

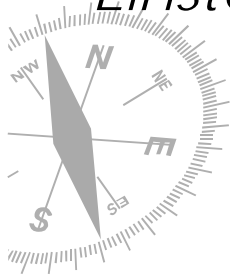
Faraday  
Maxwell  
Lorentz  
Einstein



Heaviside



# Relatively moving ..... *Einstein's special relativity*



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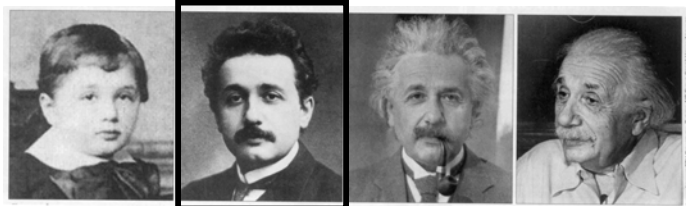


Physics Lectures for VCE Students, April 29 2010

## The VCE Study Design

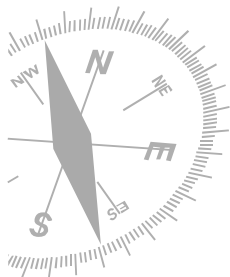


- ▶ Maxwell's equations and the speed of light
  - No absolute frame of reference
- ▶ Einstein's two postulates for his special theory of relativity
  - the laws of physics are the same in all inertial (non-accelerated) frames of reference
  - the speed of light has a constant value for all observers regardless of their motion or the motion of the source
- ▶ Michelson-Morley experiment
- ▶ Thought experiments to show that:
  - time interval between two events differs depending on the motion of an observer relative to the events (non-simultaneity)
  - length contraction of an object occurs in the direction of its motion when observed from a different frame of reference;
- ▶ Proper time and proper length
- ▶ Modelling time dilation and length contraction using the equations  $t = \gamma t_0$  and  $L = L_0/\gamma$  where  $\gamma = (1 - v^2/c^2)^{-1/2}$
- ▶ Total 'mass-energy' of an object is given by  $E_{\text{tot}} = E_k + E_{\text{rest}} = mc^2$  where  $m = m_0\gamma$  and so kinetic energy,  $E_k = (\gamma - 1)m_0c^2$
- ▶ Explain that mass can be converted into energy and vice versa,  $E = \Delta mc^2$ ;
- ▶ Explain the impossibility of motion faster than light in terms of relativistic mass  $m = m_0\gamma$  at speeds approaching  $c$



Einstein

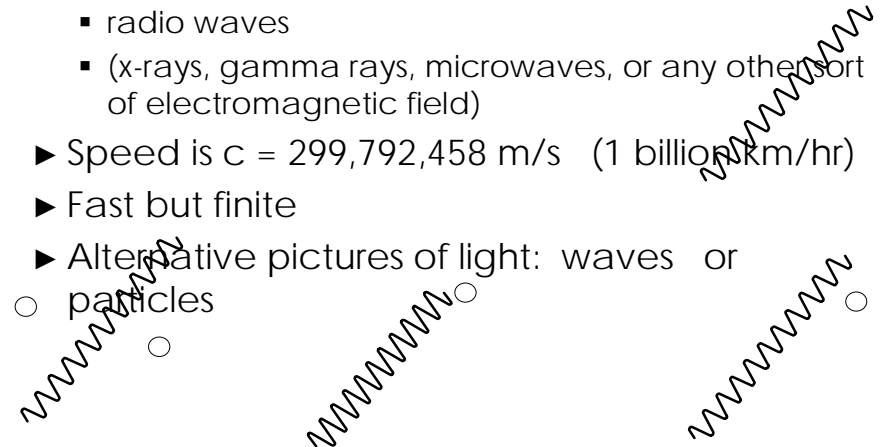
1879-1955

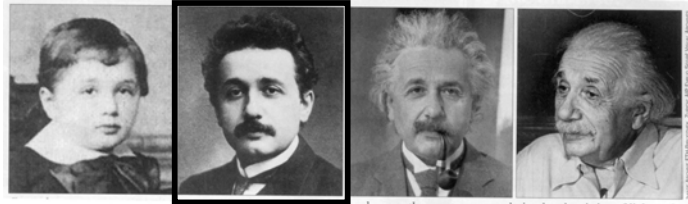


Light



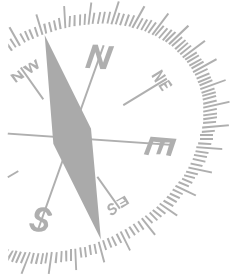
- ▶ "Light"
  - real light
  - radio waves
  - (x-rays, gamma rays, microwaves, or any other sort of electromagnetic field)
- ▶ Speed is  $c = 299,792,458 \text{ m/s}$  (1 billion km/hr)
- ▶ Fast but finite
- ▶ Alternative pictures of light: waves or particles



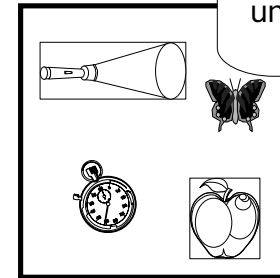


## Before Relativity

*Galileo & Newton*

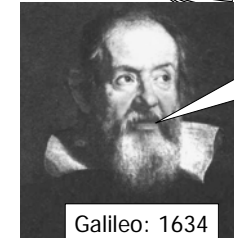
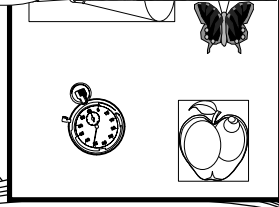
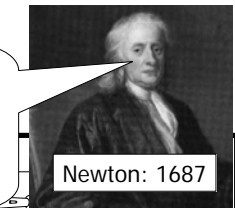


What's the difference?



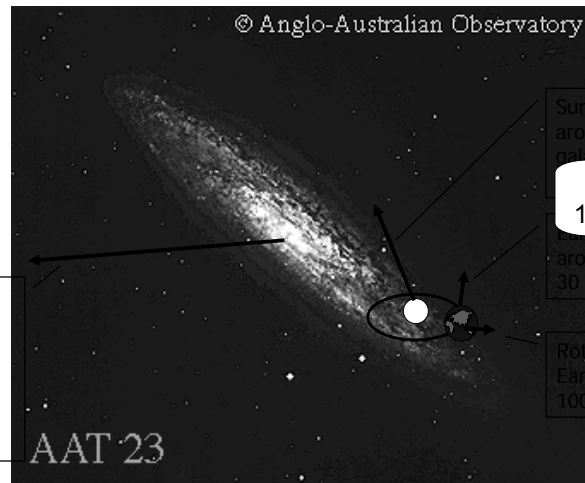
Constant velocity

...and this one continues on its way unless subject to an external force!



There is no difference!

How fast are we going anyway?



Milky Way Galaxy trajectory towards Great Attractor: 7000 km/s

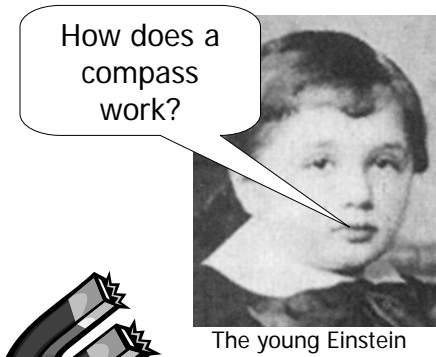
AAT 23

Sun's Orbit around galaxy: This is 108,000 km/hr

Earth's orbit around Sun: 30 km/s

Rotation of Earth: 1000 km/hr

Mysterious Magnetism



The young Einstein



Green electron beam

## Can you catch a beam of light?



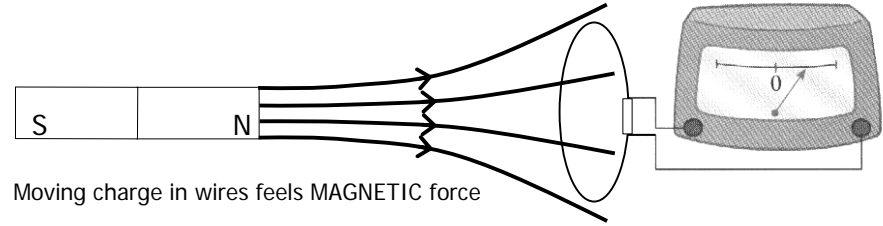
Light is an electromagnetic wave!



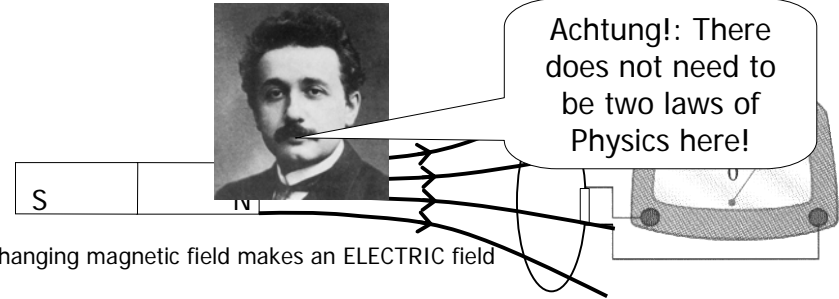
Maxwell



## Two ways to make electricity!



Moving charge in wires feels MAGNETIC force



Changing magnetic field makes an ELECTRIC field

Induction 1 & 2

## How does light behave?



- Like sound waves?
- Propose a medium for light: Aether

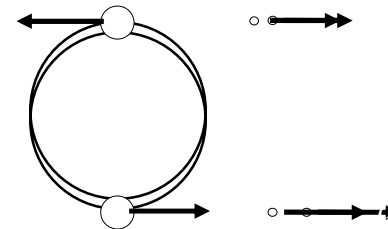
### ■ Sound in Air

- Air has pressure
- Made of O, N, Ar
- Has mass
- You breath it
- ...

### ■ Light in Aether?

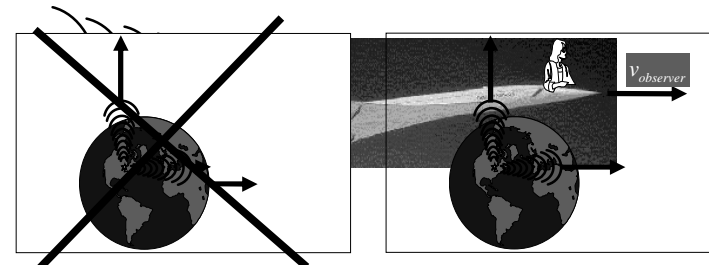
- Aether is insubstantial
- Very elastic
- Other properties???

## Double Stars: Mechanics



Speed of light independent of the speed of the source

## Speeding Earth: Sound

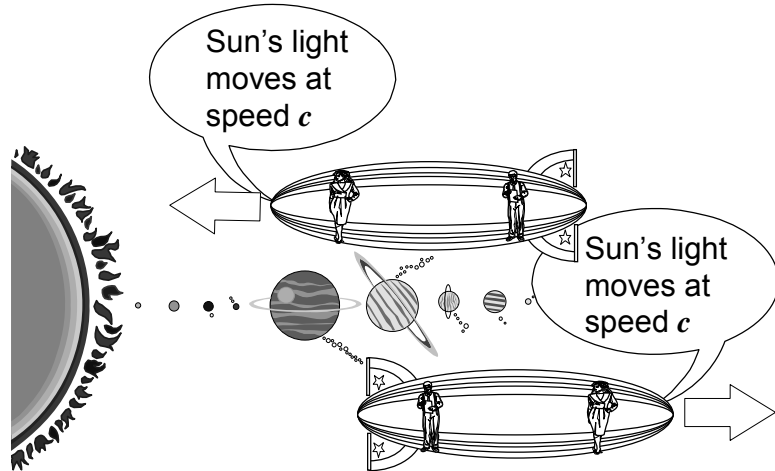


Speed of light independent of the speed of the observer

Michelson - Morley Experiment in 1887

# The Postulates of the Special Theory of Relativity

- Laws of Physics the same for everybody
- The speed of light the same for everybody



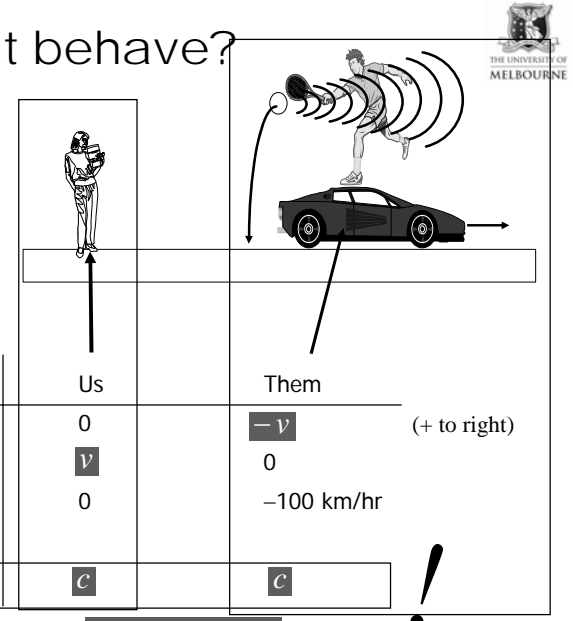
## How does light behave?

### ► Summary

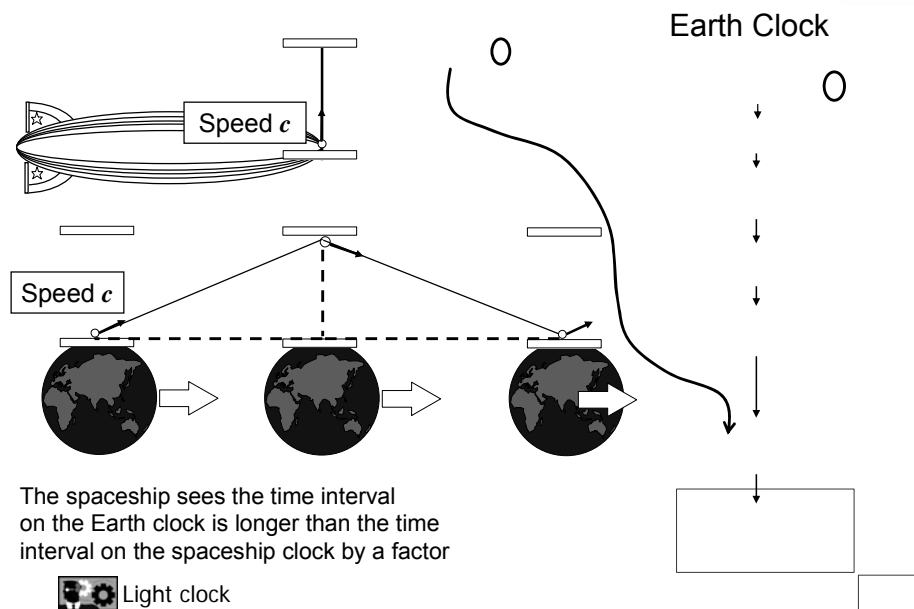
- Speed of light *independent of speed of source*
- Speed of light *independent of speed of observer*

Object	Us	Them	
Us	0	$-v$	(+ to right)
Them	$v$	0	
Tennis Ball	0	$-100 \text{ km/hr}$	
Sound Wave			
Light	$c$	$c$	!

$c = 3 \times 10^8 \text{ m/s}$



## Two Light Clocks...



## Summary

### The Special Theory of Relativity

- First Result: Moving clocks run slow

$$t = \frac{t'}{\sqrt{1 - v^2 / c^2}} = \gamma \cdot t'$$

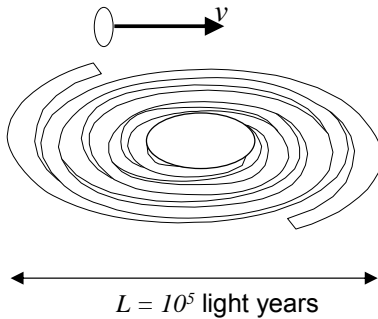
$$\gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}$$

# Galaxy crossing protons



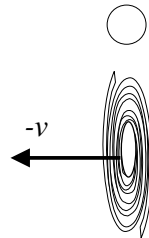
## ► Galaxy view

proton speed  $v < c$  (just)  
 $\gamma = 10^{10}$   
 Cross galaxy in  $\Delta t = 10^5$  years



## ► Proton view

Elapsed time:  
 $\Delta t' = \Delta t / \gamma = 10^{-5} \text{ years} = 315 \text{ s}$   
 Galaxy speed  $v < c$  (just)  
 $L' = \Delta t' \cdot c = \Delta t / \gamma \cdot c$   
 $= 10^5 / 10^{10} = 10^{-5} \text{ l.y.}$   
 $= 95 \text{ million km} = 0.7 \text{ A.U.}$



# Summary



## The Special Theory of Relativity

- First Result: Moving clocks run slow
- Second Result: Moving objects contract

$$L' = L / \gamma$$

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

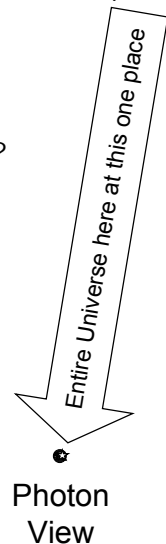
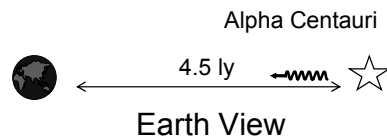
# The universe seen by a photon



- Only weightless objects can travel at the speed of light
- All clocks freeze
- All distances contract to zero
- Where would you like to go today?
- What if  $v > c$ ?

*Violate causality!*

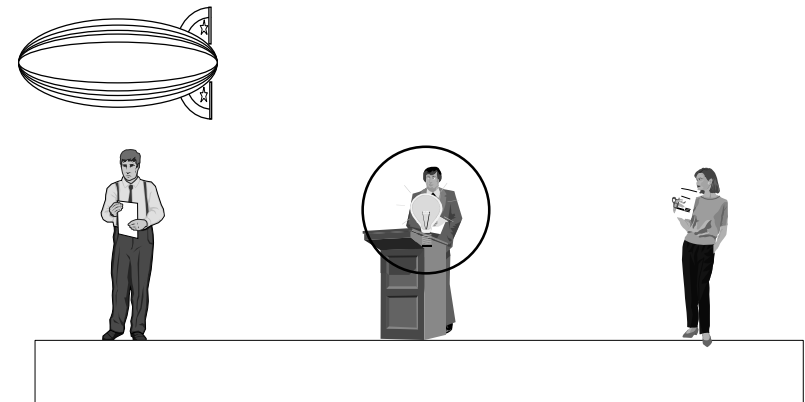
*Cannot happen in our universe!*



# Relativity of Simultaneity



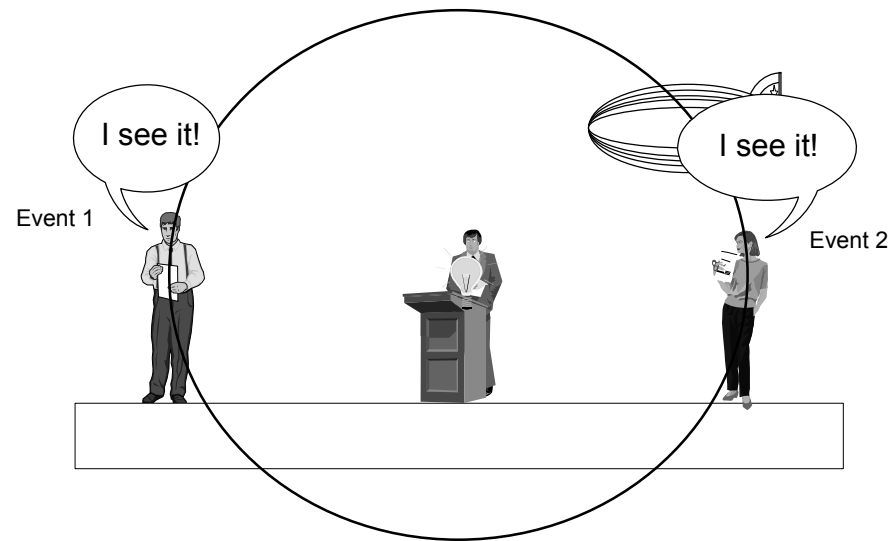
- Lecture theatre experiment



## Relativity of Simultaneity



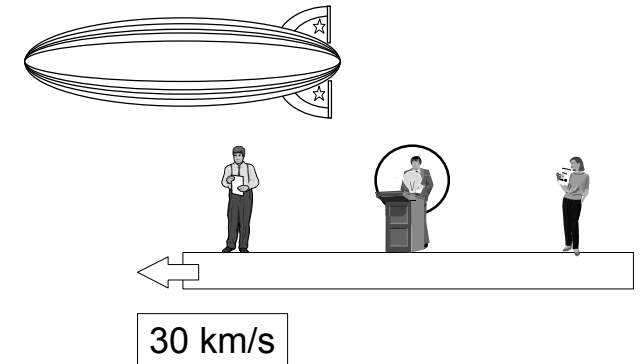
### ► Lecture theatre experiment



## Relativity of Simultaneity



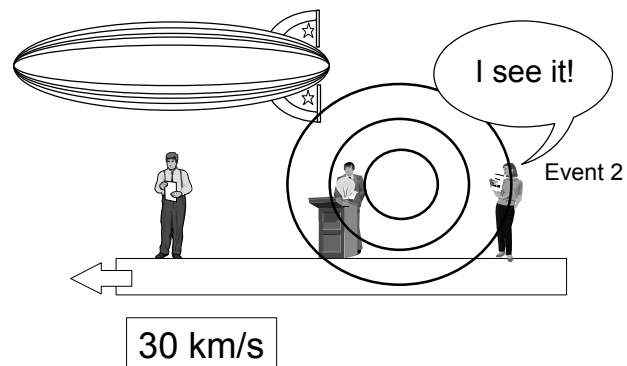
### ► Space view of lecture theatre experiment



## Relativity of Simultaneity



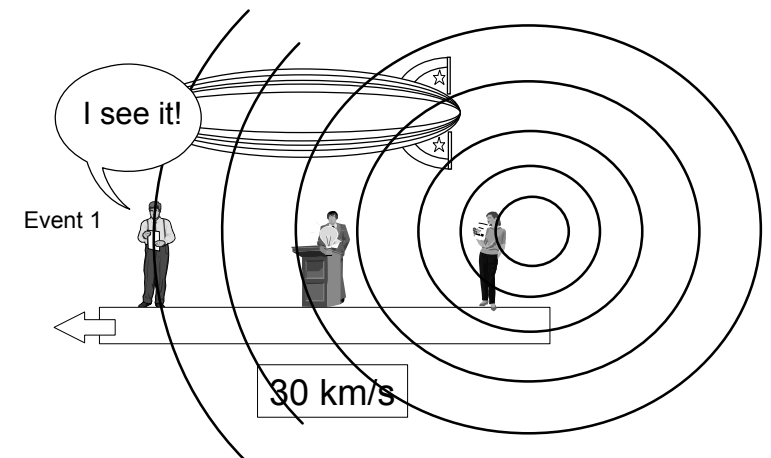
### ► Space view of lecture theatre experiment



## Relativity of Simultaneity



### ► Space view of lecture theatre experiment



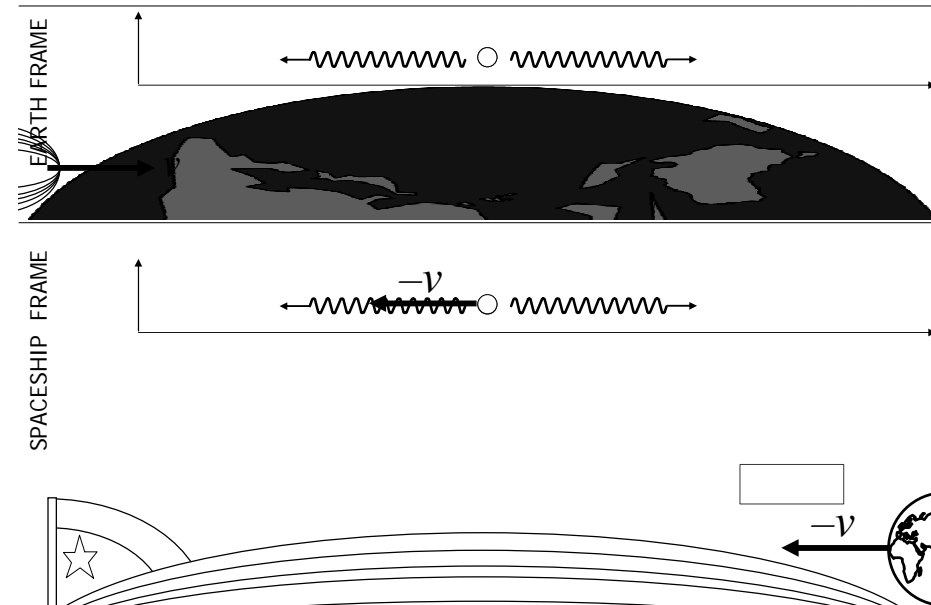
## Summary



### The Special Theory of Relativity

- First Result: Moving clocks run slow
- Second Result: Moving objects contract
- Third Result: Simultaneity is Relative

## What about $E=mc^2$ ?



## Summary



### The Special Theory of Relativity

- First Result: Moving clocks run slow
- Second Result: Moving objects contract
- Third Result: Simultaneity is Relative
- Fourth Result: Energy has mass!

Resting

$$E = mc^2$$

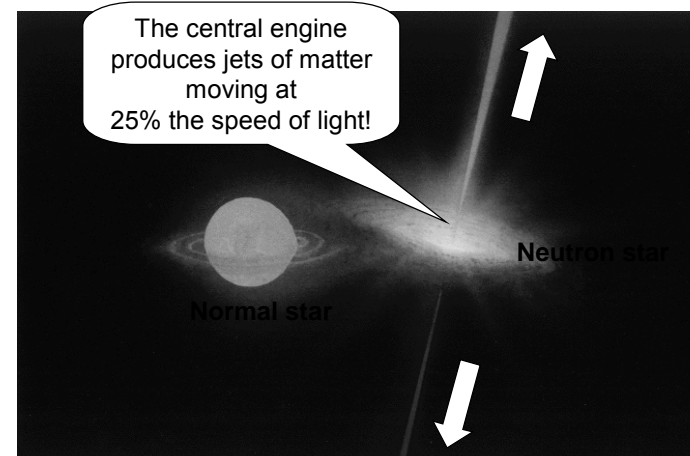
With Kinetic Energy

$$E = \gamma mc^2 \quad \gamma = \frac{1}{\sqrt{1 - v^2 / c^2}}$$

$$E = mc^2 + (\gamma - 1)mc^2$$

Can we use Relativity to for long distance space travel?

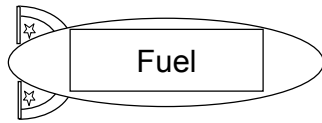
## SS433 - The strangest object in our galaxy



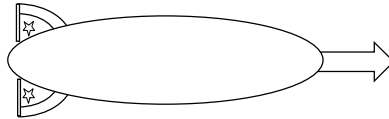
# Relativity and Space Travel



- Before
  - Rocket and fuel at rest



- After
  - Fuel thrown away
  - Rocket goes forward by conservation of momentum



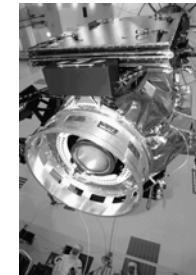
# High Speed Exhaust - Ion Engine



- Use  $Hg^+$ ,  $Xe^+$  or  $Cs^+$  as reaction mass
- Accelerate ions to 1% $c$  by electric fields
- Low thrust (not many ions per second)
- But be patient!



Laboratory test



Prelaunch

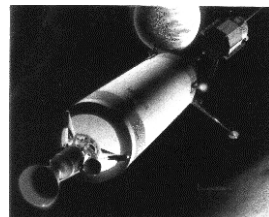
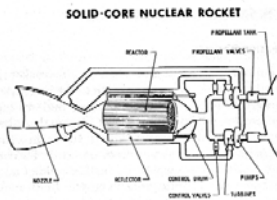


In flight

# High temperature exhaust - Nuclear Engines



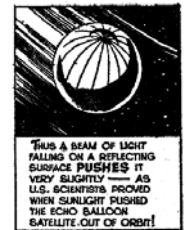
- NERVA nuclear rocket prototype
- Built in USA in 1960's
- Suffered from failure of the nuclear core



# Ultra fast exhaust - Light ( $v_e = 3 \times 10^8 \text{ m/s}$ )



- Use light as the exhaust
- Better still, leave engine behind on Earth



Before

$$\text{Photon momentum: } P = E/c = hc/\lambda$$

Mirror

After

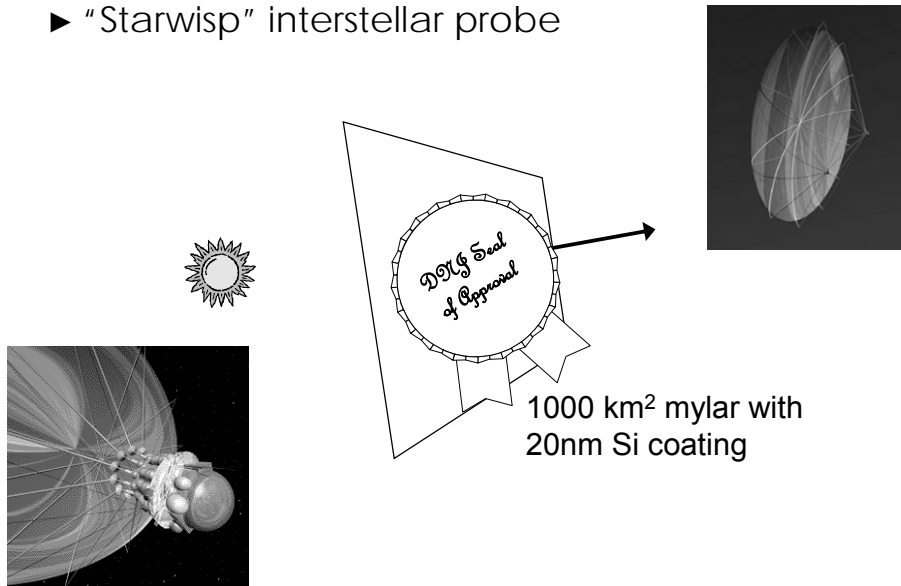
$$\text{Photon momentum: } -P$$

Mirror momentum:  
 $2P$



# Ultra fast exhaust - Light

## ► "Starwisp" interstellar probe



# Unbelievable amounts!



Speed (v/c)	$\gamma = 1/(1-v^2/c^2)^{1/2}$	Kinetic Energy (J/kg)
100 km/hr	1	400
0.001	1.0000005	$4.5 \times 10^{10}$

Compare:

World annual electric energy (2008)

$5 \times 10^{20}$  J

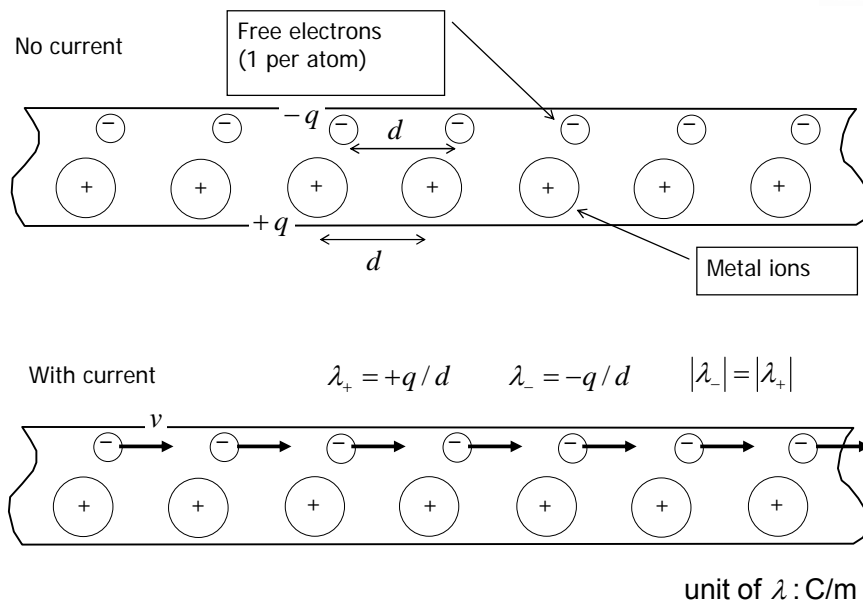
Solar flux on Earth for 1 year

$5 \times 10^{24}$  J

0.8	1.67	$6.0 \times 10^{10}$
0.9	2.29	$1.2 \times 10^{17}$
0.99	7.1	$5.5 \times 10^{17}$
0.99999998	7,000	$6.3 \times 10^{20}$

7 TeV proton  
in the LHC ring  
at CERN

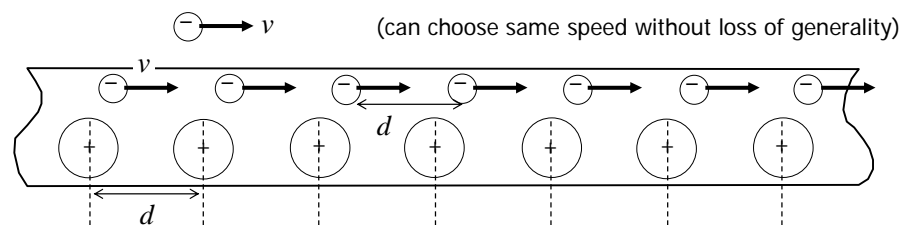
## ⚠ Current in wire: Force from magnetism



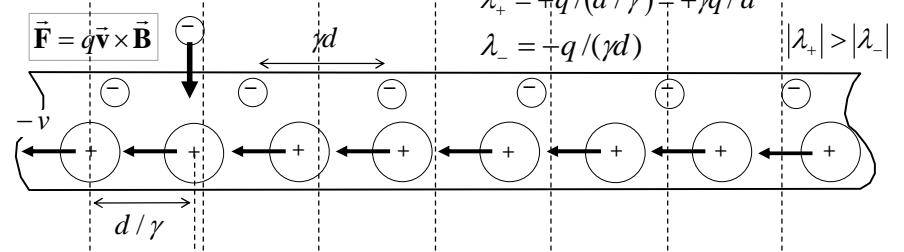
## ⚠ The origin of the magnetic force



Adjacent moving electron



Adjacent moving electron frame



## Some numbers

- ▶ For a current of 10 Ampere in a wire of area 1 mm<sup>2</sup>
  - Electron density in Copper  $N_e = 8.5 \times 10^{22}$  atoms/cm<sup>3</sup>
  - The atom density is the same as the electron density because each atom contributes 1 free electron to the metal
- ▶ From theory, the speed of electrons in this wire will be:

$$v = \frac{i}{eAN_e}$$

- $e$  = electron charge =  $1.6 \times 10^{-19}$  Coulombs
- $A$  = cross sectional area of wire = 1 mm<sup>2</sup>
- Gives

$$v = \frac{10}{1.6 \times 10^{-19} \cdot (1 \times 10^{-6}) \cdot 8.5 \times 10^{22}} = 0.7 \text{ mm/s}$$

- ▶ What is the gamma factor for this very slow speed?

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = 1 + 3 \times 10^{-24}$$

This is incredibly small!  
But we see magnetic effects because of the enormous strength of the electromagnetic force!

## More reading

- ▶ A. Einstein, *The Meaning of Relativity* (Princeton Science Library, 1988)
- ▶ A. Einstein, et al. in *The Principle of Relativity*, ed. by A. Sommerfeld (Dover, 1952)
- ▶ A. Pais, *Subtle is the Lord... The Science and Life of Albert Einstein* (Clarendon, 1982)
- ▶ S. Weinberg, *The First Three Minutes* (Basic Books, 1977)
- ▶ K. Thorne, *Black Holes and Time Warps: Einstein's outrageous legacy* (W.W. Norton, 1994)
- ▶ J.A. Wheeler, *Gravity and Spacetime* (Scientific American Library, 1990)
- ▶ T.A. Herring, *The Global Positioning System* (Scientific American, Feb 1996)
- ▶ G. Gamow, *Mr Tomkins in Wonderland* (Cambridge University Press, 1993)