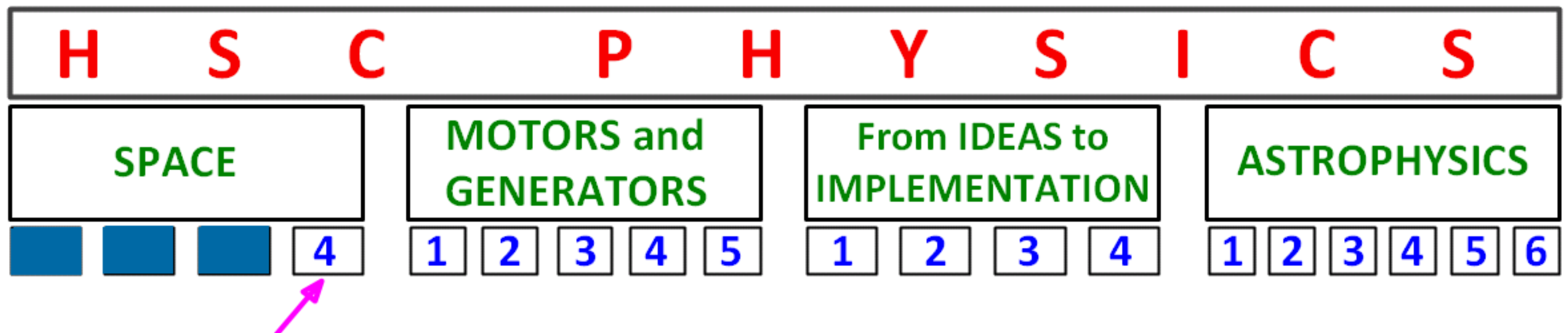


# SPACE

1<sup>st</sup> Quarter; Module 1

## PERIOD 28

Mass-Energy Equivalence, Space Travel



## Space 4

Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

*Students learn to:*

- outline the features of the aether model for the transmission of light
- describe and evaluate the Michelson-Morley attempt to measure the relative velocity of the Earth through the aether
- discuss the role of the Michelson-Morley experiments in making determinations about competing theories
- outline the nature of inertial frames of reference
- discuss the principle of relativity
- describe the significance of Einstein's assumption of the constancy of the speed of light
- identify that if  $c$  is constant then space and time become relative
- discuss the concept that length standards are defined in terms of time in contrast to the original metre standard
- explain qualitatively and quantitatively the consequence of special relativity in relation to:
  - the relativity of simultaneity
  - the equivalence between mass and energy
  - length contraction
  - time dilation
  - mass dilation
- discuss the implications of mass increase, time dilation and length contraction for space travel

## Space 4

Current and emerging understanding about time and space has been dependent upon earlier models of the transmission of light

*Students:*

- gather and process information to interpret the results of the Michelson-Morley experiment
- perform an investigation to help distinguish between non-inertial and inertial frames of reference
- analyse and interpret some of Einstein's thought experiments involving mirrors and trains and discuss the relationship between thought and reality
- analyse information to discuss the relationship between theory and the evidence supporting it, using Einstein's predictions based on relativity that were made many years before evidence was available to support it
- solve problems and analyse information using:

$$E = mc^2$$

$$l_v = l_0 \sqrt{1 - \frac{v^2}{c^2}}$$

$$t_v = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$m_v = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$



# EINSTEIN'S THEORY OF SPECIAL RELATIVITY:

- ★ The laws of physics are the same in all frames of reference; that is, the principle of relativity always holds
- ★ The speed of light is independent of the motion of the observer; that is, everyone always observes the same speed of light regardless of their motion

## RESULTS OF 'CONSTANCY OF SPEED OF LIGHT'

- ✓ Time Dilation
- ✓ Length Contractions
- ✓ Relativity of simultaneity
- ✓ Mass dilation
- ✓ Mass - Energy Equivalence

# MASS DILATION > another result of 'constancy of speed of

**Mass dilation** is the increase in the mass of an object as observed from a reference frame in relative motion.

$$m_v = \frac{m_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$m_0$  = mass measured in the rest frame of reference, rest/proper mass

$m_v$  = mass as seen from the frame of reference in relative motion to the rest frame

$v$  = relative velocity of the frames

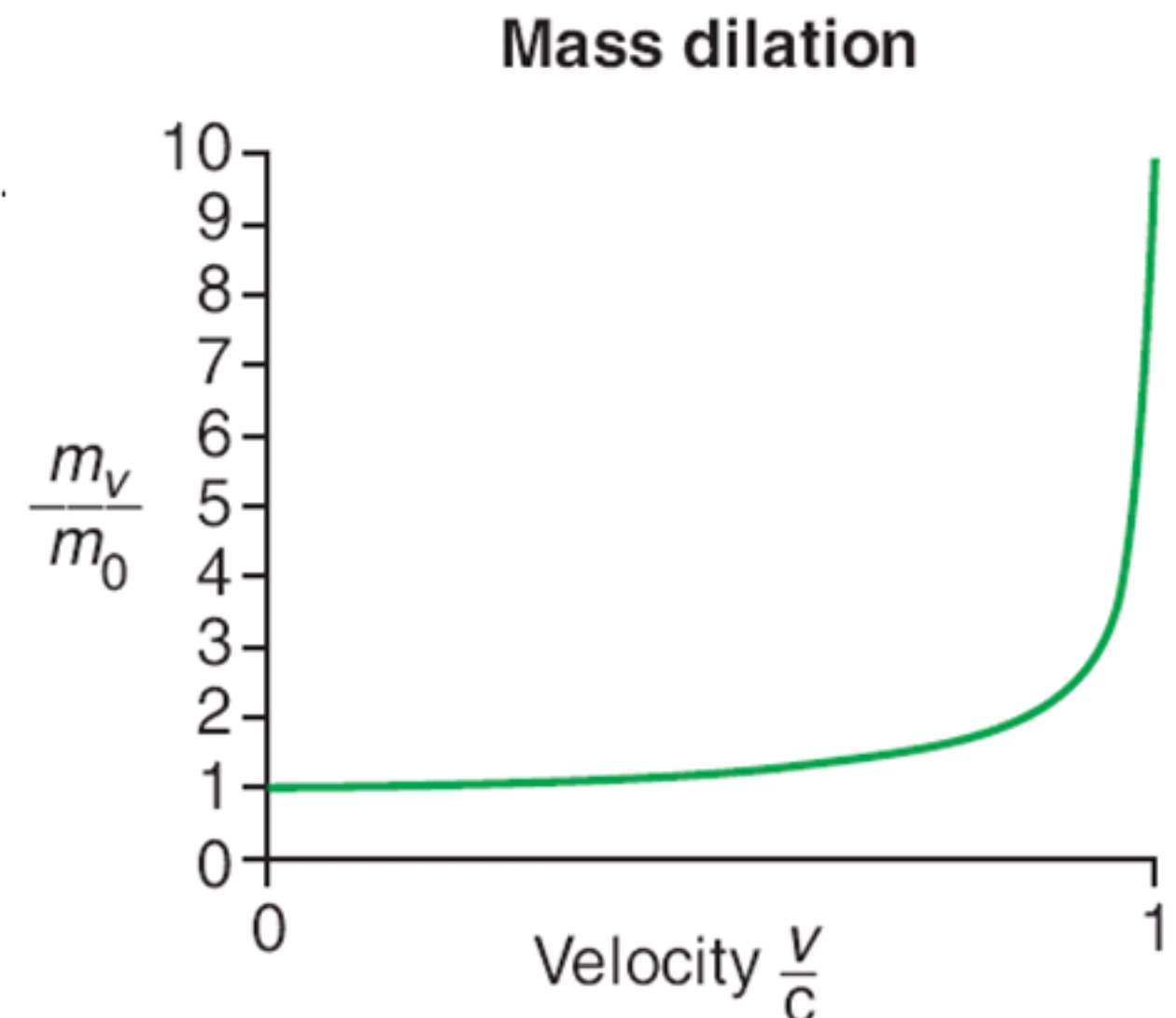
$c$  = speed of light

**Mass dilation** can be stated as follows: The mass of an object within its own rest frame is called its rest mass  $m_0$ . Measurements of this mass  $m_v$ , made from any other inertial reference frame in relative motion to the first, are always greater.

$$m_v > m_0$$

The effect can be most simply stated as: Moving objects gain mass.

The degree of mass dilation varies with velocity as shown in the graph.



# WHY IS IT IMPOSSIBLE TO REACH THE SPEED OF LIGHT?

As the speed of an object approaches the speed of light  $c$ , its mass approaches an infinite value. It is this enormous increase in mass that prevents any object from exceeding the speed of light. This is because;

- ✦ An applied force is required to create acceleration.  $a = \frac{F_{\text{net}}}{m}$
- ✦ Acceleration leads to higher velocities, which eventually leads to increased mass.  $\text{as } v \uparrow, m \uparrow \text{ (acc. to sp. relativity)}$
- ✦ This means that further accelerations will require ever greater force.  $\text{as } m \uparrow, \text{ greater force is needed}$
- ✦ As mass becomes infinite, an infinite force would be required to achieve any acceleration at all.  $a = \frac{F}{m}$
- ✦ Sufficient force can never be supplied to accelerate beyond the speed of light.  $\text{at } c, m \rightarrow \infty$   
 $F \text{ should be } \infty!$

# WHY IS IT IMPOSSIBLE TO REACH THE SPEED OF LIGHT?

As the speed of an object approaches the speed of light  $c$ , its mass approaches an infinite value. It is this enormous increase in mass that prevents any object from exceeding the speed of light. This is because;

✦ .

✦ .

✦ .

✦ .

✦ .



## THE EQUIVALENCE OF MASS AND ENERGY according to Newton

if  $F \times t$ ,  $a \times t$ ,  $\Delta v \times t$

But herein lies a problem:

- ✦ If a force is applied to an object, then work is done on it. Another way to say this is that energy is given to the object.  $\text{Work done} = F \cdot x$
- ✦ This energy would take the form of increased kinetic energy as the object speeds up.  $= \Delta KE$
- ✦ But at near light speed the object does not speed up as we would normally expect

### SO WHERE IS THE ENERGY GOING?

- ✦ The applied force is giving energy to the object and the object does not acquire the kinetic energy we would expect.
- ✦ Instead, it acquires extra mass. Einstein made an inference here and stated that the mass (or inertia) of the object contained the extra energy.



$$E = m_0 \cdot c^2$$



rest  
energy  
(J)



rest  
mass  
(kg)



speed of  
light  
(m/s)

## 5.7

## The rest energy of an electron

What is the energy equivalent of an electron of mass  $9.109 \times 10^{-31}$  kg?

$$E = 9.109 \times 10^{-31} \times (3 \times 10^8)^2$$
$$= 8.2 \times 10^{-14} \text{ J}$$

$$9.109 \times 10^{-31} \equiv 8.2 \times 10^{-14} \text{ J}$$



equivalent  
to

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according to  $E = mc^2$

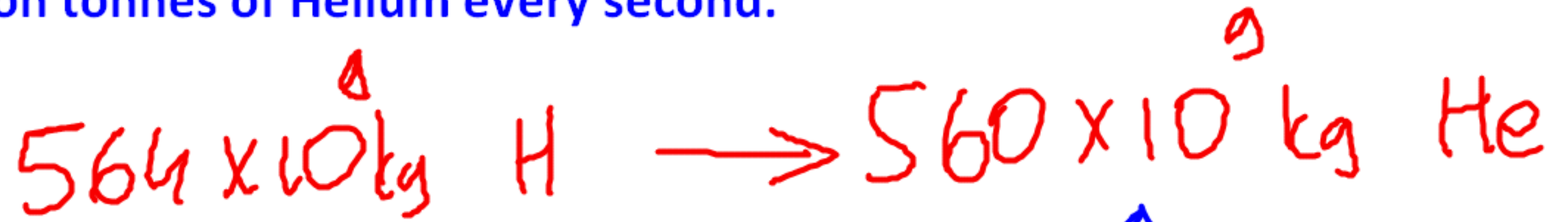
Estimate the energy equivalent of the mass of a granny smith apple

$$m_0 \cong 200\text{g} = 0.2\text{kg}$$

$$E = m_0 c^2 = 0.2 \times (3 \times 10^8)^2 = 1.8 \times 10^{16} \text{J}$$



Find the power rating of our SUN, if 564 million tonnes of Hydrogen turns into 560 million tonnes of Helium every second.



$P = \frac{E}{t}$

we only get  $\frac{4}{2} \times 10^9$  of it

$4 \times 10^9 \text{ kg}$  of mass is converted into energy

$$E = \frac{4 \times 10^9 \times (3 \times 10^8)^2}{1}$$

$$= 3.6 \times 10^{26} \text{ J}$$

$$P = \frac{3.6 \times 10^{26} \text{ J}}{1 \text{ s}} = 3.6 \times 10^{26} \text{ Watts}$$



# SPACE TRAVEL

Designers of a new kind of spacecraft called a light sail make the remarkable claim that these craft could journey to Proxima Centauri (the distance to Proxima Centauri is approximately four light-years, or  $3.8 \times 10^{13}$  km), our closest neighbouring star and shortest interstellar journey, at a speed of  $0.6c$  or 60% of the speed of light ( $6.5 \times 10^8$  km/h). This is far<sup>3</sup> in excess of current achievable velocities. Assuming it to be true, how long would such a journey take?

2 frames  $\rightarrow$  1. earth  
2. light sail

$$t = \frac{d}{v}$$

$$t = \frac{3.8 \times 10^{13} \text{ km}}{6.5 \times 10^8 \text{ km/h}} = 5.8 \times 10^5 = 585000 \text{ h}$$
$$\approx 2435 \text{ days}$$
$$\approx 6.7 \text{ years}$$

$$t = \frac{4 \text{ ly}}{0.6 c} = 6.7 \text{ years.}$$

## 3 Golden Steps in Relativity Problems

1 - Identify the (inertial) Frame of References; there must be two

2 - (Once you identify the frame of references) decide which one is

Rest frame ( $t_0$ ,  $L_0$ ,  $m_0$ ) and which one is Travelling frame ( $t_v$ ,  $L_v$ ,  $m_v$ )

Ask yourself "What am I measuring/recording?" and "from where?"

3 - Choose the appropriate formula and solve it for unknown



$$t_v = 6.7$$

how long for the astronaut?

$$t_0 = ?$$

$$t_v = t_0 / \gamma \Rightarrow t_0 = t_v \times \sqrt{1 - \left(\frac{0.6c}{c}\right)^2}$$

$$L_0 = 4 \text{ ly}$$

$$L_v = 3.2 \text{ ly}$$

$$t = \frac{L_v}{v} = \frac{3.2 \text{ ly}}{0.6} = 5.4 \text{ years}$$

$$t_0 = 5.4 \text{ years}$$



A COMPARISON OF RELATIVISTIC EFFECTS

SPACECRAFT	SPEED (km h <sup>-1</sup> )	RATIO $\frac{v}{c}$	TIME PASSED ON SPACECRAFT IN ONE EARTH DAY			CONTRACTED LENGTHS AS % OF ORIGINAL
			HOURS	MINUTES	SECONDS	
Space shuttle	28 000	0.000 026	23	59	59.999 972	99.999 999 97
Fast space probe	100 000	0.000 093	23	59	59.999 630	99.999 999 6
Light sail	108 000 000	0.1	23	52	46.92	99.499
Starship <i>Intastella</i>	972 000 000	0.9	10	27	40.89	43.59
Starship <i>Galactica</i>	1 079 892 000	0.999 9	0	20	21.85	1.4
EVO-10	260	$2.4 \times 10^7$				
Dream-X	0.60c					
	5 km/h					
	0.9999999c					
	1c					
	2c					



# P28

## H/W

"Solutions of P26, P27 and P28 will be given with P29"

- c** Briefly describe the results of their experiment.
- 22** An aeroplane can fly at  $130 \text{ m s}^{-1}$  through the air. The pilot wants to fly to a destination 500 km due north and then fly straight back. However, there is a west wind blowing at  $50 \text{ m s}^{-1}$ .
- a** In the absence of any wind, how long would the return trip take?
- b** Given the  $50 \text{ m s}^{-1}$  west wind, how long will a return trip take if the pilot heads the plane so that the actual ground velocity is due north or south?
- c** On another occasion, there is a  $50 \text{ m s}^{-1}$  north wind blowing. Compare the time for a return trip to the same destination on this occasion with that in the part b.
- 23** Compare and contrast the situation in Question 22 and the Michelson–Morley experiment. If the result of the M–M experiment had also applied to the aeroplane in Question 22, what would the pilot have found?
- 24** If you were riding in a very smooth, quiet train with the blinds drawn, how could you tell the difference between the train (i) being stopped in the station, (ii) accelerating away from the station, (iii) travelling at a constant speed?
- 25** Very briefly explain why Einstein said that we must use four-dimensional spacetime to describe events that occur in situations where high speeds and large distances are involved.
- 26** You are in a spaceship travelling at very high speed past a new colony on Mars. Do you notice time going slowly for you; for example, do you find your heart rate is slower than normal? Do the people on Mars appear to be moving normally? Explain your answers.
- 27** Star Xquar is at a distance of 5 light-years from Earth. Space adventurer Raqu heads from Earth towards Xquar at a speed of  $0.9c$ .
- a** For those watching from Earth, how long will it take for Raqu to reach Xquar?
- b** From Raqu's point of view how long will it take her to reach Xquar?
- c** Explain why it is that, although Raqu knew that Xquar was 5 light-years from Earth, and that she was to travel at  $0.9c$ , it took much less time than might be expected from these figures.
- 28** The space shuttle travels at close to  $8000 \text{ m s}^{-1}$ . Imagine that as it travels east–west it is to take a photograph of Australia, which is close to 4000 km wide. Because of its speed, the space camera will see everything on Earth slightly contracted.
- a** About how much less than 4000 km wide will Australia appear to be in this photograph?
- b** Will the north–south dimension of Australia be smaller as well?

- 29** As we watch a traveller from Earth to Vega travelling at 99.5% of the speed of light, we will see that their clocks slow down by a factor of about 10 times.
- a** Explain how this factor of 10 was arrived at.
- b** Does this mean that they experience this slowing down of time?
- c** Vega is about 25 light-years from Earth, so in our frame of reference it takes light from Vega 25 years to reach us. How long will it take our space traveller to reach Vega?
- d** How long will the traveller find that it takes to travel to Vega?
- e** Does your answer to part d imply that they were able to get to Vega in less time than light? Explain your answer.
- f** If we could travel at the speed of light, how long would it take us to reach Vega?
- 30** The electrons in the Australian synchrotron will be travelling at about 99.9999% of the speed of light. According to our theory of electromagnetism, an electron travelling at this speed in a 1 tesla magnetic field will experience a perpendicular force of  $F = qvB = 4.8 \times 10^{-11} \text{ N}$ . Now we know that the centripetal force on the electron will be given by  $F = mv^2/R$ . (The mass of an electron is  $9.1 \times 10^{-31} \text{ kg}$ .)
- a** Using this equation, what is the radius of the path of the electron in this magnetic field?
- b** Is this answer consistent with what you know about the synchrotron construction?
- c** What is the reason for this anomaly?
- 31** In a nuclear power reactor, over the lifetime of the fuel rods about 1 g of every 1 kg of uranium 'disappears'.
- a** Has this mass really disappeared?
- b** If a reactor was loaded with 1 tonne of uranium fuel, how much energy would be produced from the core of the reactor over the life of that fuel?
- c** Melbourne uses electric power at an average rate of about 5 GW ( $1 \text{ GW} = 10^9 \text{ W}$ ). Given that about a third of the energy from the nuclear core will produce electricity, how long would this 1 tonne of uranium fuel power the city?
- d** What is the mass of the electrical energy produced by the power station? Why don't we notice this mass?
- 32** The fusion reaction that powers the Sun effectively combines four protons (rest mass  $1.673 \times 10^{-27} \text{ kg}$ ) to form a helium nucleus of two protons and two neutrons (total rest mass  $6.645 \times 10^{-27} \text{ kg}$ ). The total power output of the Sun is a huge  $3.9 \times 10^{26} \text{ W}$ .
- a** How much energy is released by each fusion of a helium nucleus?
- b** How many helium nuclei are being formed every second in the Sun?
- c** How much mass is the Sun losing every day?
- d** What happens to this lost mass?



# **HOMEWORK**

- ✦ Homework is an integral part of your "Learning Curve", take it seriously!
- ✦ Target minimum 1 hour of Physics everyday
- ✦ Divide your physics home study in three segments;
  - ✓ Revision (past)
  - ✓ Homework (present)
  - ✓ Tomorrow (future)
- ✦ Homework is due next period, unless otherwise stated
- ✦ If you cannot do all, at least do a few from each piece

*Apart from **reading the relevant pages from the textbook and solving the rest of the questions in this booklet**  
your homework is:*

- ✓ Personal Notes - at least 5 pages every day
- ✓ New booklet
- ✓ chapter 5 all questions
- ✓ Study CSU Space 4 notes
- ✓ New questions in this booklet
- ✓ Relevant pages in Multiple Choice Dot Points Book (DPB). Bring the book for Monday.
- ✓ Space 4 Past year questions

**NEXT PERIOD > THEORIES MAY CHANGE OR ABANDONED ALTOGETHER!**