Astronomy 330

This class (Lecture 25):
Rockets
Nick Kopp

Next Class:
Space Travel
HW 10 due
David Zordan
Sean Rohan

Music: Rocket Man – Elton John

Final Papers

- You must turn final paper in with the graded rough draft.
- Unless you are happy with your rough draft grade, then email me to convert.
- Final paper is due on last day of class.

Final

- December 12th @1:30-4:30pm in this classroom
- Designed to be a 2-ish hour exam, but allowed 3 hours.
- Will probably consist of 40 multiple choice/ true-false questions (2 points each), 3 small essay questions (17 points each), and 2 large essay question (40 points each).
- A total of 210 points graded out of 200 points.
- A normal-sized sheet of paper with notes on both sides is allowed.
- Multiple-choice is heavily weighted toward the last half of the course.
- Bring a calculator for easy math.

Presentation

- Nick Kopp: Theory/Reality of Interstellar Travel

Outline

- Interstellar Travel
- The speed limit
  - What's up with time and distance when you travel fast?

Issues and Incentives

- Assume there is intelligent life out there.
- Will they try to travel to us?
  - Is it worth it?
  - Exploration?
- If a civilization has been around for 1 million more years than ours…
- But interstellar travel is HARD!!!!
- Back thinking about autonomous probes..

Space Probed

- A single probe is constructed and dispatched to a nearby star system
- It surveys the system in an intelligent and exhaustive manner
- After which, the probe uses the energy and available raw materials of the system to reproduce itself .

Space Probed

- Dispatches its "children" onwards to repeat its mission in other star systems
- The parent probe is then able to choose whether it wants to stay in the system or not, depending on what it found
- Still need a way to get to other worlds.

http://www.biochem.wisc.edu/wickens/meetings.html

Energy into Propulsion

- For any type of space travel, we need an energy source to propel the vehicle.
- The basic idea is to convert some stored energy into *energy of motion* for the spacecraft
- Two ways basically:
  1. Process some sort of fuel
     - Carried onboard
     - Collected from space and processed
  2. Other, non-fuel-like energy source:
     - Solar (if near a star)
     - Gravity (using an astronomical body's gravity field to propel a ship)

We got a speed limit!

- No matter what we do, we can not go faster than the speed of light!
- That naturally occurs when one demands that the speed of light *must* be the same regardless of who measures it.
- This is completely counter-intuitive!
- Basis of Einstein's Theory of Special Relativity.

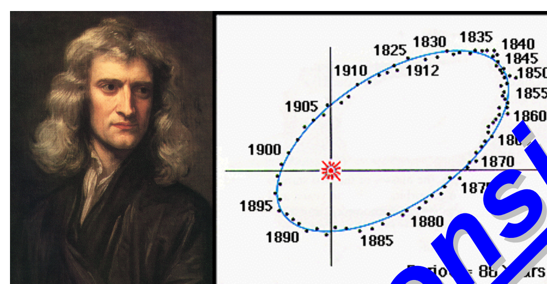
http://www.rpi.edu/dept/phys/Dept2/APPhys1/optics/optics/node4.html

How Fast is Light?

- The speed of light is $c = 3\times10^8$ m/s (186,000 miles per second)!
- How fast is that?
  - Around the Earth over 7 times in a second
  - From Earth to the Moon in under 2 seconds (it took the astronauts 2 weeks)
  - From the Sun to the Earth in a little over 8 minutes
  - From the Sun to Pluto in about 5½ hours
  - From the nearest star to Earth, about 4 years

Two Threads of Thought in Physics up to 1900

Mechanics
(Newton's Laws)



All motion is relative
No speed is special

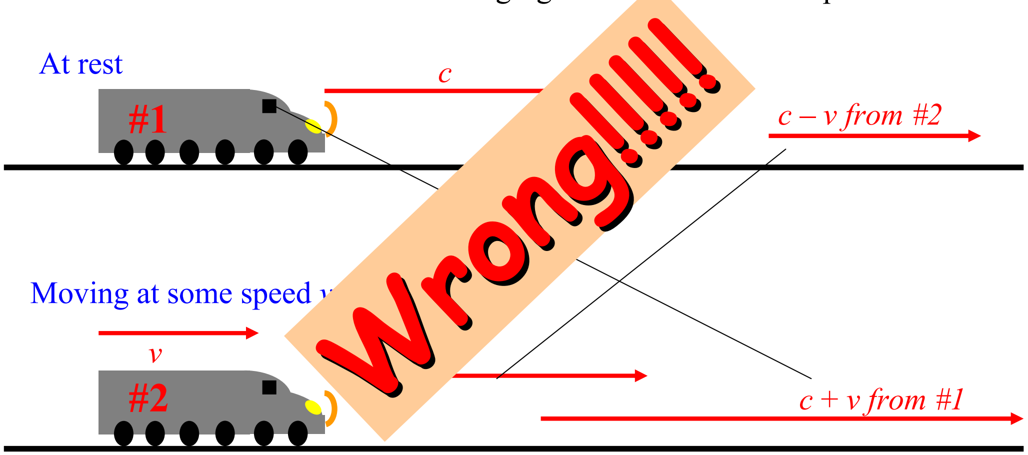
Electromagnetism
(Maxwell's Equations)

The speed of light is the **same** for all observers

Inconsistent!

Why Galileo and Maxwell Can't Both Be Right

Consider two locomotives emitting light from their headlamps:



Why Galileo and Maxwell Can't Both Be Right

So the speed of light can't be the same for everyone if Galileo – and our intuition – are right. But Maxwell says it is constant!

Something must happen. And what must happen for Galileo and Maxwell to be both right, is that there is a modification of time and distance. Remember

$$speed = \frac{dist}{time}$$

Distance and time become relative to the observer.

Approaching the "c"

- The clocks on a ship accelerating to "c" would appear to stop completely from someone at rest.
- The ship would appear infinitely thin in length along its direction of motion.
- The mass of an object as it approaches "c" becomes infinite
  - So does its kinetic energy– requires more power.

http://www.richard-seaman.com/Travel/Japan/Hiroshima/AtomicBombMuseum/IndividualArtifacts/

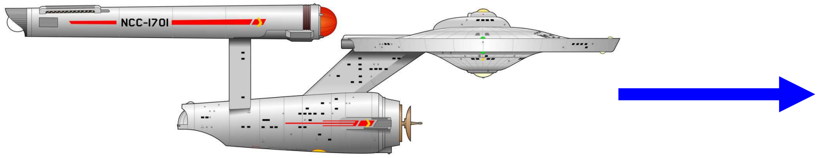
Gamma

The factor by which all of these changes occur is called "gamma"

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Counterintuitive Result #1

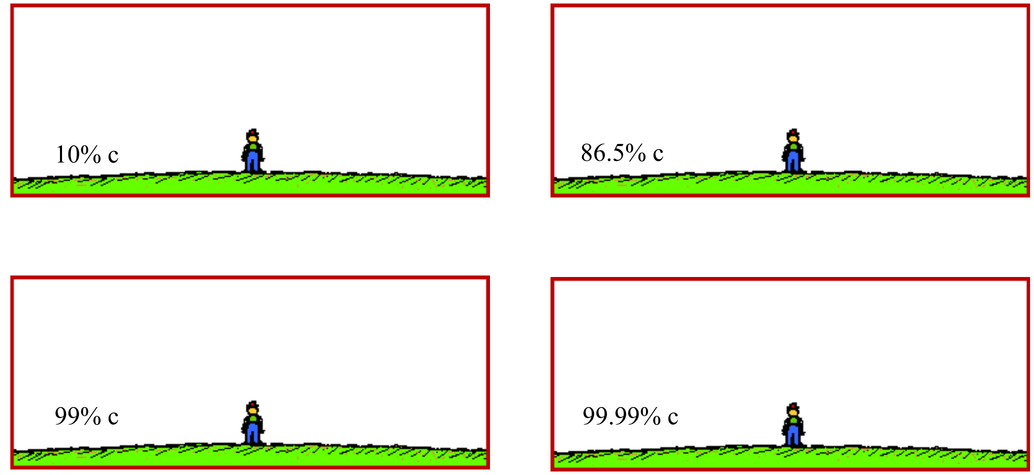
Moving objects appear shorter in the direction of relative motion (<u>Lorentz contraction</u>)



Fraction of the speed of light	% of original length
0.00	100%
0.001	99.99995%
0.01	99.995%
0.1	99.5%
0.5	86.6%
0.9	43.6%
0.99	14.1%

Counterintuitive Result #1

Moving objects appear shorter in the direction of relative motion (<u>Lorentz contraction</u>)



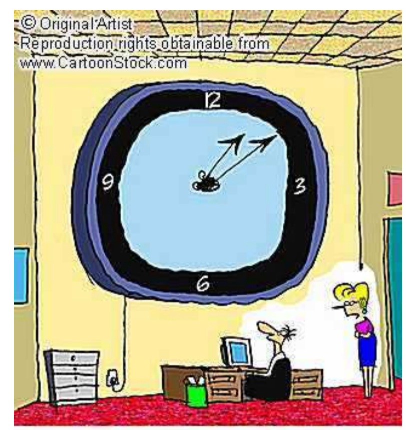
http://www.physicsclassroom.com/mmedia/specrel/lc.html

Length Contraction

- This effect has some benefits:
  - Outside observers will see that the length of the spaceship has shrunk.
    - This doesn't really help or harm us
  - But, from the astronaut point of view, the entire universe outside their window has shrunk in the direction of motion, making the trip shorter!
- It's all relative.

Counterintuitive Result #2

Clocks on Moving objects slow down

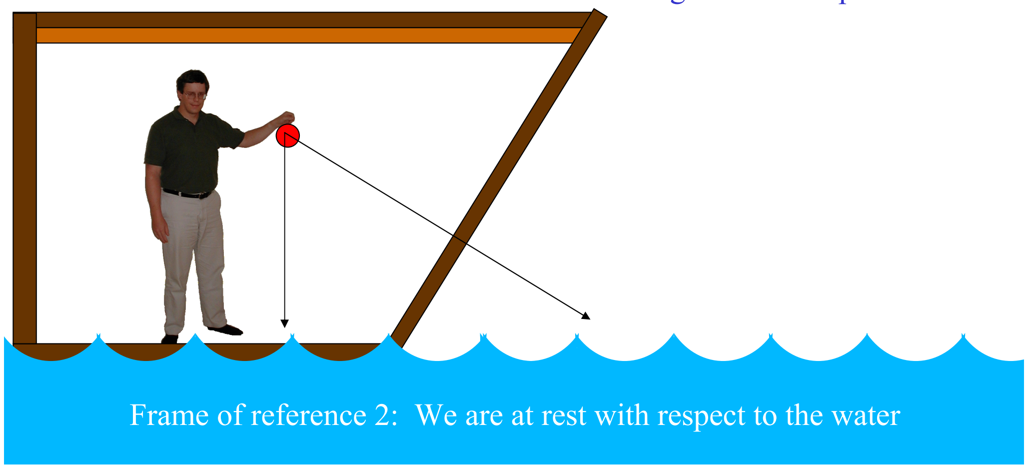


"Try not to watch the clock. It only makes the day go slower."

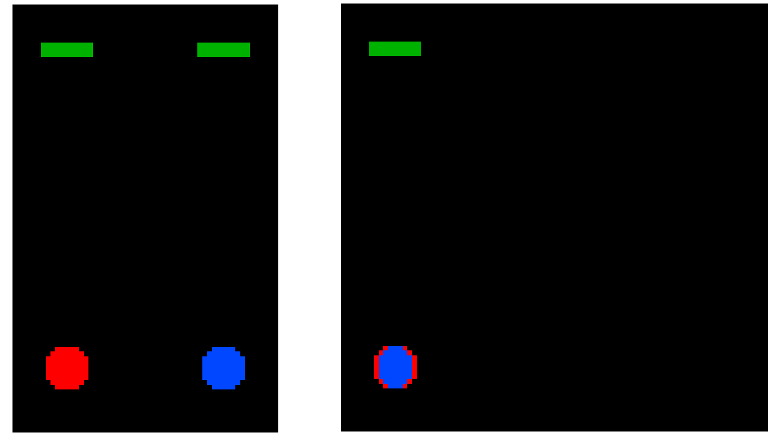
Galileo's ship thought experiment

No experiment within the ship's cabin can detect the ship's motion if the ship moves in the same direction at a constant velocity. This is still true, even when considering the speed of light.

Frame of reference 1: We are moving with the ship

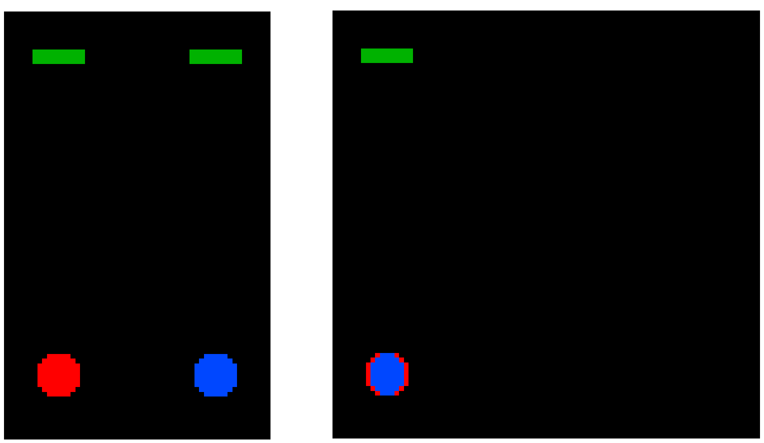


If the Ball is light?



Counterintuitive Result #2

Time appears to advance more slowly for moving objects (<u>time dilation</u>)



Red & blue at rest Blue moving to right

Time Dilation

- The effects of time dilation are curious but not prohibitive for space travel
  - Astronauts will age less than the Earth-bound folks waiting for the return. Can spoil the homecoming celebrations.
  - The faster you go, the bigger difference between astronaut time and Earth time
- Example: Trip to the center of the Galaxy and back. Accelerate at 1g for the first half and decelerate for second half and you can go 30,000 ly in 20 years! But more than 30,000 years has elapsed on Earth!

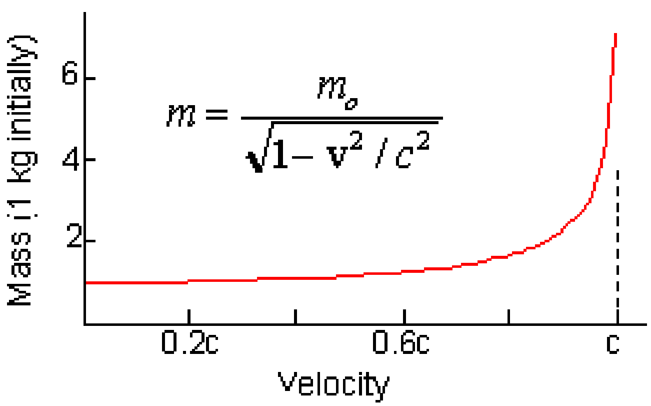
Counterintuitive Result #3

Mass appears to increase for moving objects

Mass Increase

- The increase of effective mass (and kinetic energy) with velocity makes acceleration and deceleration more difficult if you intend to travel close to "c"
  - This translates to very costly starflight in terms of required energy.
  - And now the interstellar dust that you strike at relativistic speeds appears as larger mass.
  - For 99% speed of light travel, 5.5 meters of shield would erode every year.

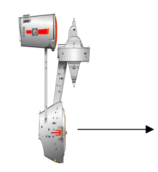
The gamma factor and mass:



Infinite Mass!!!!

So, what does that mean?

- If you're on a 100m spaceship going near the speed of light (.99 c), the spaceship would look 100m long, but someone on the Earth would observe the spaceship to only be 14m long.
- As you speed by the Earth your clock would tick 1 second, and an observer would tick about 7 seconds– $\gamma = 7$.



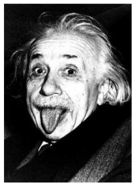
0.99 c

14.2m

Paul's Twin brother (on the Earth) is 7 seconds older for ever second.

And Paul's mass increased by a factor of 7.

Special Relativity Summary



All motion is relative, except for that of light.
Light travels at the same speed in all frames of reference.

Objects moving close to the speed of light appear to shrink in the direction of travel.

Time appears to advance more slowly for objects moving close to the speed of light.

Objects moving close to the speed of light appear to have larger mass.

The future:

- May bring us closer to the speed of light
  - Right now we can travel through space at about c/25,000
  - Maybe fusion-powered crafts could in the near future reach 0.01c or maybe even 0.10c

http://www.jedisaber.com/SW/wallpaper/light%20speed.jpg

Rocket Science

Momentum and Rockets

- Rockets are propelled by the same principle (on Earth or in space):
  - Rocket fuel releases tremendous energy.
  - The by-product is directed out the back of the rocket.
  - The rocket is pushed forward just like the “rocket” chair.
  - The high momentum is created by high velocity and a large mass of fuel ejected.

http://bagocrap.1accesshost.com/drawings/rocketwheelchair.gif

The Rocket Principle

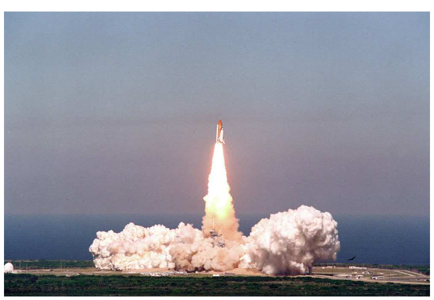
- Conservation of momentum (mass x velocity):
  - Sit in a chair with wheels and throw a heavy ball.
  - You and the chair will recoil in the opposite direction
  - This is the famous “action-reaction” mechanism. Newton’s 3rd law.

The Rocket Principle

- Conservation of momentum (mass x velocity):
  - Your “rocket” chair would work by throwing a heavy ball
    - Achieving a high momentum with a large mass
  - Or, you could throw a light baseball, but very fast!
    - Achieving a high momentum with a large velocity
    - This is why a gun recoils when its fired.

Rocket Man: 4 Quantities

1. V_e : the exhaust velocity, usually in km/s.



Rocket Man: 4 Quantities

2. Thrust : force exerted by the exhaust (Newtons or pounds).

$$Thrust = \frac{mass}{\sec} \times V_e = Force = mass \times acceleration$$

Rocket Man: 4 Quantities

3. Mass Ratio :

$$R_M = \frac{M_{total}}{M_{payload}} = \frac{M_{fuel} + M_{payload}}{M_{payload}}$$

– This should be low: close to 1 is best. Of course, it depends on how fast you want to go & how efficient the fuel. And usually, the faster you go, the larger the R_m. But, the larger the R_m the more inefficient. Consequently, we need a fuel that produces more thrust per unit mass of fuel.

Rocket Man: 4 Quantities

4. Specific Impulse:

$$s.i. = \frac{thrust}{Fuel\ Rate} = \frac{\frac{mass}{s} \times V_e}{\frac{mass}{s}}$$

In metric

$$= \frac{Newtons}{\left(\frac{kg}{s}\right)}$$

In British Engineering System

$$= \frac{Pounds}{\left(\frac{Pounds}{s}\right)} = seconds$$

The units have traditionally been in seconds. But it is a little confusing, and has nothing to do with time.

It is a property of the fuel and engine design. Sort of like octane rating in gasoline–
a large s.i. is a good thing.

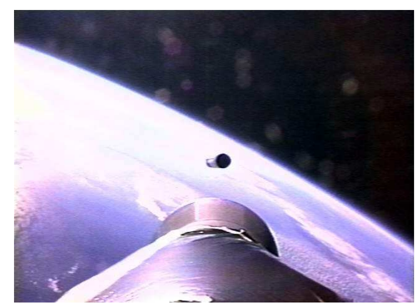
How's it work?

- For rocket to take-off, its thrust must be greater than its weight (force up > force down).
- In addition, the rocket needs to escape the Earth's pull.
- That means that the rocket velocity must exceed the Earth's escape velocity (11.2 km/s or 7 miles/s).
- Humans have never built a rocket that can do this!!!


http://www.eos.ucar.edu/mopitt/instr/rocket.jpg

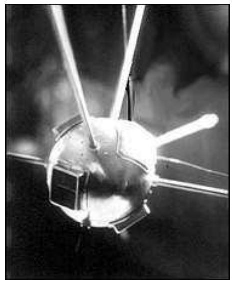
What you talking 'bout Willis?

- Humans have never built a rocket that can escape the pull of Earth?
- No, that's why we have to use multistage rockets.
- Once the fuel from the first stage is spent, it's dropped.
- Then, the next stage is higher up, so the escape speed is less than from ground level.
- To escape the Earth's gravity many stages are necessary.


http://www.utahredrocks.com/stardust/launch6.jpg

Not Good

- Multistage rockets are wasteful.
- The Mass Ratio can be huge!
- The first US satellite was the Vanguard launched on March 17, 1958.
- 6.4 inch diameter with 2 radio transmitters.
- Weighed 6.3 lbs = 13.9 kg.
- Rocket mass was 36,000 kg.
- $R_M = \frac{36000 + 13.9}{13.9} = 2590 >> 1$
- Major ventures in space impossible with R_M this large.



http://www.bafsat.com/h3.html

Kiss and Make Better

- Can lower the mass ratio by increasing either the exhaust velocity or the specific impulse.
- Shuttle is **state-of-the-art**.
- Payload = 2.95×10^4 kg
- $M_{takeoff} = 2 \times 10^6$ kg
- $R_M = \frac{2 \times 10^6 + 2.95 \times 10^4}{2.95 \times 10^4} = 67.8$

Kiss and Make Better

- Shuttle thrust is 29×10^6 N with 80% from solid rocket boosters– they fall off at 40km.
- s.i. = 455 seconds
- Good, but not good enough to leave Earth's orbit (shuttle orbits @185 km)

Combustion Rocket Terminology

- A *fuel* is combusted, which means it 'burns', which means it reacts with oxygen.
- In space, there is no oxygen around, so the rocket must carry its own source of oxygen. Also known as an *oxidizer*.
- This forms a new waste compound called a *propellant* that is ejected out the back, thrusting the rocket forward by conservation of momentum.

Propellant-based

- Eject something backwards, you go forwards. **Newton's da man!**
  - Chemical : Burn fuel, exhaust is propellant
  - Nuclear : Reactor heats propellant
  - Electric/Ion : Ionize fuel atoms, push them out with electric fields
  - Anti-matter : Use energy from matter-antimatter annihilation to generate light thrust.

Fuels

- Look at the "octane" of various fuels available today.
- $H_2 + O_2 \rightarrow$ s.i. = 455 sec
- O_2 + hydrazine (N_2H_4) $\rightarrow$ s.i. = 368 sec
- H_2 + fluorine (F) $\rightarrow$ s.i. = 475 sec
  - But exhaust gas is hydrofluoric acid
- **Note: No chemical fuel can achieve s.i. > 500 sec.**

Rocket Combustion: Chemical Fuels

- Petroleum : Refined kerosene with LOX (liquid oxygen) oxidizer. *(Saturn V first stage)*
- Cryogenic : Ultra cold hydrogen fuel with LOX oxidizer. Propellant is…water! *(Space Shuttle Main Engines)*
- Hypergolic: A fuel and oxidizer that combust with no need for ignition. Fuel can be "monomethyl hydrazine" (MMH) and the oxidizer is "nitrogen tetroxide" (N_2O_4). *(Space Shuttle Orbital Maneuvering Subsystem)*
- Solid: Oldest form (like in model rockets), exists in solid form, hard to stop burning. Has oxidizer mixed together with fuel. *(Space Shuttle Boosters– SRBs)*

http://www-pao.ksc.nasa.gov/kscpao/nasafact/count2.htm

Rocket Combustion: Chemical Fuels

1. Petroleum
2. Cryogenic
3. Hypergolic
4. Solid

http://www-pao.ksc.nasa.gov/kscpao/nasafact/count2.htm

Petroleum rocket fuel in action

The mighty Saturn V 1st stage (launched Apollo 11).

http://vesuvius.jsc.nasa.gov/er/seh/movies.html#Saturn

http://www.hq.nasa.gov/office/pao/History/alsj/a16/ap16-KSC-72PC-184.jpg

Cryo fuel in action

The Shuttle's main engines!

http://www.slivka.com/Trips/ShuttleLaunch/pics/LOX_tank_750,000_gallons_at_launch_complex_39A_T.jpg

http://engineering.newport.ac.uk/StaffPer/StaffEngPer/DevansPer/Space-Shuttle.JPG

http://www.physicscurriculum.com/Photos/Space3.JPG

Shuttle Links

http://www-pao.ksc.nasa.gov/kscpao/shuttle/countdown/sts100/liftoffvideo.htm

http://science.ksc.nasa.gov/shuttle/missions/sts-90/vrtour/checkpoint.html

http://imedia.ksc.nasa.gov/shuttlesim/index.html

Hypergolic

Space shuttle orbital maneuvering system uses hypergolic fuel

Solid fuels:

Space shuttle launch uses solid fuel (like model rocket).

1.3 Mlbs at launch. The fuel for each solid rocket motor weighs approximately 1.1 Mlbs. The inert weight of each SRB is approximately 192,000 pounds.

- Ammonium perchlorate (oxider)
- Aluminum (fuel)
- Iron Oxide (catalyst)
- Polymer (binder)

Fuel Efficiency

- To really think about interstellar travel or even going to Mars, we need the most bounce for the ounce:
  - Need to carry (probably MUCH) fuel
  - Must be very thrifty about efficiency
  - In other words, if we are going to carry fuel mass on a ship, we had better get as much energy from it as possible!