flying through rings has some surprising consequences

The most interesting is that the rings actually give you thrust if the spacecraft's apoapsis is in a ring

If you can withstand the dust environment

Note that rings make circular orbits

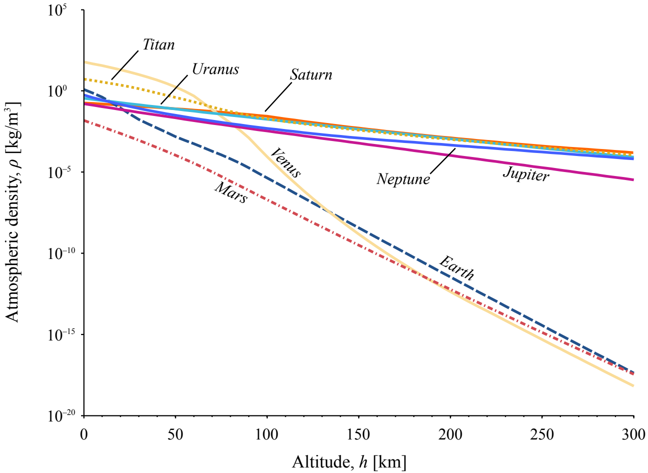
By actively controlling attitude, a lot can be done

For example, reducing cross-sectional area at periapsis

"Thrust" in the gossamer rings is small, around 10^{-5} N for a 3U

Titan is Really an Exception!

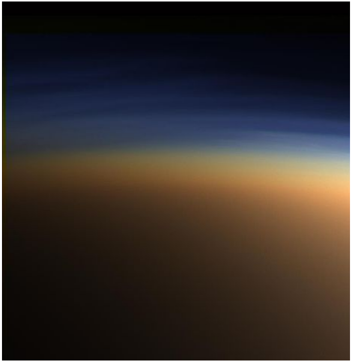
Why does it's atmosphere look like a gas planet's?



With the combination of low gravity and an extremely spread-out atmosphere, some unique things are possible.

Some Details of Titan's Atmosphere

And what it means for blurring the lines between spaceflight and aerodyanmics



True-color image of Titan's atmosphere

Very massive atmosphere (1.5 bar surface pressure)	Allows low-heating entry to atmosphere
Extends to high altitudes	Low-power flight
Low gravity	Helium balloons equilibrate
Super-rotating atmosphere	at *very* high altitude

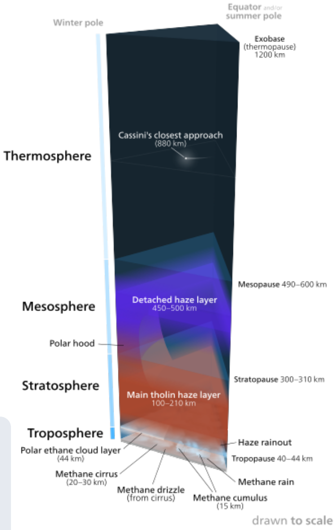
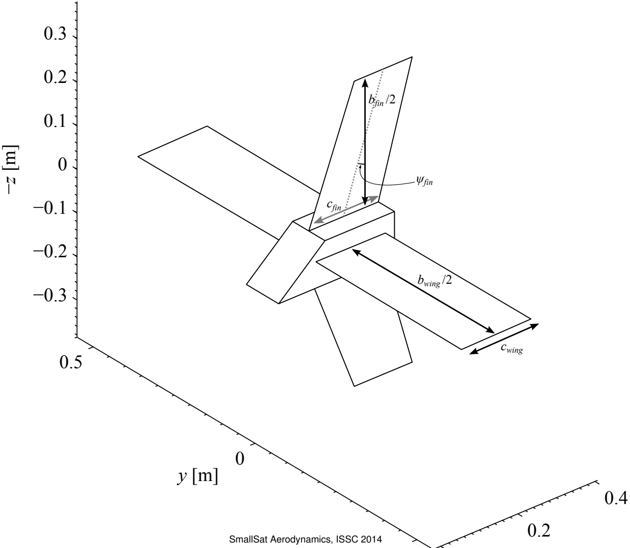


Image credit: Kelvinsong

Atmospheric Entry

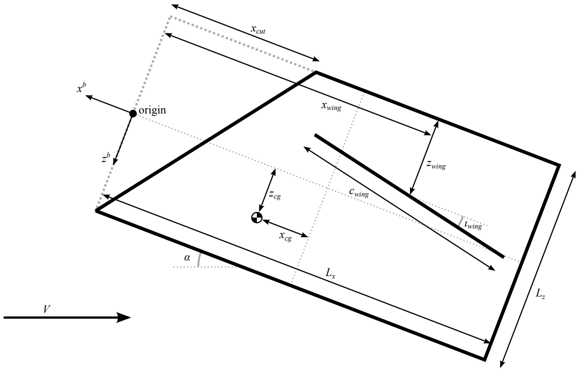
Options available that wouldn't be elsewhere

Isometric view of modified 3U CubeSat



Unusual 3U CubeSat Derivative

Important design parameters

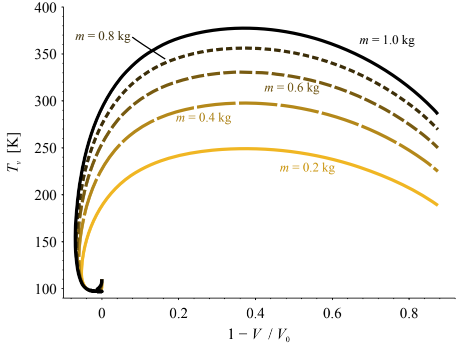


- Center of gravity shifted to stabilize at nonzero angle of attack
- Front of vehicle cut to increase L/D
- Wing location and incidence angle also important
- If done properly little/no heat shielding needed

Example Trajectories – Surface Temperature

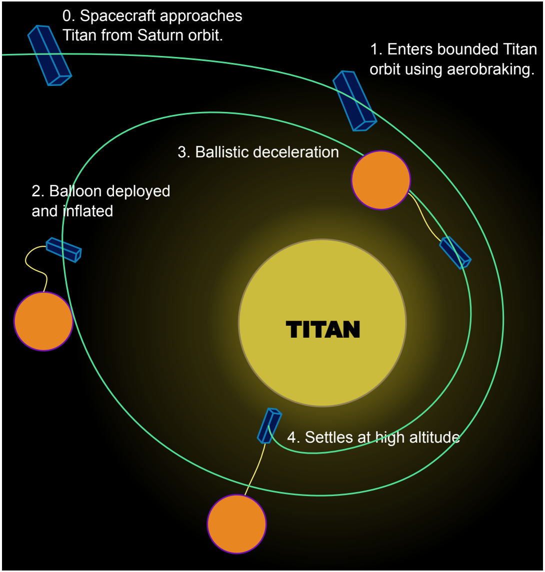
Varying mass for Titan entry

- Initialized in a circular orbit at the altitude with atmospheric density of $1 \times 10^{-8}\ kg/m^3$
- Loosely optimized design with trimmed L/D of about 1.0
- Plot of surface temperature history as vehicle slows down



Mass	Max T_v	Max q	No. of orbits	No. of days
0.2 kg	249.12 K	1.52 Pa	25	4.45
0.4 kg	297.77 K	3.11 Pa	50	8.72
0.6 kg	330.75 K	4.73 Pa	75	12.99
0.8 kg	356.12 K	6.38 Pa	100	17.26
1.0 kg	377.51 K	8.03 Pa	125	21.53

High-Altitude Inflatables



Inflatable serves two purposes

Decreases ballistic coefficient

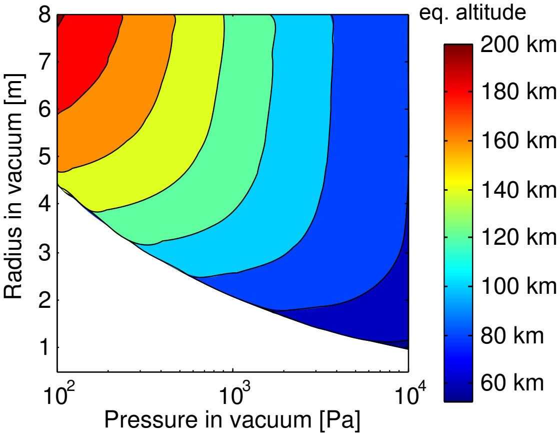
Provides bouyancy (this is a very unusual way to get L/D)

Eventually settles at an altitude with an atmospheric pressure below that of the balloon

Becomes a packaging and materials problem

Equilibrium Altitude

1 kg payload; vacuum temperature = 100 K



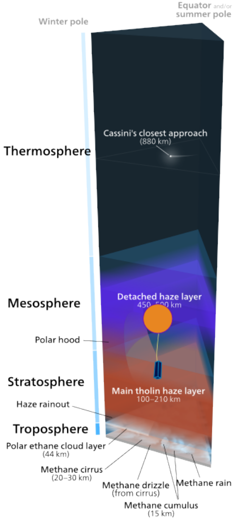


Image credit: Kelvinsong

Long-Endurance Aircraft on Titan?

Probably not, but the aerodynamics are amenable

Let's take it as an assumption that a spacecraft shaped like an airplane could enter Titan's atmosphere.

How much power would it require to stay in the air?

$$P_R = \frac{C_D}{C_L}\sqrt{\frac{2W^3}{\rho_\infty S C_L}} \quad (1)$$

That is, for a fixed aircraft, changing planet and atmosphere,

$$P_R \propto \sqrt{\frac{g^3}{\rho_\infty}} \quad (2)$$

A plane flying at "sea level" on Titan requires only 2.5% as much power as one on Earth

But there's no oxygen, and very little sunlight.
Is the methane usable? Can you have a glider?

Conclusions

- Small spacecraft can be subjected to an interesting variety of gas dynamic environments
- Some of them are unique, and others apply to all spacecraft
- Some result in new opportunities, such as reduced heat shielding to enter and explore the atmospheres of Solar System planets and moons
- Others could be useful based only on optimistic assumptions
- The more relevant conclusion is that these environments will impact the mission, and they must be taken into account during planning

Acknowledgments

- Sara Spangelo, for talking me into making a talk for this conference
- Caltech, for hosting our event for the second time
- Gregory Josselyn at NASA Ames for helping me setup NASA Research Park as an alternate site (and thumbs down to the government shutdown for putting an end to this alternative).
- The rest of the committee for doing most of the work
- All the NASA authors whose public-domain images I used!