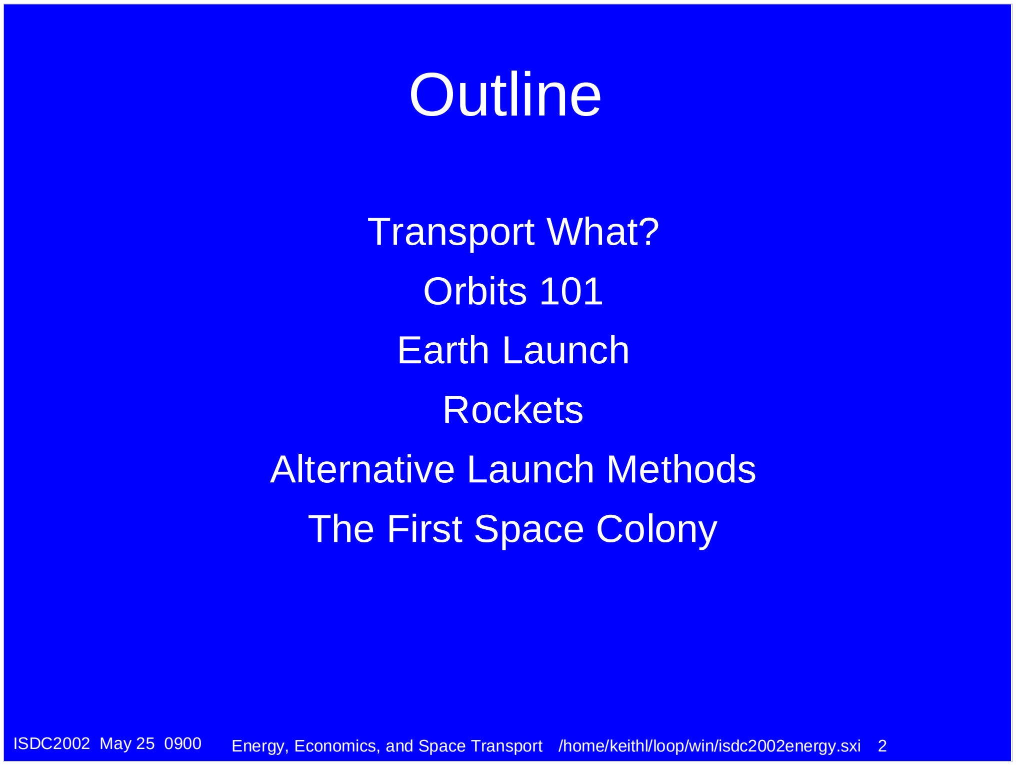
Good morning. When I was planning my Launch Loop paper for the afternoon, I mentioned to our session chair Dale Amon that somebody needed to talk about the economics and physics of alternative space transport. We need to define what we are doing before we talk about how to do it.

Well, guess who **somebody** turned out to be?

I'm getting too old for this...

So let's spend some time thinking about what is useful and what isn't. What you are about to hear is a mixture of physics, economics, engineering, opinion, speculation, and ignorance.

I hope I will leave you with a little more skepticism, and a little more hope. The space movement needs both.



I'lll start with a discussion of what we are really moving around out there.

Orbits figure into everything we do in space, so I will do a five minute mini-lecture - Orbits 101.

It all starts with earth launch, so we will discuss that.

I'll say a bit about rockets, and then move on to a few alternative launch schemes.

Finally, I'll share some surprising insights about the first space colony.

Metric Units

1 kilogram (kg) = 2.2 pounds

1 metric ton (T) = 1000 kg =0.9 english tons

1 kilometer (km) = 0.6 miles

1 meter/second (m/s) = 2.2 miles/hour

1 Joule (J) = 1 watt-second

1 Newton (N) = 0.22 pounds of force

1 gee = 9.8 meters/second/second

This talk will be in metric units. Here's some conversion factors for the non-scientists in the room.

A metric ton is 1000 kilograms or 0.9 english tons.

A kilometer is 0.6 miles.

One meter per second is 2.2 miles per hour

A joule is a measure of energy equal to one watt for one second.

A newton measures force, and is about 0 point 22 pounds of force.

One gee isn't metric, but I'll throw it in anyway. One gee is a velocity change of 9.8 meters per second every second.

What are we transporting, anyway?

+ People

+ Machines

-Frozen Spinach

-Rocks (shielding)

-Waste (engines, shrouds, …)

ISDC2002 May 25 0900 Energy, Economics, and Space Transport /home/keithl/loop/win/isdc2002energy.sxi 4

What are we transporting in space, anyway? We can talk about moving raw materials, but it is people and machines that make raw materials into something useful. People and machines require low acceleration, protection from radiation, and minimal transit times.

If an alternative launch system can't do that, it isn't worth very much.

Some launch systems abuse their payloads with high gees.

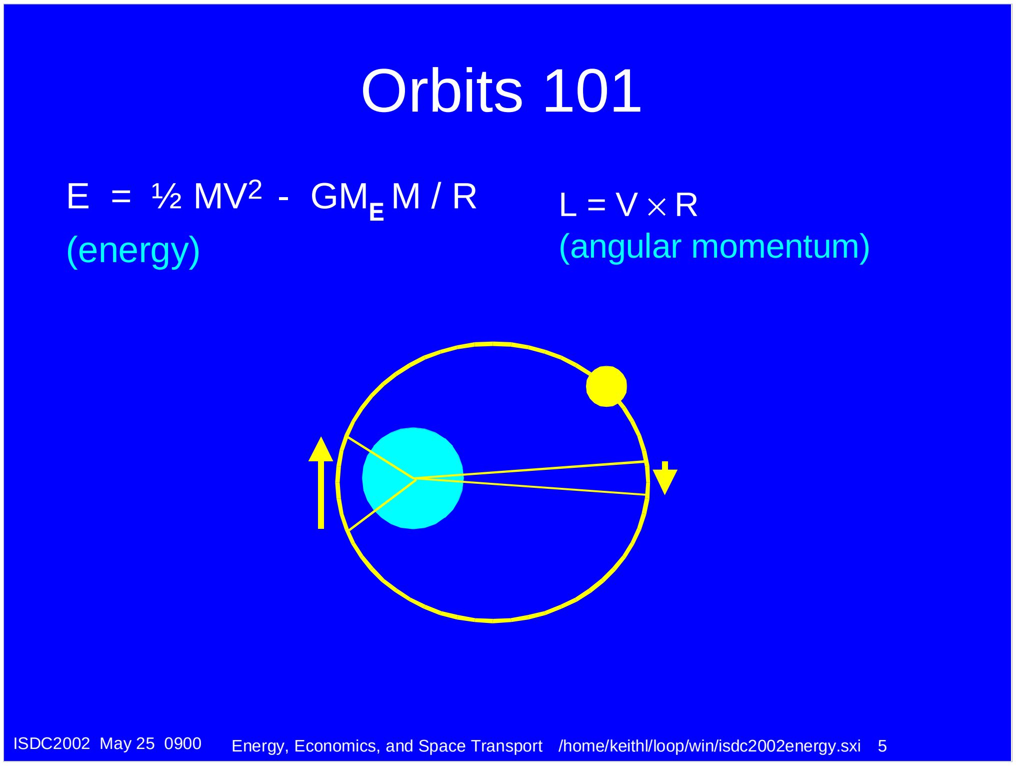
I call these "frozen spinach" launchers, because there is not much else they are good for. Some transport systems are designed for moving "space raw materials", that is, rocks.

But about all rocks are good for is shielding -you need fragile machines to turn rocks into something you can use.

Some of what gets moved has no intrinsic value.

Used rocket engines, tanks, shrouds, etc. are just useless mass.

You need them to operate, but they are a nuisance after you use them.



All orbits can be characterized by their energy and angular momentum, along with some other parameters.

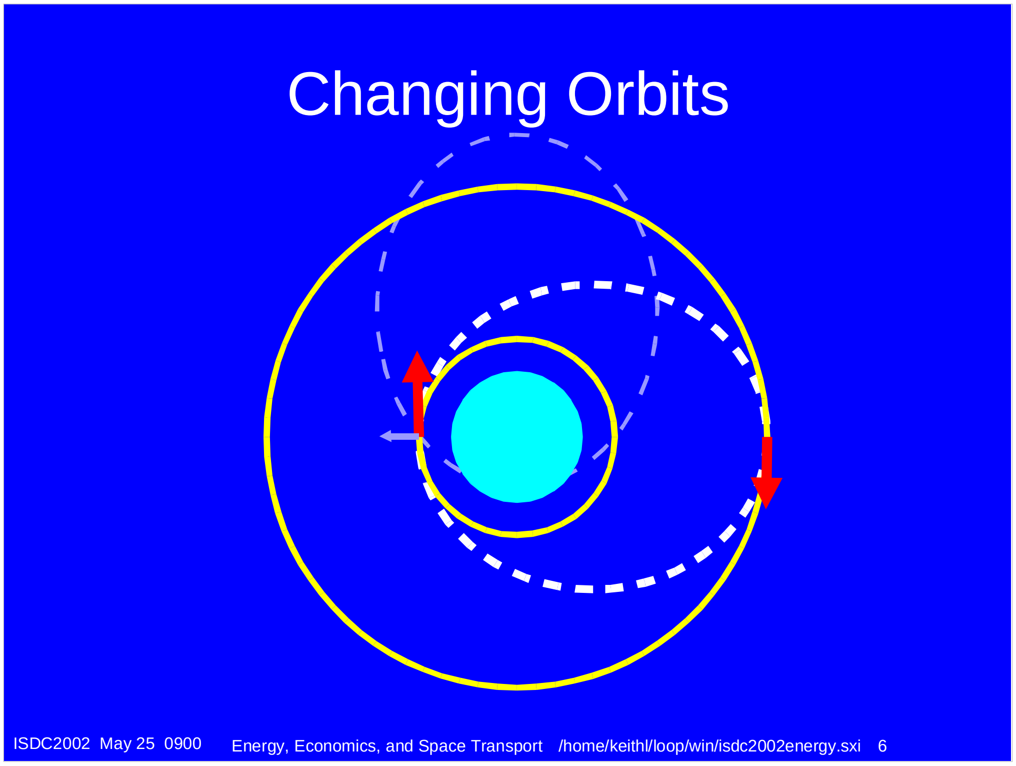
The energy values from this equation are actually negative, and become more negative the deeper into the gravity well you go.

As R gets smaller the negative energy increases.

L is the angular momentum, and is constant for a given orbit.

For a given energy and angular momentum, these two equations say is that the closer you get to the body you orbit, the faster you go.

To climb out of the gravity well, you must add energy, that is, reduce the negative gravitational energy.

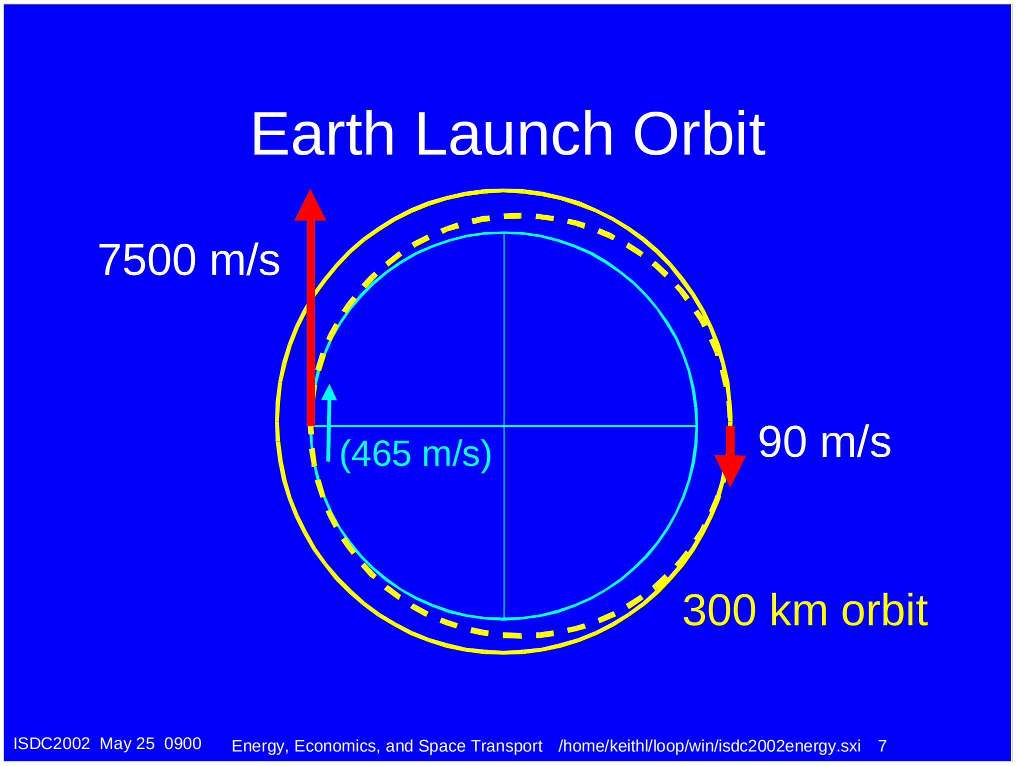


To get from anywhere to anywhere else involves changing orbits. To go from a low circular orbit to a high one involves two velocity changes, one HERE that puts you into an elliptical transfer orbit, and one OUT HERE that takes you out of the elliptical transfer orbit and injects you into a circular orbit.

You always need at least two velocity changes to move between circular orbits. With solar sails, the velocity change is continuous, and the transfer orbit is a spiral.

The velocity change should always be in the direction of orbital travel.

Thrust up or down mostly changes the shape of the orbit, possibly making it intercept the body you are orbiting. In other words, thrust up can make you crash down, half an orbit later.



Launching from the equator adds the rotation speed of 460 meters per second to all launches.

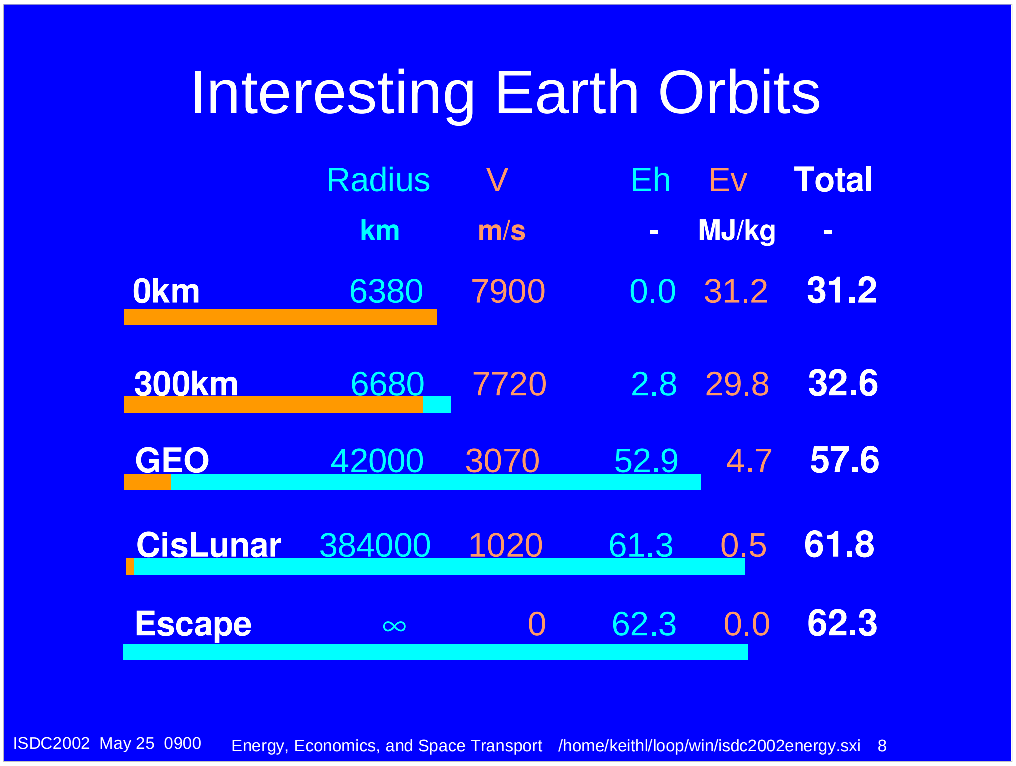
Launching into an elliptical transfer orbit with an apogee of 300 kilometers requires an addtional 7500 meters per second.

If you stayed in that transfer orbit, you would come back down to the surface about 90 minutes later.

To move into a circular orbit, you need to add an additional 90 meters per second, half an orbit later.

Any space transport system that can add only one of these velocity vectors is only half a system.

Some other method, such as a rocket, is needed to complete the orbit change.



People and machines will mostly be going to Earth orbits.

This table and graph shows the energy necessary to get from the Earth's surface to various interesting orbits. The orange part is the velocity or kinetic energy, and the blue part is the gravitational or potential energy. I've normalized the energies so they are positive, relative to the earth's surface.

Without mountains or air, we could orbit at the surface, at a speed of 7900 meters per second. A practical orbit at 300 km altitude is slower, 7700 meters per second, with a relatively small amount of gravitational energy. Way up at geosyncronous orbit, orbits move more slowly and most of the energy change is gravitational.

The moon orbits very slowly, and is close to escape energy.

So a low orbit orbit requires about 30 megajoules per kilogram, and escape requires about 60, with the rest of the orbits between.

Interesting Solar Orbits

	Radius M km	V km/s	Eh MJ/kg	Ev MJ/kg	Delta MJ/kg
Earth Escape					60
Mars	230	24	310	290	150
Asteroids	420	18	570	160	280
Pluto	5900	5	860	10	420
Solar Escape	∞	0	880	0	430

After escaping from the earth, we need additional energy to move outwards.

Getting to Mars requires an additional 150 Megajoules per kilogram, the asteroids 280 megajoules.

Pluto and solar escape both need a bit over 400 megajoules per kilogram.

These tasks are made somewhat easier by clever choice of trajectory.

By swinging around planets and firing rockets deep in gravity wells, you can steal some momentum and energy and move to higher orbits with less fuel.

So, What's A Megajoule?

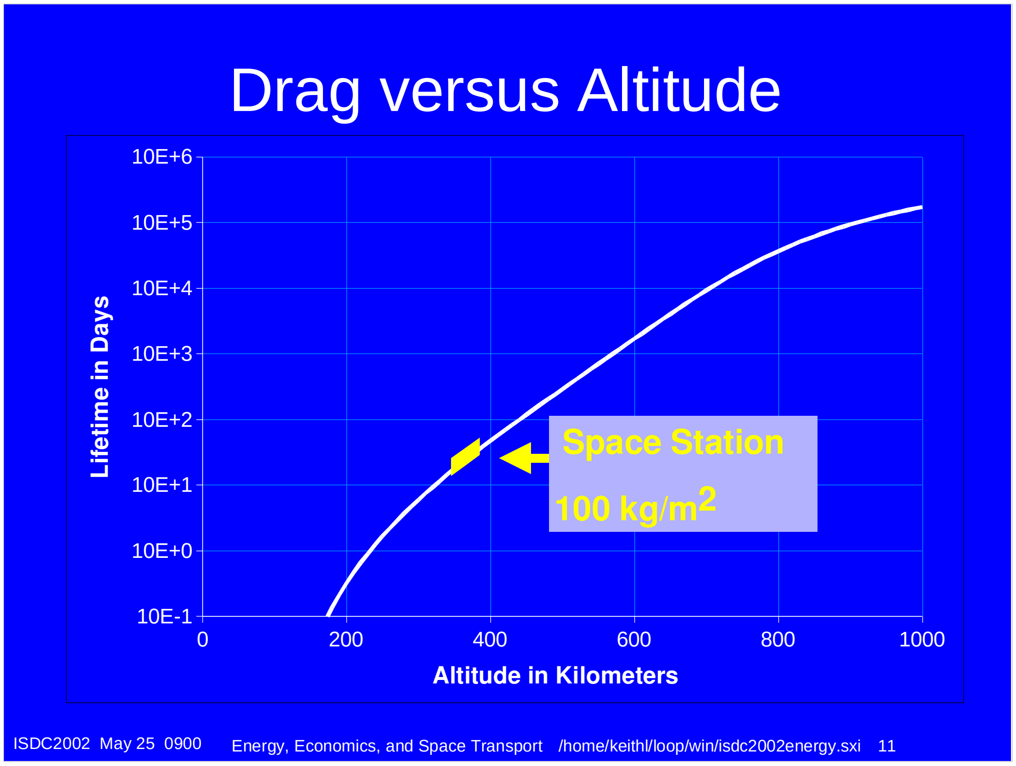
- » 32 MJ per kilogram to orbit
- » 9 kilowatt-hours - $0.40 to $1.40
- » 0.22 gallons gasoline - $0.25 to $0.40
- » 1.1 $meters^2$ daily sunlight, Denver
- » 2.3×10^{-6} space shuttle fuel energy
- » 9.2×10^{-6} daily earth tidal energy loss

So, what the heck is a megajoule, anyway? We need about 32 megajoules to put a kilogram into a decent orbit, assuming 100% efficiency. As electrical energy, that is about 9 kilowatt hours, which costs between 40 cents and a buck forty depending on where you buy your power. 32 megajoules is about a quarter gallon of gasoline, or the sunlight on a square meter of Denver on a sunny day. 32 megajoules is about 2 millionths of the energy required to launch a shuttle,

or 9 millionths of the energy lost to tidal friction in a day.

We'll have fun with the last number later in the talk.

The main thing to remember is that the kinetic and gravitaional energy actually needed to orbit a kilogram is pretty cheap - about a buck - and a tiny fraction of the energy that goes into launching a space shuttle.



The achilles heel of space launch is air drag.

Without air, you could launch at full orbital velocity from the earth's surface, and orbit just above the mountaintops, as you can do over the moon.

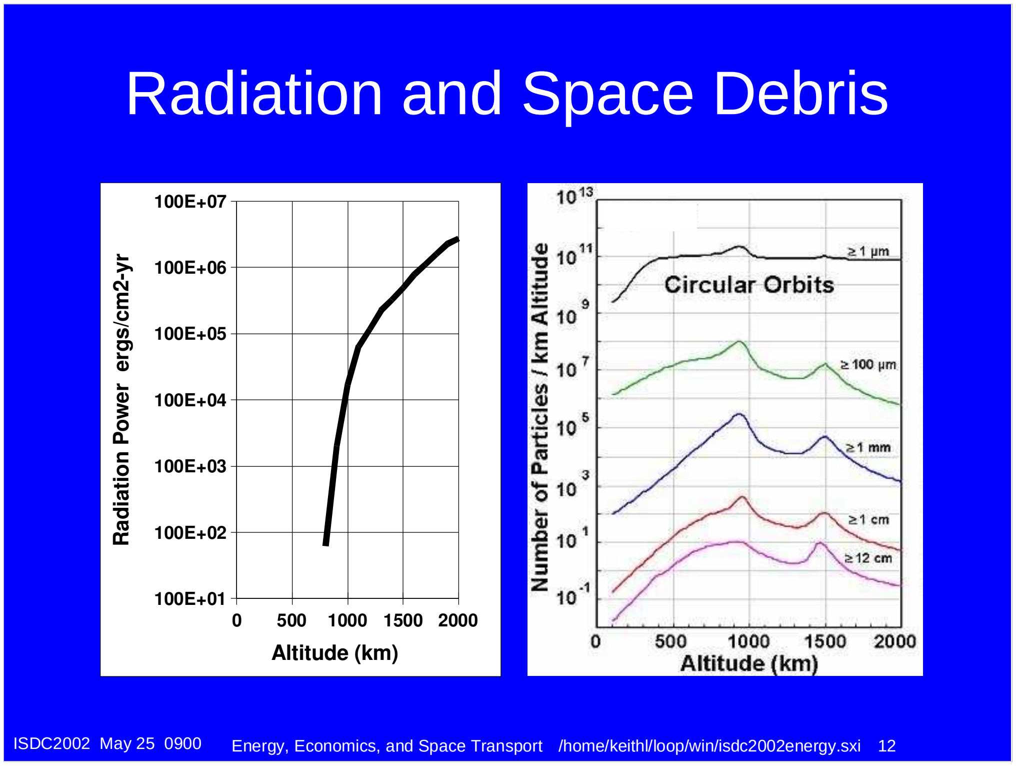
The atmosphere gets thinner with altitude at an exponential rate, but even at 400 kilometers altitude, there is enough air drag to bring down the space station in about a year.

This sets the lower limit of useful long term orbits.

Orbiting space transport systems must spend most of their lifetime at high altitudes, or they must devote a lot of energy simply to staying in orbit.

Even if you manage to stay in orbit, the drag behaves like a high velocity atomic bombardment, which will erode orbiting structures at rates of microns per year. At low orbits, the paint gets etched off the space shuttle doors in just a few days.

Thin structures do not last long in low orbit.



So why not orbit higher? When the drag goes away, the space junk will play. There are two flavors of space junk - particle radiation belts, and debris from previous space missions.

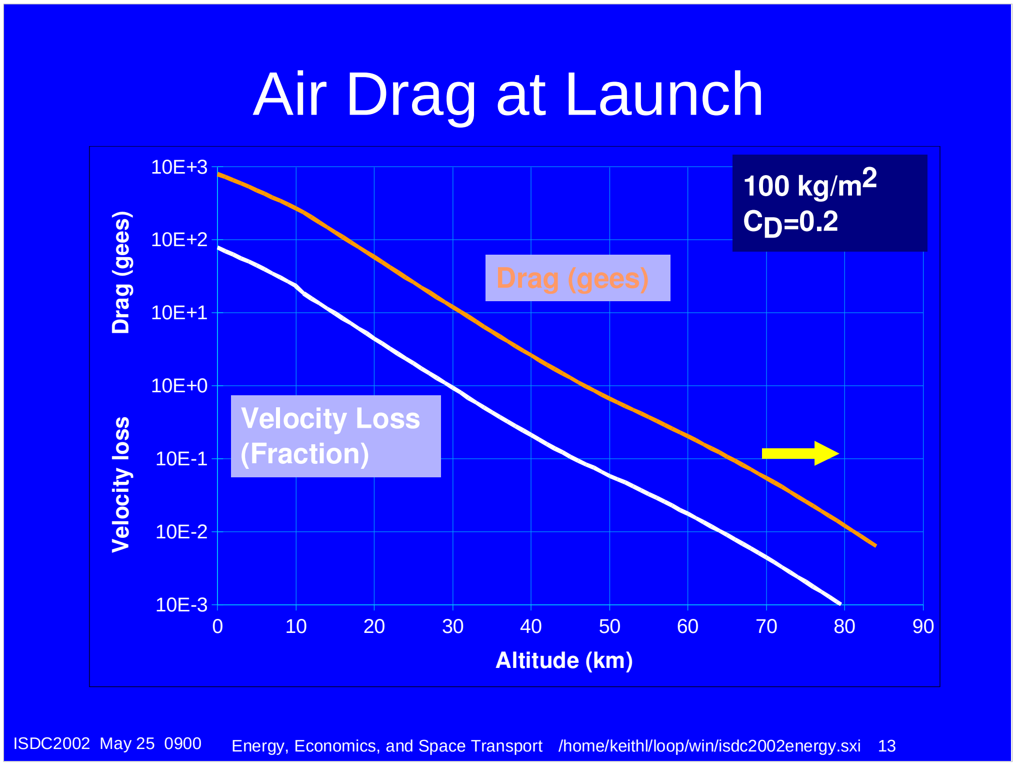
Without drag to remove this garbage, it accumulates to bombard space systems with hypervelocity bullets and radiation.

The result of a successful high volume launch system might be to increase orbital debris to the point that space travel becomes impossible.

And every time something is hit by space junk, it emits fragments that add to the problem.

Mass driver propulsion systems, that get around by emitting streams of bullets, are pretty heinous when you think about it. Even the gas from our rockets will be orbiting for a long time, slowly etching away the vehicles that follow, until it is blown away by solar light pressure.

So we can't orbit too high, or too low either.



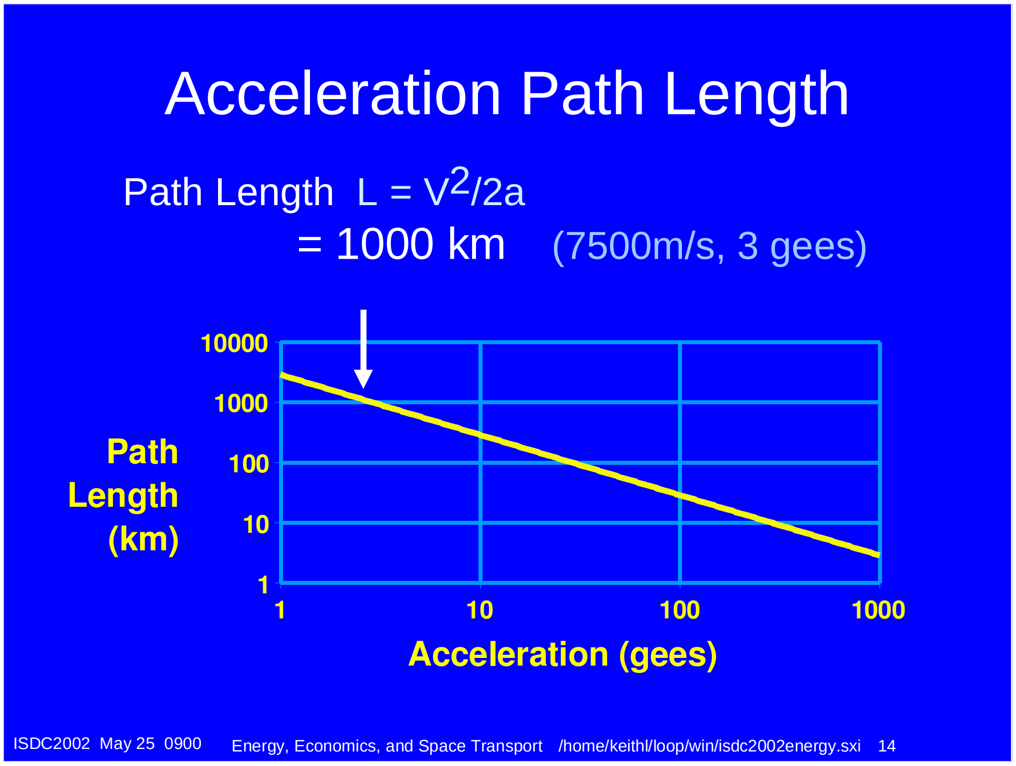
What if we apply all 7500 meters per second down here at the surface, with only a little apogee boost up there?

Well, there's that pesky atmosphere again.

For a streamlined vehicle of about space shuttle density, the air drag is enormous at the surface; tens of thousands of gees.

In fact, you want to be above 70 kilometers altitude or you will lose most of your initial horizontal velocity just punching through the remainder of the atmosphere.

If you don't do your surface acceleration in a vacuum chamber, you will lose even more. When you exit the vacuum chamber you will be thrown against your straps with a strong negative gee force. Launchers that travel up the side of mountains will never reach orbital velocity, and as first stages they are inferior to solid rocket boosters which operate at much higher altitudes.



Another problem with the "up the mountain" launchers is that mountainsides are far too short.

From freshman physics, we know that we need an acceleration path length equal to the velocity squared divided by twice the acceleration.

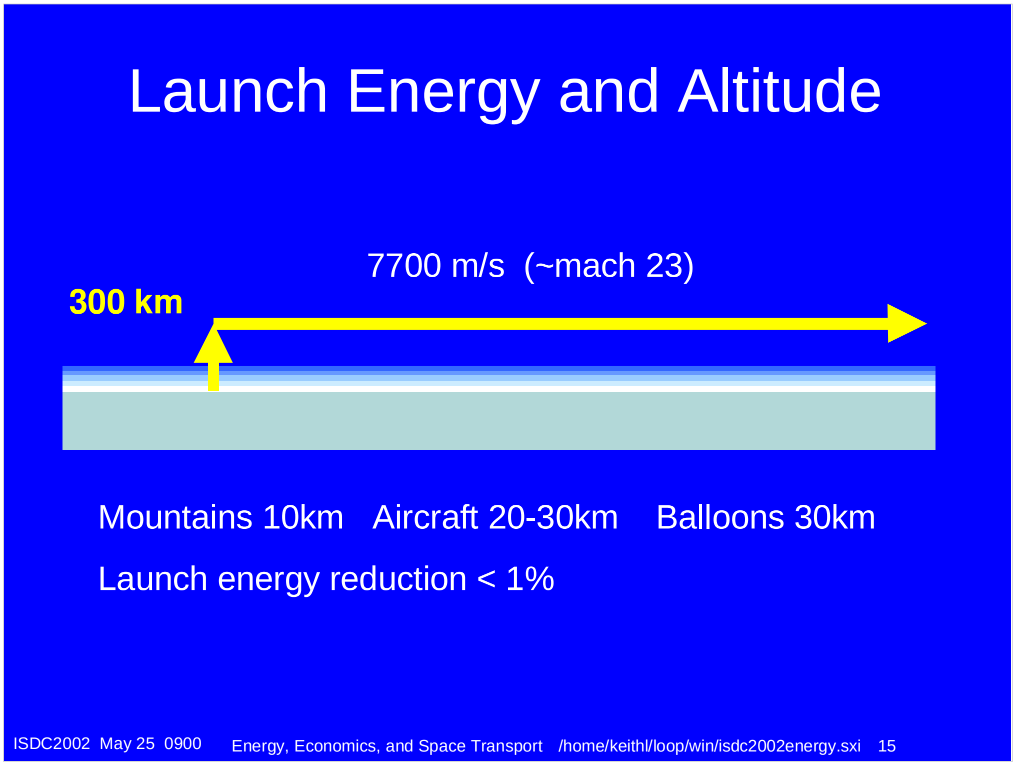
Accelerating to orbital velocity at the equator requires a path length of 1000 kilometers at a tolerable 3 gees.

At 100 gees, the path length is reduced to 30 kilometers, but you will also crush your ribcage into your spine.

Your equipment will not fare much better.

Commercial machinery falls apart under gee loads most people can stand, and semiconductor manufacturing equipment can be trashed by fractions of a gee.

High gees means no high tech.



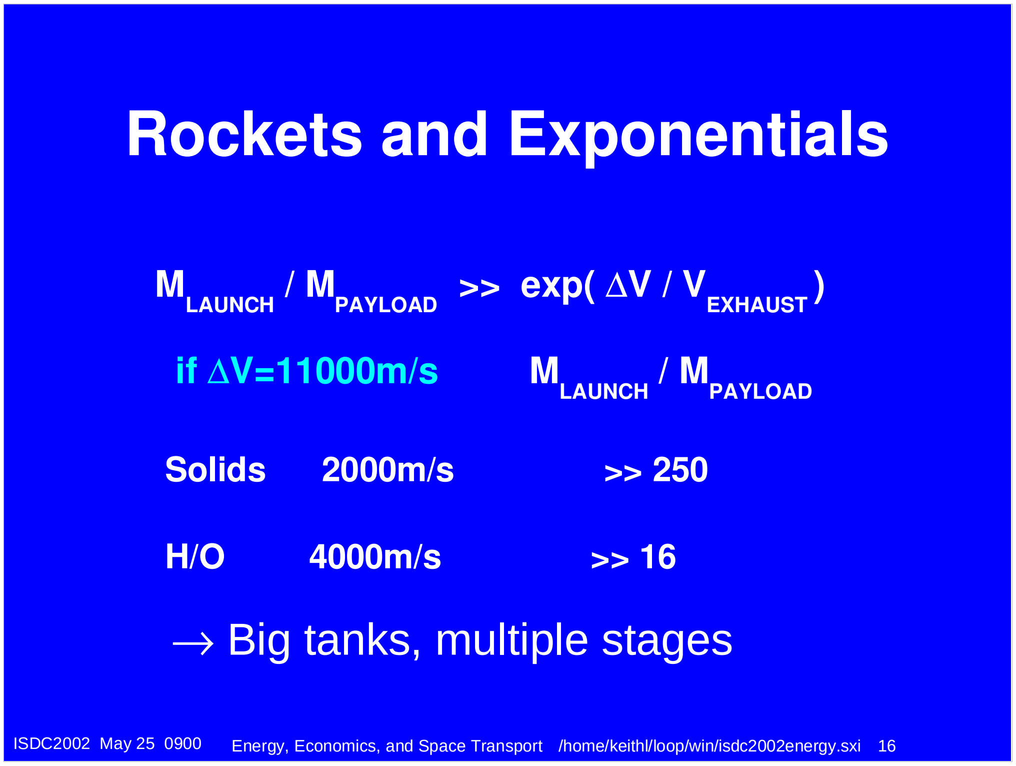
Some folks talk about launching from balloons or aircraft to reduce the amount of energy necessary to get into space.

This diagram shows the relative amounts of energy required for altitude versus the energy needed for orbital velocity.

No atmospheric vehicle is going to get high enough to significantly reduce the gravitational energy, much less the total energy.

The main thing you get from an aircraft launch is less air drag, which means you can build a lighter vehicle, and that saves a little money.

But now you must equip a plane as a launch pad.



Rockets are how we get around in space, now. What's wrong with rockets?

The problem is the nasty exponential.

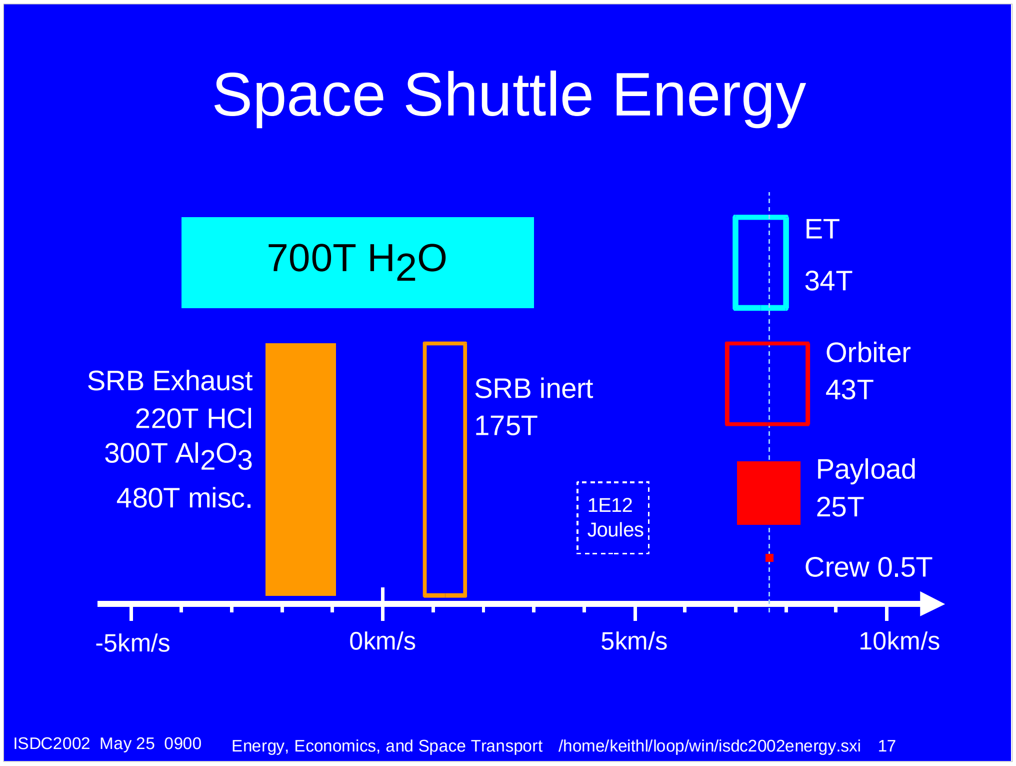
Rockets spend most of their energy lifting the fuel they will need later in the launch, along with the tanks to store it and the engines to burn it.

Even if tanks and engines were weightless, lifting the fuel follows this exponential equation, a function of the delta V velocity change needed and the velocity of the rocket exhaust.

Solid rocket boosters are simple and relatively cheap, but you need much more than 250 times as much fuel as payload to ride solids into orbit..

Liquid hydrogen engines are better, the ideal ratio is only 16.

But hydrogen is an expensive propellant and the engines are complicated and dangerous. As a result of the nasty exponential, you need big tanks and multiple stage rockets.



For a chemical rocket, the space shuttle is pretty good.

Solid rocket boosters are cheap, and make a good first stage. Liquid hydrogen rockets have faster exhaust and make a good second stage. The area of these rectangles represent the energy and velocity of the components of the space shuttle.

The horizontal position is the velocity of the component when jettisoned, and the area is the energy. Note that the solid exhaust, and the solid tanks, represent most of the energy of the shuttle.

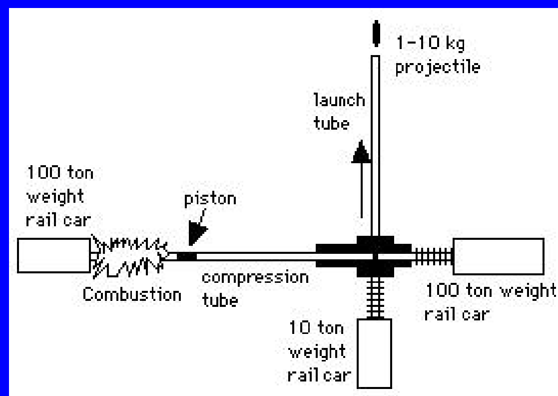
The next biggest chunk of energy is the hydrogen engine exhaust. This rectangle represents the external tank. Most of the orbiter mass is the main engines, and the wings needed to return them to Earth. The really useful parts are the payload and the crew.

If we could do without the rest, we could accomplish our missions much more cheaply.

Accelerator Launchers

External Energy & Mass supply

(i.e.) Gas Guns

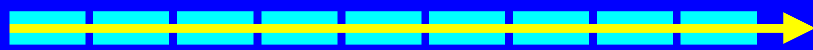


The next few slides will present some accelerator launchers. These get around the "rocket problem" by using both external energy sources and external reaction mass. Thus, we bypass the exponential scaling of rocket systems. The classical accelerator launcher is the cannon, and its modern equivalent is the gas gun. Gas guns produce a stream of very high energy hydrogen that pushes small payloads to high speeds. However, we have not made one yet that can reach orbital velocity.

The gee loads are tremendous, and atmospheric drag limits surface-based launchers to a fraction of orbital speed.

In general, no surface-based launcher can do the whole job of launching useful payloads to orbit and beyond. Most of the launch velocity must be added above 70 kilometers altitude.

Lunar Mass Drivers



Cost scales with $M \times V^3$

Electronics \$ = $K \times$ peak power

$P_{SEGMENT} = M \times v \times acc.$

Acceleration = V^2 / L_{TOTAL}

$\therefore \$ = {}^1/_2 KMV^3 / L_{SEGMENT}$

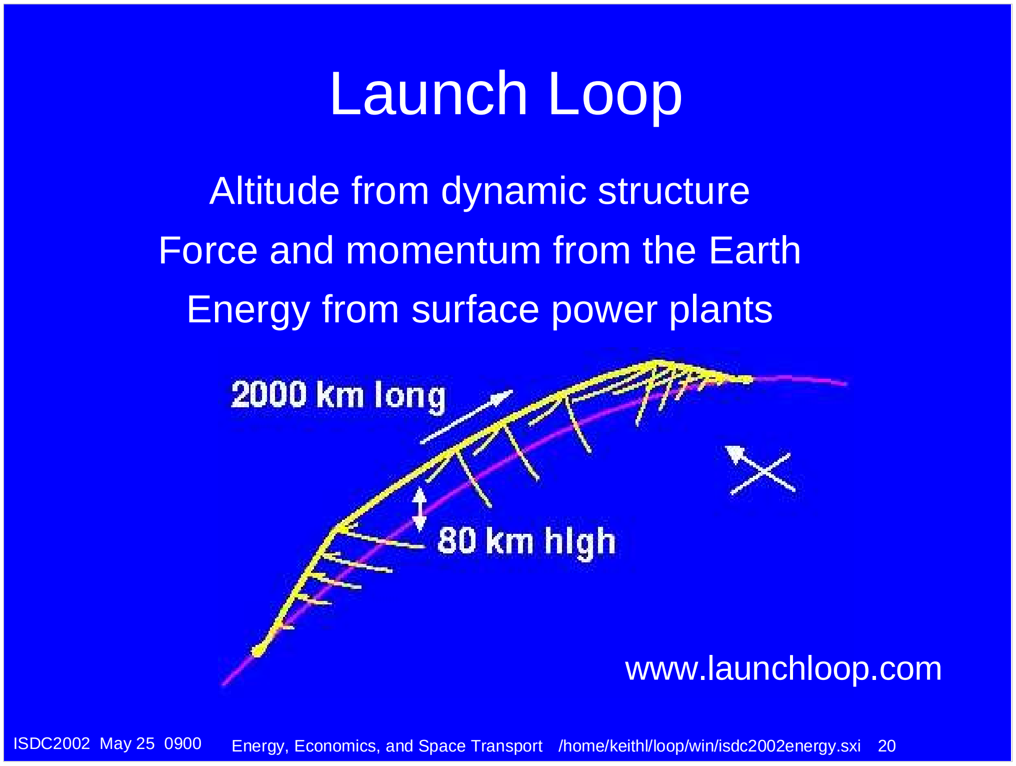
$(1T / 40g) \times (2.4km/s / 20m/s)^3 \rightarrow \mathbf{4 \times 10^{10}}$

We have a lot of electomagnetic mass driver fans here.

Some have proposed using them for launching payloads off the Moon. There is a problem, though.

The power handling circuitry of a mass driver scales with the mass, and the cube of the velocity. The power needed for acceleration goes up with velocity, while the acceleration needed goes up with the square of the velocity. Switched segments of mass driver coils can't get a whole lot longer than the payload.

If we scale from the original Princeton experiments, with a payload of 40 grams and an exit velocity of 20 meters per second, to one ton payloads and the lunar escape velocity of 2400 meters per second, we get a scaling factor of 40 billion. If the Princeton model cost 25 dollars, a lunar mass driver might cost 100 billion. Longer segments might improve this, but not by orders of magnitude. Mass drivers cost too much!



I'll be telling you more about Launch Loops this afternoon.

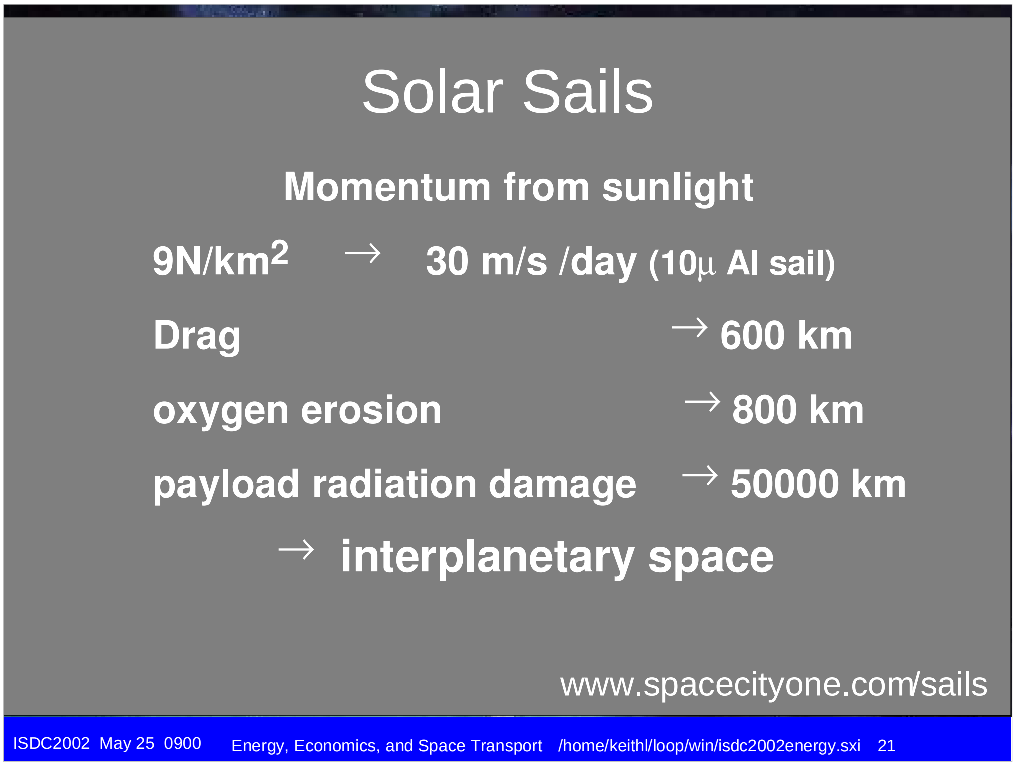
The Launch Loop stores energy and momentum in a very thin, very long continuous iron loop moving at 14 kilometers per second.

This supports a dynamic structure at 80 kilometers altitude.

The launch path is 2000 kilometers long, allowing payloads to be launched at up to 11 thousand meters per second with an acceleration of less than 3 gees.

The whole structure is supported by the Earth's surface, and is powered by conventional electric power plants on the surface.

The Launch Loop can put hundreds of tons into orbit per hour at costs below 10 dollars per kilogram.

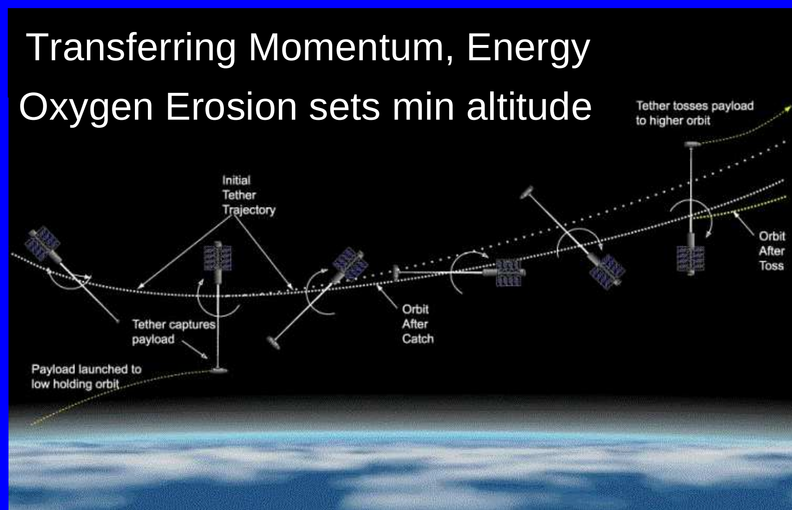


It's always fun to get something for nothing. Solar sails gather momentum from sunlight. Light provides very weak thrust, though, so sails have to be very large to move significant payloads. However, they can be very thin.

If you are patient, a few years of continuous solar sail thrust can get you almost anywhere in the solar system.

The tiny thrust limits the lower altitude at which a sail can work, about 600 km. Up to about 800 km, it will slowly get etched away by monatomic oxygen. It will take months to travel through the Van Allen radiation belt, and this will destroy most sensitive payloads -certainly humans! But for radiation-hardened small spaceprobes, solar sails may be just the ticket.

Tethers



www.tethers.com

Tethers are neat. Later today, Robert Hoyt of Tethers Unlimited is going to tell us about using tethers to store energy and momentum for boosting payloads to higher orbits.

Like solar sails, tethers are thin and are easily eroded by atomic oxygen at lower altitudes.

But if you have a "partial" launch system that can give you some altitude and some of the launch velocity, tethers can take you the rest of the way.

Tethers can form the "other half" of a complete low cost space launch system.

And now for something completely different - the first space colony.

Here's a picture of the first space colony. It was terraformed by these cyanobacteria about 2 billion years ago.

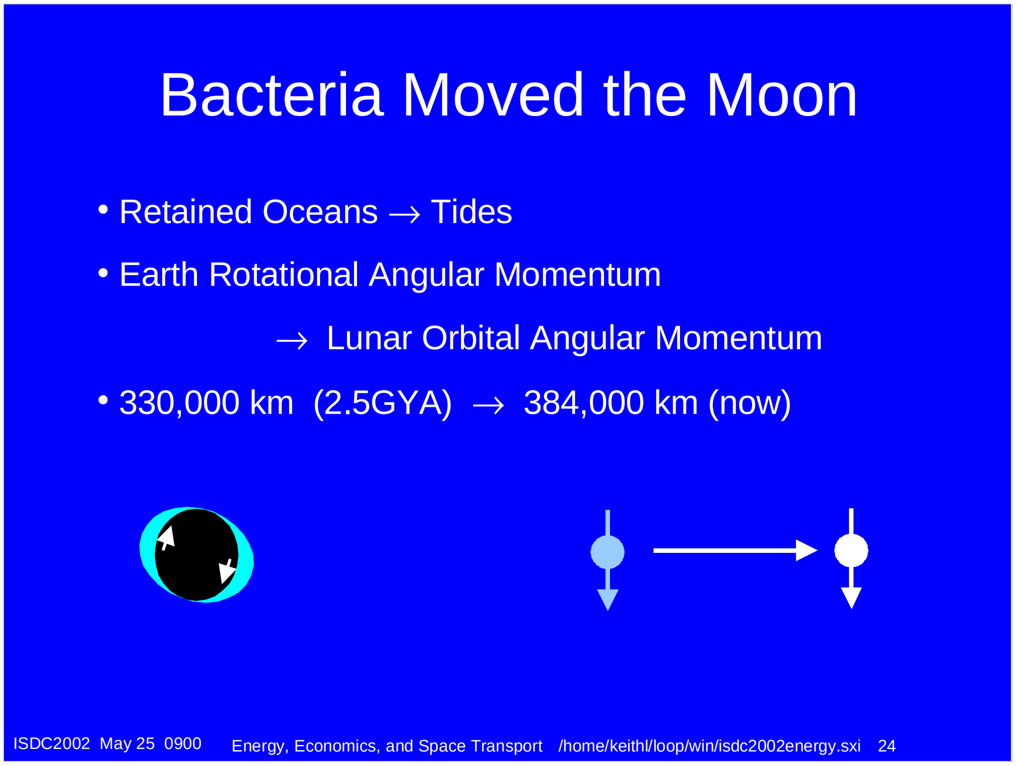
They caused the Earth to retain its liquid ocean.

They maintained the earth's temperature and created an oxygen atmosphere. Free oxygen produced the minerals that allowed plate tectonics, concentrated mineral deposits, and did many other things that make this ball of rock livable.

Without the bacteria, the Earth would be a furnace like Venus, or an frozen airless rock like Mars, and there would be no exploitable mineral ores.

But what does this have to do with space transportation?

These little bacteria did more than just terraform a planet.



Bacteria moved the moon.

Because we still have liquid oceans, we have tides.

The friction of ocean tides against bottom and shore causes the tidal bulge of the ocean to lead the moon, which slows down the Earth’s rotation and speeds up the Moon.

This caused the moon to move quite a ways outwards in its orbit.

Without life, the ocean would evaporate or freeze, there would be no tides and no large changes in the moon’s orbit.

Therefore, cyanobacteria, or blue-green algae, or SEA SCUM, moved the moon.

Conclusions

If scum can do it, we can

The energy needs are modest

The attention needs are high

Wishing won't do it

Well, if SCUM can do it, WE can do it, too. We can move moons and create new, living worlds. The energy needs are modest, if we develop practical low-cost alternatives to rockets.

However, the attention needs are high. Many of us will have to devote long hours to inventing, raising money, cutting metal, and pushing payloads. There will be a lot of embarassing failures.

But wishing, writing letters, begging politicians, and sitting here watching someone talk will NOT GET US OUT THERE.

We need the energy that is in this very room, applied to study, finding customers, writing papers, designing and BUILDING MACHINES.

Space will still be there in billions of years, but you and I won't be. LETS GET OFF OUR BUTTS AND DO IT.

Extra Slides Follow

Space Shuttle Launch

T (s)	H (km)	V (m/s, including Earth rotation)	
0	0	410	KSC 28° N
50	12	870	max Q
120	50	1680	SRB staging
510	110	7900	MECO
2400	300	7700	Apogee (OMS2)

Rockets

Reaction mass for momentum

~10 Tons/sec (shuttle)

Power Levels

~40 GWatt (shuttle)

Non-Chemical Energy Sources

Less Reaction Mass, Higher Power

Nuclear Thermal, Laser, Orion, ...

Rockets are self contained. They provide their own energy and reaction mass. At launch, the space shuttle is producing over 10 tons of exhaust per second, with a power level of 10 billion watts.

MORE LATER