AEROSPACE ENGINEERING

UNIVERSITY of MICHIGAN ■ COLLEGE of ENGINEERING

Characterization of Entry to Solar System Atmospheres for Chip-Sized Spacecraft

First Interplanetary Small Satellite Conference

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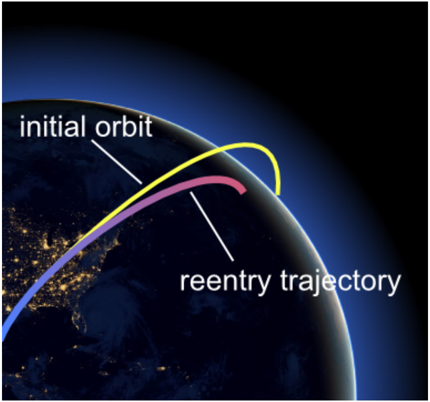
Basics of Atmospheric (Re)entry



Important trends

Density: $\rho_{atm} \propto \exp(-h)$

Drag:

$$D = \frac{1}{2}\rho_{atm} V^2 C_D A_{sc}$$

Heating:

$$\dot{q} \propto \rho_{atm} V^3$$

- Use the atmosphere to slow down (w.r.t. planet/moon surface)
- But descending tends to make you speed up!
- Max heating occurs a bit after the point where the two are equal

A survey of unexpected reentry results

***Columbia*:**

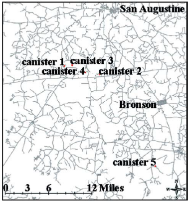


Image credit: Szewczyk, N. J., Mancinelli, R. L., McLamb, W., Reed, D., Blumberg, B. S., and Conley, C. A. "*Caenorhabditis elegans* Survives Atmospheric Breakup of STS-107, Space Shuttle *Columbia*.", *Astrobiology*. 2005, Vol. 5, 1-16

Mir:

http://www.eagletribune.com/latestnews/x1912985329/NASA-Amesbury-rock-came-from-Soviet-spacecraft, accessed June 15, 2013

Cosmos 954: (with a nuclear reactor on board!)

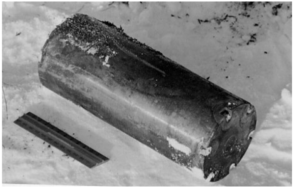


Image credit: Patera, R. P. and Ailor, W. H. "The realities of reentry disposal." *Advances in Astronautical Sciences*, 1998. Vol. 99, pp. 1059–1071, Figure 5

Some less well-known reentry incidents

Survey continued

Stardust: heat shield appeared to have been dramatically over-designed

Freedom 7 (John Glenn): Decided to reenter with retro rockets attached

Zond 5 and Zond 8: Missed skip re-entry after circumlunar flight; 20+ g max acceleration

Vostok 1: Service module failed to detach and spherical reentry vehicle; large oscillations but pilot remained conscious

Image credit: SiefkinDR (Creative Commons, RKK Energiya Museum)

"Usual" breakup pattern for (unprotected) reentry

Why don't we see more very thin debris?

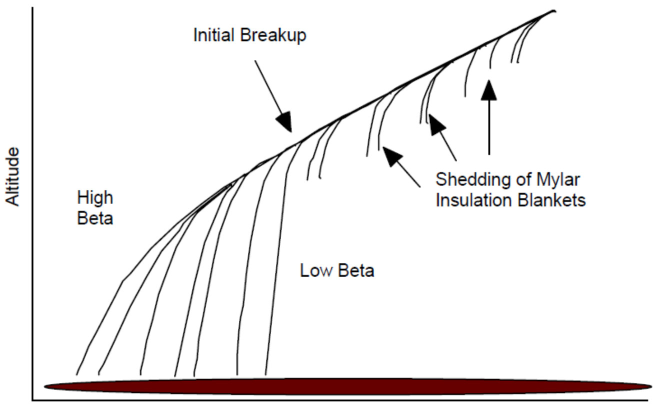


Image credit: Patera, R. P. and Ailor, W. H. "The realities of reentry disposal." *Advances in Astronautical Sciences*, 1998. Vol. 99, pp. 1059–1071, Figure 4

But the Mylar blankets are pulled down to a lower altitude than they would normally be if they reentered alone.

What it means for small (small == thin) spacecraft

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

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

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

(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.

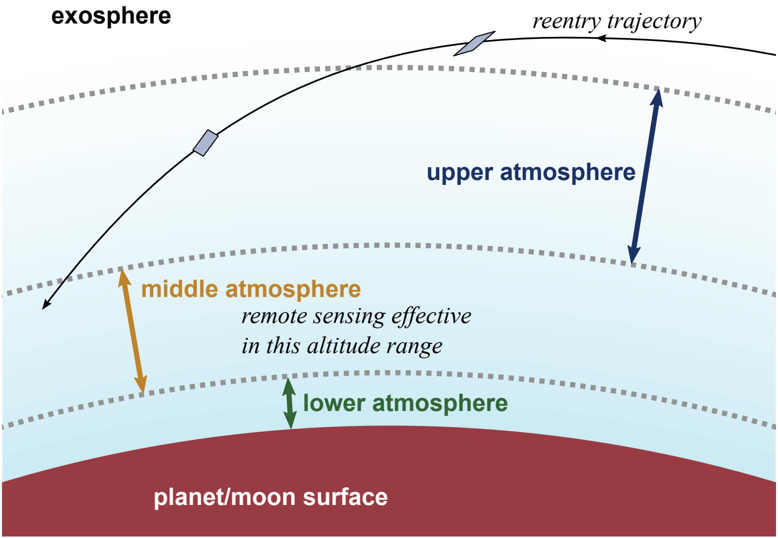
Max heating:

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

Heating is proportional to spacecraft thickness.

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

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



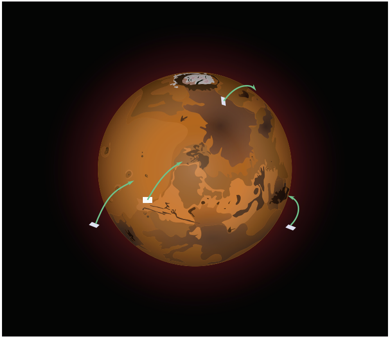
Alternatives. . .

Some favorable aspects of chip-scale atmospheric sensors

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

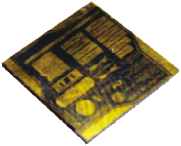
Advantages of chip-scale atmospheric entry sensors:

- 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 about other atmospheres?

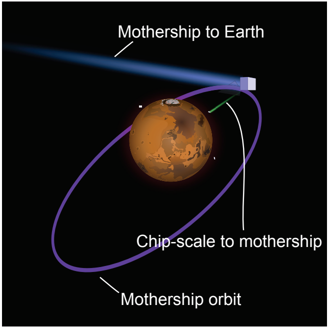
Motivation for larger, more capable satellites

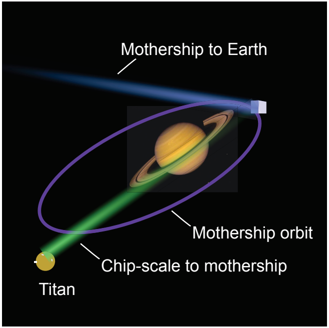


Very small (1 cm × 1 cm × 0.03 mm) chip-scale spacecraft are great for entry.

Image credit: Atchison, J. A. and Manchester, Z. R. and Peck, M. A. "Microscale Atmospheric Re-Entry Sensors." *International Planetary Probe Workshop.* 2010. "Sprite," slide 7.

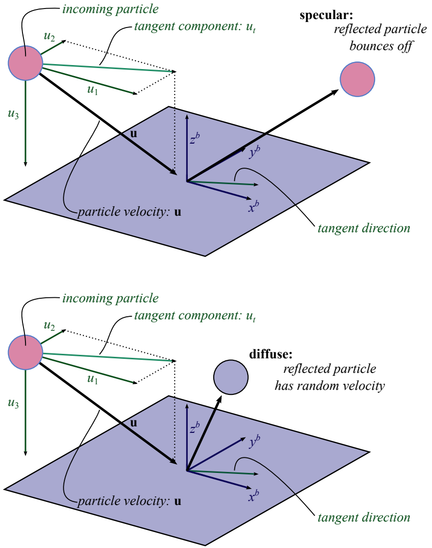
But communication is more challenging away from Earth





Justifies larger spacecraft . . . if you can get them to enter.

Free molecular aerothermodynamics



Essentials:

Molecules are sparse enough that they impact the surface with their full velocity (i.e. they don't interact with each other)

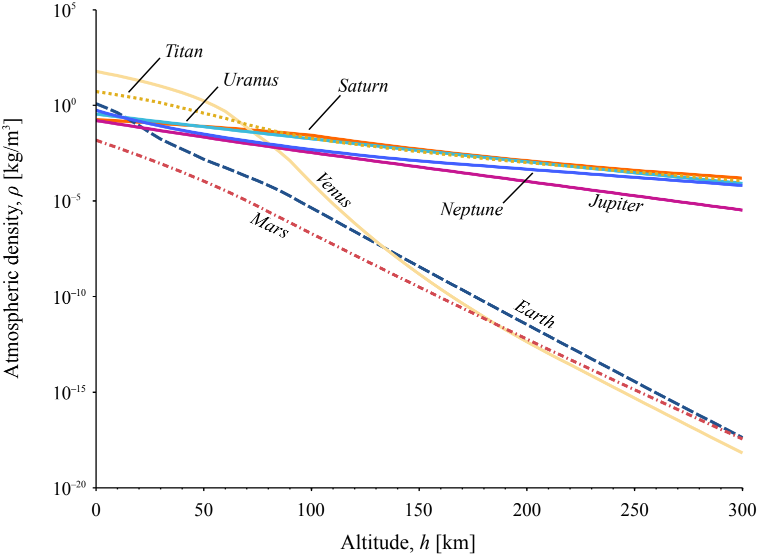
Most of them (85-100%) reflect off in equilibrium with the surface

Important effect for thin bodies because it creates a force along the surface

Specular reflections don't transfer any heat!

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



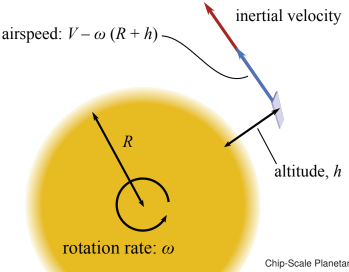
What makes an atmosphere hard (or easy) to enter?

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? $\dot{q} \propto \rho_{atm} V^{3}$

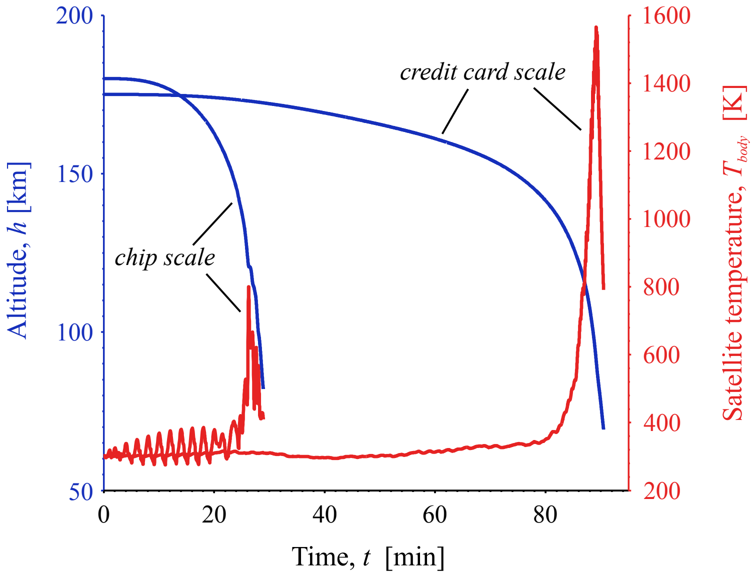


A planet's rotation can also be very important.

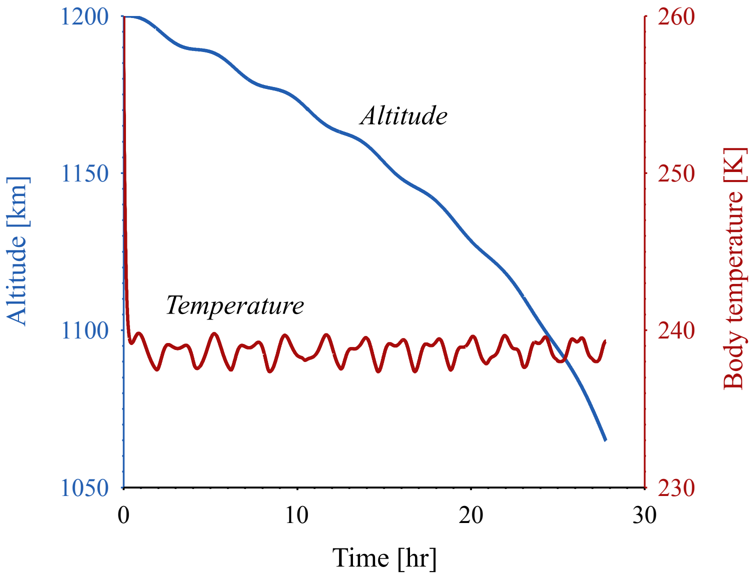
Especially for the gas planets (which rotate really fast, ~once per 10 hrs)

Sample results for Earth

Tumbling, credit-card–scale (1mm thickness) and chip-scale (0.032 mm thickness)

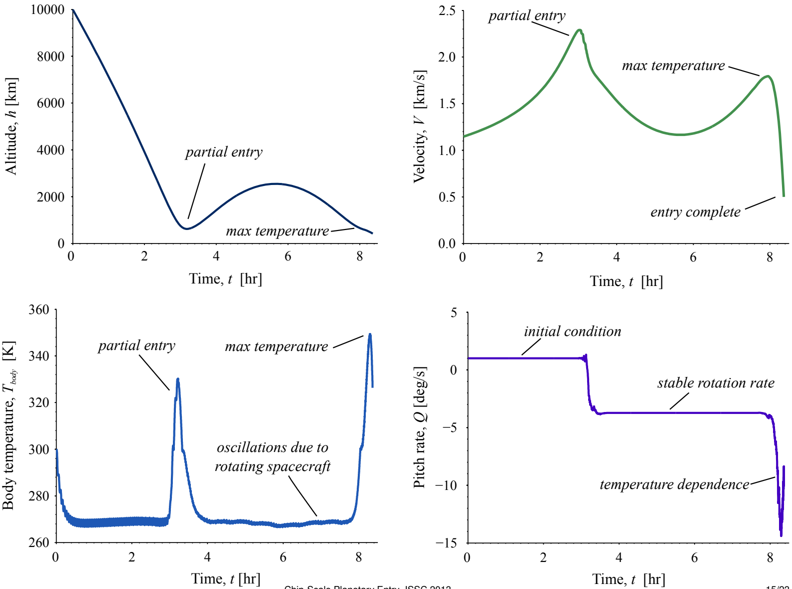


Ok, what about Titan?
Easy from orbit, but a mothership in Titan orbit is hard



Superorbital Titan entry example

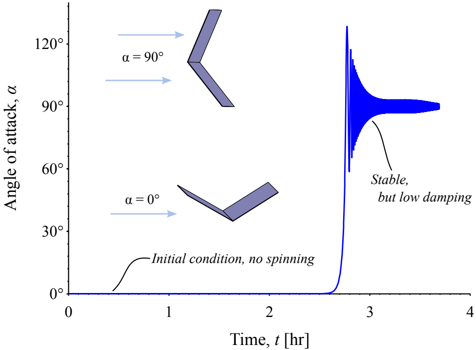
Even a credit-card–scale satellite can make it, but window is narrow



Conclusions so far. . .

- Can maybe survive entry for Earth, Venus, Mars, and Titan with tumbling if thickness $<$ about 0.05 mm
- Not feasible even in optimistic assumptions if thickness is about 1 mm
- Except for Titan!

Aerodynamic stabilization



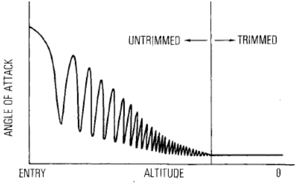
Angle of attack during entry into Titan's atmosphere, initialized from a Saturn orbit.

Goes to high drag (α close to $90°$), but takes a long time to damp.

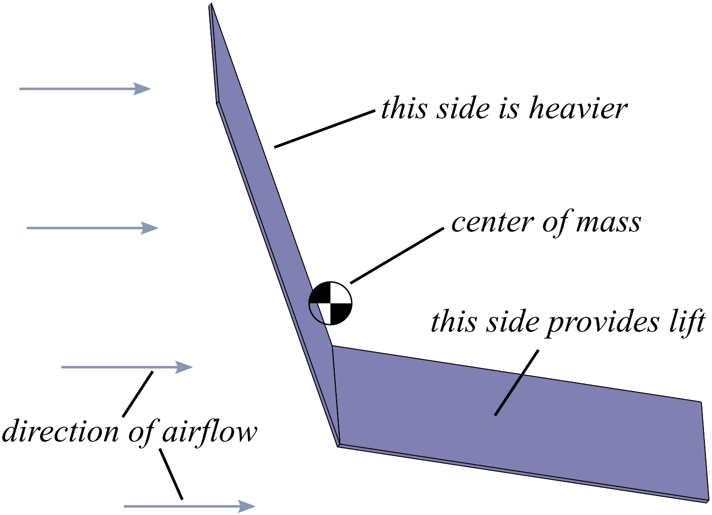
Doesn't dampen if initial rotation exceeds $\sim 10°$ per second

Similar behavior observed for "ballistic entry vehicles" (warheads):

Image credit: Platus, D. H., "Ballistic Re-entry Vehicle Flight Dynamics." *Journal of Guidance*. 1982. Vol. 5 pp. 4–16

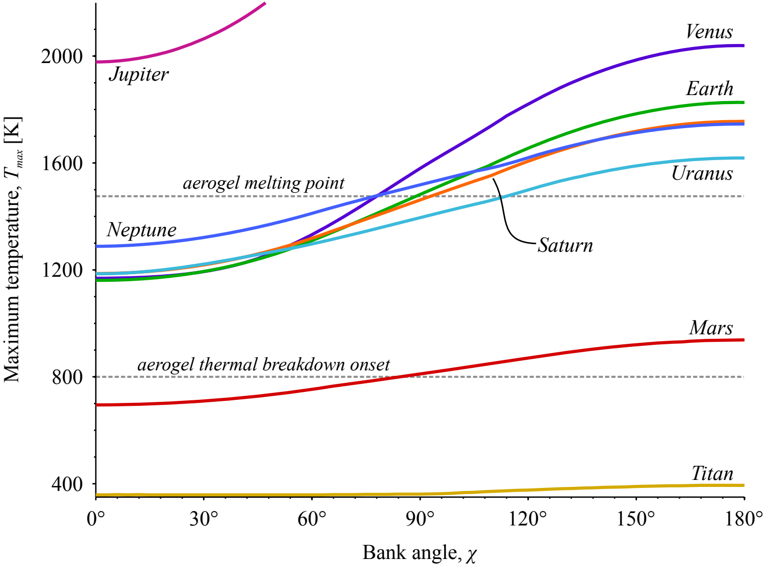


Passive lift?



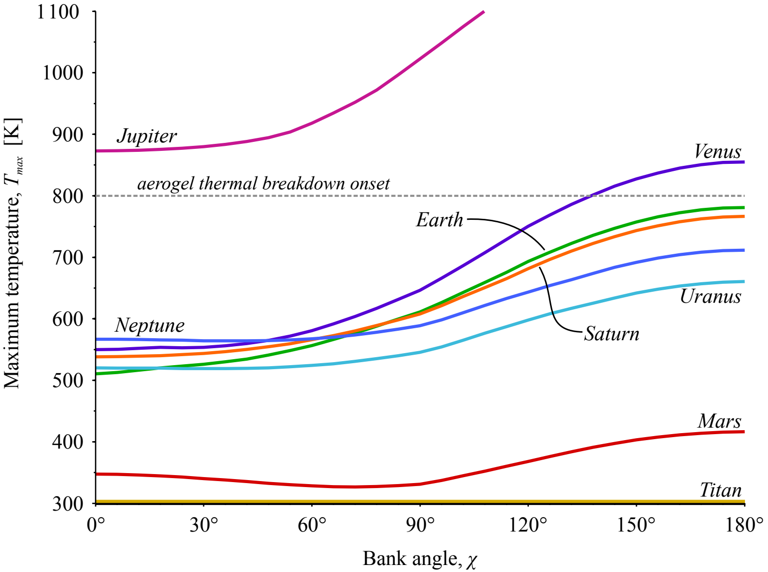
Results: credit-card–scale (1mm thickness)

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



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

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



Conclusions

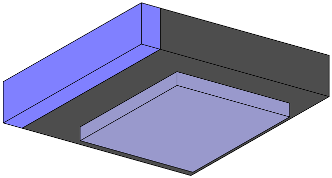
- Aerodynamic stabilization decreases heating
- Possible to stabilize in a lifting (or “dunking”) orientation with a shifted center of mass
- Dampens initial rotation rates up to about 10 deg/s
- Martian entry is possible if starting from orbit and thickness < 0.05 mm
- Each atmosphere except Jupiter is feasible with some minor heat shielding (aerogel?)
- Used fairly conservative assumptions, except that probably cannot start in a circular equatorial orbit for the gas planets

Acknowledgments

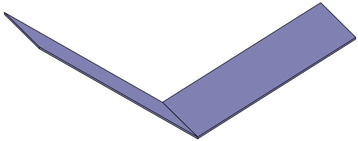
- This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.
- James Smith (JPL, Caltech)
- Prof. James F. Driscoll (University of Michigan)
- AFRL (funding for computers, etc.)

I really had no idea where the results would take us in the design space.

What I thought initially:



Where it went:



Thank you for your time!

Questions?