

STELLAR EVOLUTION

Alan C Pickwick

Manchester Grammar School (United Kingdom) Retired

Abstract

The workshop will outline the ways stars form, live and die. When the gas and dust of a giant molecular cloud collapses under gravity, a hot rotating ball of material that we call a star is created. The enormous temperature and pressure inside the star forces the nuclei of hydrogen together to form helium. This nuclear fusion releases energy that causes the star to shine. The size and temperature of the star is the result of the balance between gravity pulling inwards and the heat and light pushing outwards. As the star ages, the fusion of hydrogen to helium is succeeded by the fusion of helium to carbon. The greater energy output causes the star to change in temperature and size. Eventually the star runs out of its nuclear fuel and dies. If the star is small like our Sun, the event is unspectacular, but if the star is large, the result is a massive explosion and the possible creation of a Black Hole!

Introduction

The workshop will cover the formation, life and death of stars. There will be some simple exercises to do and some sounds to hear but the most important aspect is to link the theory here to the observations of the night sky that you make yourself.

The Formation of Stars

Stars form in Giant Molecular Clouds such as:

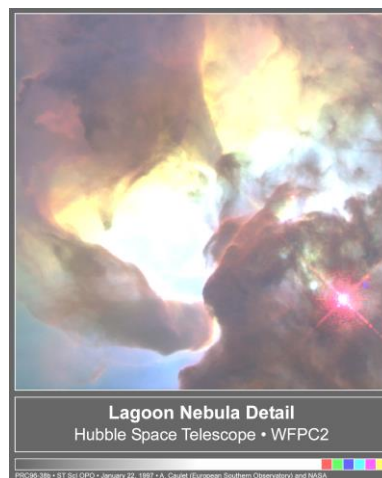
- The Orion Nebula. (Winter observing opportunity.)



The Orion Nebula

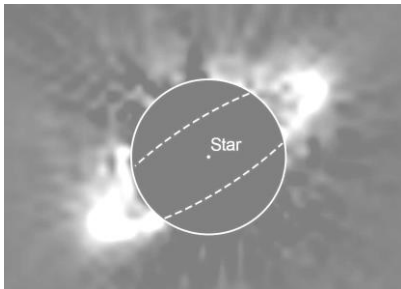
The Orion Nebula is easily visible in the winter night sky. To the naked eye it is a small fuzzy patch of light below the three stars of Orion's Belt. Through binoculars or a telescope you can see the blues and reds of the gas and dust cloud. It is almost certainly a place where dust clouds are collapsing to form new stars and planets. Image courtesy of the European Southern Observatory.

- The Lagoon Nebula (M8, NGC 6523) (Observing opportunity.)



The Lagoon Nebula in Detail

- The clouds contain very low density gas and dust. The dust is diffuse like the smoke from a fire.
- The clouds are very large, containing enough material to form many stars.
- Very slowly, gravity pulls sections of the cloud together.
- In the photographs we see dense clumps of gas and dust.
- Using infrared photography, we can see heat sources at their centres.
- This is evidence of stars that have started fusion reactions.
- There are spherical volumes that have been cleared by these stars.
- We see evidence of the formation of planetary systems. There are dust rings round stars.



A Dust Ring around a Star

This is a Dust Ring around a star in our Galaxy. The ring would fit inside Pluto's orbit. It is a good place to look for planets. The central star is very bright compared to the dust of the ring. To make the image, the star's light had to be blocked out by a black disk in the telescope, hence the missing central portion. Image courtesy of NASA Hubble Space Telescope.

- From the spectrum of the light coming from these clouds we know that the material has come from stars that have already lived and died.
- We know this because the material from the Big Bang had only hydrogen, helium and a trace of lithium. The material in the clouds has elements from across the Periodic Table.
- The clouds also contain molecules such as H₂O that will be incorporated into new planets and into comets orbiting the stars.

What is Fusion?

- The cores of stars are so hot that the nuclei have lost all their electrons. The nuclei are totally ionised. The electrons play no part in the fusion reactions.
- The nuclei are positively charged and so repel each other.
- To make nuclei fuse together they must approach to about 10^{-15} meter. This is 100 000 times closer than their spacing in normal matter.
- To achieve this, the nuclei need to be moving very quickly.
- This is possible when they have a temperature of at least 10 million degrees.
- As they 'touch' the Strong Nuclear Force becomes greater than the Electrostatic Repulsion and the nuclei merge together.
- They release kinetic energy in the form of fast moving elementary particles and neutrons. They also release electromagnetic energy in the form of gamma rays.

Types of Star

- Jupiters and Brown Dwarfs.
- Sun-like Stars.
- Massive Stars.

Evolution – Starting Up

- All stars convert Gravitational Potential Energy to Heat as they collapse. (See experiment in appendix.)
- Jupiters and Brown Dwarfs. Up to 8% mass of Sun. No Fusion.
- Red Dwarfs. From 8% to 51% of mass of Sun. Little Fusion.
- Sun-like Stars. Fusion and Long Bright Life.
- Massive Stars. Vigorous Fusion and Short Very Bright Life.

Evolution – Main Lifetime

Jupiters and Brown Dwarfs

- No Fusion – Energy from gravitational collapse.
- They just radiate their heat away and cool down.

Red Dwarfs

- Little Fusion – Just a few percent of the Sun.
- The most common star – 80% by number in our Galaxy.
- Will burn for perhaps 100 times longer than the Sun.

Sun-like Stars

- Convert less than 0.1% of their mass to energy.
- They look yellow / gold. (Observing Opportunity – The yellow star in Albireo.)
- They have a lifetime of perhaps 10 billion years.

Massive Stars

- Higher pressure and temperature causes much more vigorous fusion reactions.
- They look pale blue. (Observing Opportunity – Vega and the Blue star in Albireo.)
- They have a lifetime of perhaps only 200 million years.

Evolution – Towards the End of Life

Jupiters, Brown and Red Dwarfs

- Cold lumps of matter – The End.

Sun-like Stars

- After about 10 billion years, most of the hydrogen in the core is used up.
- The core collapses slightly and the temperature and density increase to allow helium fusion to begin.
- The outer envelope is pushed outwards by the increased heat output. However, the envelope's surface area is greater so its temperature is lower – it is a Red Giant. This phase lasts for about 1 billion years.

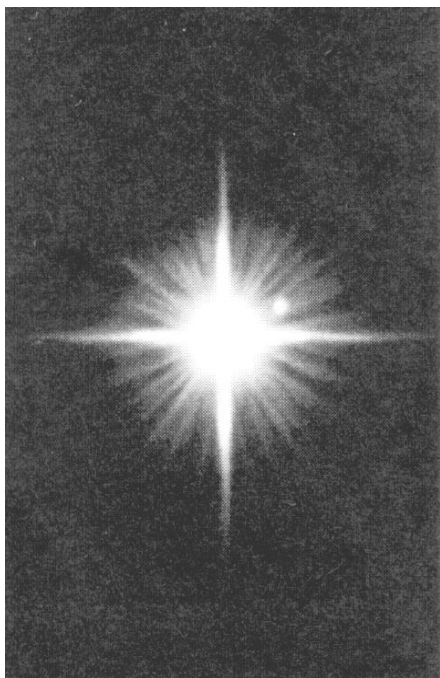
Massive Stars

- Massive stars go through a similar process to Sun-like stars but convection currents mix all the gases inside them allowing more of the hydrogen to be fused.
- The outer envelope expands to form a super-giant star.
- It can be a Red Giant. (Observing Opportunity – Antares.) However, it can be so hot that it is a Blue Super-Giant. (Observing Opportunity – Deneb.)
- Some variability is seen as the envelope expands and contracts. This is called the Cepheid Variable phase. The Pole Star and delta-Cephei are both variable with periods of several days and so need patient observation.

Evolution – The End of Life

Sun-like Stars

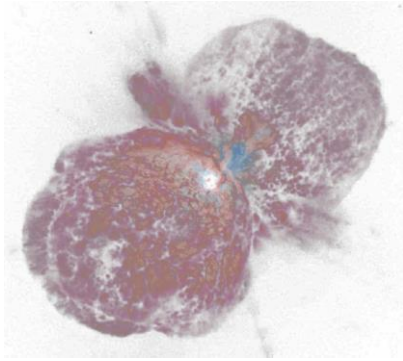
- As the fusion of helium continues the star's energy output rises.
- The outer envelope is pushed completely away.
- This can be seen in the Ring Nebula, Messier 57. (Observing Opportunity – The gas and dust shell is clearly visible but unfortunately the White Dwarf is too faint to see at 16th magnitude.)
- Another example is the Helix Nebula, NGC 7293. (Observing Opportunity – The nebula is easily visible through binoculars at magnitude 6.5 and its White Dwarf might be visible in large amateur telescopes at magnitude 13.)
- The core is left exposed. This is a White Dwarf.
- It has stopped fusion reactions.
- It radiates its heat away and so cools down.
- However it is so dense that it will take billions of years even to cool down to be red hot.
- There are no Black Dwarf stars yet, not even Red ones!!



A White Dwarf Star – Sirius B

Sirius A is easily visible in the night sky. What is not easily seen is the tiny companion in orbit round it, Sirius B. The bright light from the larger star completely swamps it but this photograph has been made using special masking techniques. Sirius B is an example of a White Dwarf star. It is only about five times the diameter of the Earth but has a mass similar to that of the Sun. Courtesy of R B Minton.

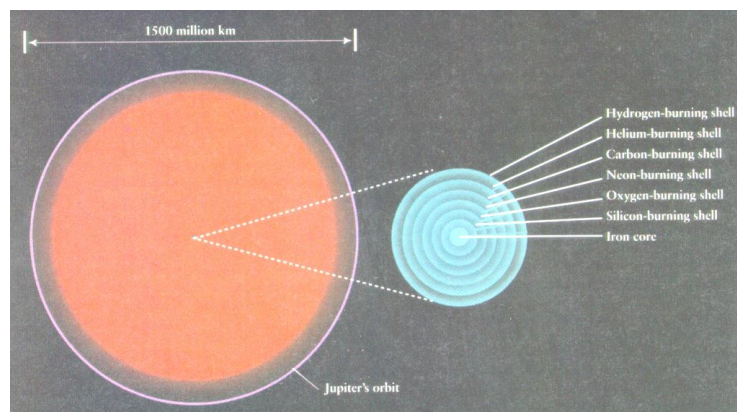
The Doomed Star Eta Carinae



Eta Carinae is about 100 times more massive than our Sun and is probably one of the most massive stars in our Galaxy. It radiates about five million times more power than our Sun. A huge, billowing pair of gas and dust clouds are captured in this stunning NASA Hubble Space Telescope image. The supermassive star is 8 000 light years away. Dust lanes, tiny condensations and strange radial streaks all appear with unprecedented clarity. Eta Carinae made a giant outburst about 150 years ago, when it became one of the brightest stars in the Southern sky. Though the star released as much visible light as a supernova explosion, it survived the outburst. Somehow, the explosion produced gas and dust clouds above its poles and a thin disk around its equator, all moving outwards at about 670 km/s. This star remains one of the great mysteries of astronomy.

Massive Stars

- When the star has fused most of the hydrogen in its core into helium, its core collapses a little, the temperature and density rise and it fuses helium into carbon at its centre.



The Onion Shell Nature of the Core of an Old Large Star

From Universe (6th Edition). Kaufmann & Freedman.

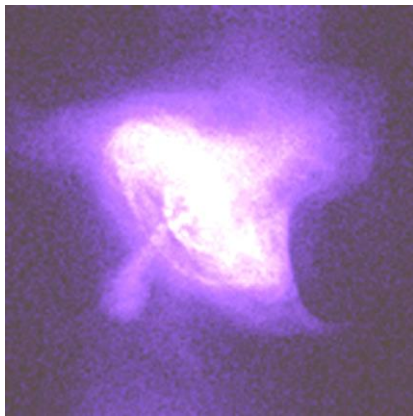
- This collapse continues until iron has been produced at its centre, after which energy is not created by fusion.
- The temperature in the core starts to fall and the pressure of the gas and radiation is unable to support the star.
- The whole structure collapses, converting Gravitational Potential Energy into heat.
- The temperature and density become so high that all the elements beyond iron in the Periodic Table are created.
- The falling material then rebounds and scatters the elements across the Galaxy. This is a Type Ib, Ic or II supernova.
- An example is the Crab Supernova (Messier 1, 3C144), seen in 1054 AD. Its remnant is visible as a Winter object.



The Crab Nebula in Taurus

When this nearby star in the Constellation of Taurus exploded as a supernova, it was recorded as a 'Guest Star' by Chinese astronomers. For days on end it was so bright that it could be seen in the daylight sky!! In a small telescope you can see it as a small fuzzy patch of light. It is known as the Crab Nebula because of its claw-like appearance. The fragments are moving outwards at about 400 km/s – Manchester to London in a second!! Image courtesy of the European Southern Observatory. Taken using the 8 metre Very Large Telescope, Kueyen.

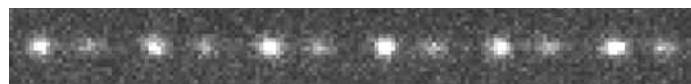
- The material in our Solar System has been through this process about five times. We know this by measuring the percentages of the heavier elements in the Solar System.
- The core of the star is likely to be a neutron star. It is also likely to be spinning and to have a strong magnetic field. This produces pulses of radio and light energy. It is then known as a Pulsar.



The centre of the Crab Nebula seen in X-rays

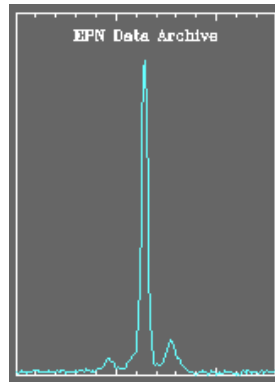
We now know that there is a rotating neutron star at the centre of the Crab Nebula. The neutron star is thought to be only 20 km across and spins at 30 revolutions per second. Imagine the city of Manchester spinning at this rate. This amazing image taken by the NASA Chandra X-ray telescope show the clouds of gas and dust swirling round the neutron star.

- The spinning star is surrounded by a large expanding cloud of debris. Pulsar activity occurs when the magnetic field of the core is not aligned with its spin axis. The rotation then causes major disturbances in the ionised debris, heating it strongly and causing the electrons to spiral around the magnetic field lines. The rotation also acts like a lighthouse, producing the pulses of energy as shown in the timeline below.
- We can receive radio pulses from the Crab Nebula and so it is called a Pulsar. A small radio telescope at Jodrell Bank has been monitoring the pulses for many years. There are 30 pulses per second and the rate is slowing very slightly. Occasionally there is a glitch in the regular pulse train and this is assumed to be a star-quake!!



Timeline Image of the Crab Pulsar

Courtesy of the European Southern Observatory.
Taken using the 8 metre Very Large Telescope, Kueyen.



Radio Pulse from a Pulsar

The Sounds of Pulsars

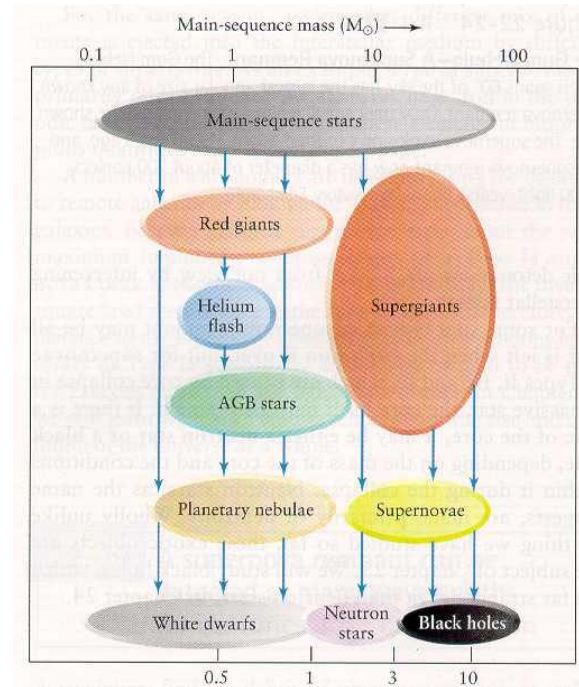
- Using a radio telescope it is possible to hear the pulses caused by the rotation of the neutron star.
- PSR B0329+54. This is a typical pulsar, rotating with a period of 0.714519 seconds. [Pulsar Sounds\B0329.au](#) (Audio File B0329.au)
- PSR B0531+21, The Crab Pulsar. This is the youngest known pulsar and lies at the centre of the Crab Nebula and rotates about 30 times a second. [Pulsar Sounds\crab.au](#) (Audio File crab.au)
- PSR B1937+21. This is the fastest known pulsar, rotating with a period of 0.00155780644887275 seconds, or about 642 times a second. The surface of this star is moving at about 1/7 of the velocity of light and illustrates the enormous gravitational forces needed to prevent it flying apart. [Pulsar Sounds\B1937 Fastest Known.au](#) (Audio File B1937 Fastest Known.au)

The Ultimate Fate

- If the remaining core has more than 1.4 times the mass of the Sun, it can become a Black Hole where the gravity is so strong that not even light can escape.

Summary

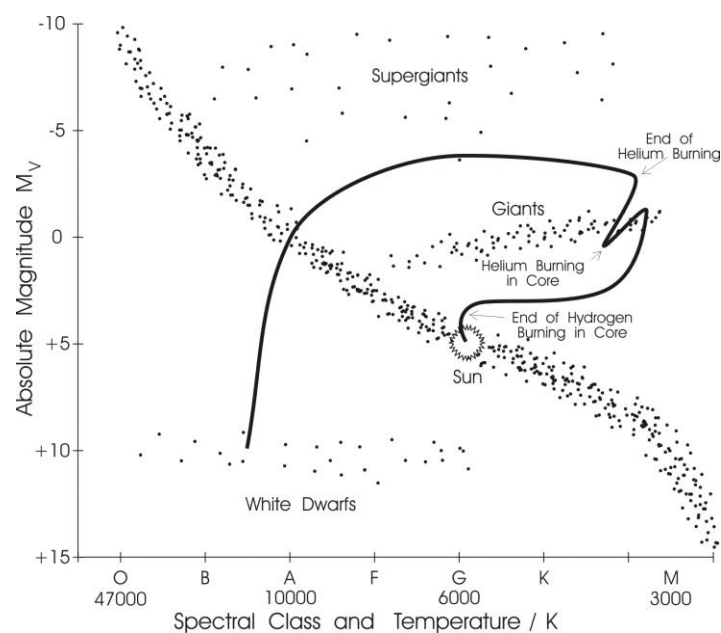
The graphic shows the various evolutionary paths of stars. The boundaries are not very sharp as a path is influenced by the amounts of heavier elements in the initial cloud from which the star formed.



Evolution of Stars.

From Universe (6th Edition). Kaufmann & Freedman.

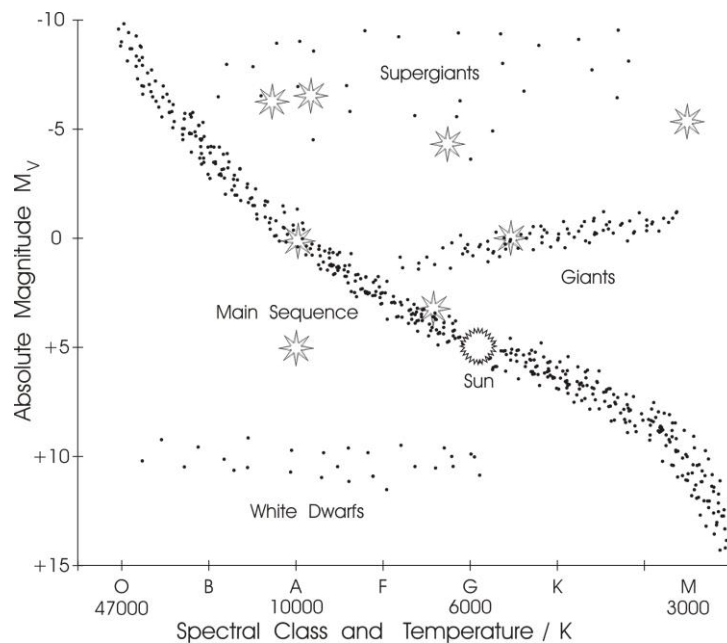
The Hertzsprung-Russell Diagram is a main-stay of astronomy. It shows that most stars fall on the diagonal 'main sequence' when they form. Later they become Giants or Super Giants and possibly White Dwarfs. The evolution of our Sun is shown.



Exercises

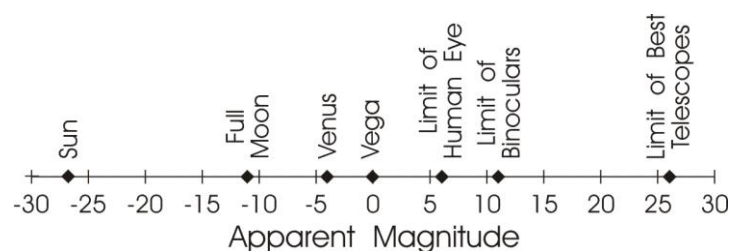
Hertzsprung-Russell Diagram Familiarisation Exercise

In the Hertzsprung-Russell diagram, several well-known stars are marked. It is your job to write their names on the diagram using the data in the table. This will help you learn the structure of the diagram.



Name	Absolute Magnitude	Temperature / K
Arcturus	0	5 500
Betelgeuse	-5	3 000
Deneb	-6	10 000
Helix White Dwarf	+5	10 000
Polaris	-4	6 500
Procyon	+4	7 000
Rigel	-6	12 000
Vega	0	10 000

For comparison, here is a table of interesting points on the Magnitude Scale. The Apparent Magnitude is what you see with the naked eye. The Absolute Magnitude is what you would see if the object was taken to the standard distance of 32.6 light years (10 parsecs).



Experiments & Calculations

1) Gravitational Potential Energy to Heat Conversion

Place a handful of sand in a long cardboard tube. Measure the temperature of the sand with a digital thermometer. Seal both ends of the tube and hold it vertically. Invert it 100 times, giving time for the sand to drop to the opposite end. Open the tube and measure the temperature of the sand again.

Any rise in temperature is due to the conversion of Gravitational Potential Energy to Heat, just as when the dust cloud collapses to form a proto-star.

You can make this experiment more quantitative:

The **heat energy** gained by the sand is given by:

Mass of Sand $\times$ Specific Heat Capacity of Sand $\times$ Temperature Rise

(The SHC of sand is 800 J/kg K.)

$$\begin{aligned} &= \text{Mass of Sand} \times 800 \times \text{Temperature Rise} \\ &= \text{Joules} \end{aligned}$$

The **gravitational potential energy** gained by the sand is given by:

Mass $\times$ Length of Tube $\times$ Number of Inversions $\times$ Acceleration due to Gravity

$$\begin{aligned} &= \text{Mass} \times \text{Length} \times 100 \times 10 \\ &= \text{Joules} \end{aligned}$$

Compare the two energies. Why is one greater than the other?

+++++

Mass of Sand $\times$ Specific Heat Capacity of Sand $\times$ Temperature Rise

(The SHC of sand is 800 J/kg K.)

$$\begin{aligned} &= \text{Mass of Sand} \times 800 \times \text{Temperature Rise} \\ &= 0.50 \times 800 \times (23.9 - 23.4) = 200 \text{ Joules} \end{aligned}$$

The **gravitational potential energy** gained by the sand is given by:

Mass $\times$ Length of Tube $\times$ Number of Inversions $\times$ Acceleration due to Gravity

$$\begin{aligned} &= \text{Mass} \times \text{Length} \times 100 \times 10 \\ &= 0.50 \times 0.57 \times 100 \times 10 = 285 \text{ Joules} \end{aligned}$$

2) Calculation of the percentage of the mass of the Sun used in its lifetime

The Sun radiates 3.90×10^{26} Joules of energy into space each second.

Assume its initial mass was 2.00×10^{30} kg.

Use Einstein's famous formula $E = mc^2$ to calculate the percentage of the Sun's mass that it will use in its lifetime of 10 billion years.

$$\begin{aligned}\text{Total Energy Created} &= 3.90 \times 10^{26} \times 10\,000\,000\,000 \times 365.25 \times 24 \times 60 \times 60 \\ &= \quad \quad \quad \text{Joules.}\end{aligned}$$

$$\text{Total mass used to create this energy} = \text{Energy} / (3 \times 10^8)^2 = \quad \quad \quad \text{kg.}$$

$$\text{Percentage of mass used} = (\text{Used Mass} / \text{Original Mass}) \times 100 \% = \quad \quad \quad \%.$$

+++++

$$\begin{aligned}\text{Total Energy Created} &= 3.90 \times 10^{26} \times 10\,000\,000\,000 \times 365.25 \times 24 \times 60 \times 60 \\ &= 1.23 \times 10^{44} \text{ Joules.}\end{aligned}$$

$$\text{Total mass used to create this energy} = \text{Energy} / (3 \times 10^8)^2 = 1.37 \times 10^{27} \text{ kg.}$$

$$\text{Percentage of mass used} = (\text{Used Mass} / \text{Original Mass}) \times 100 \% = 0.068 \%.$$

3) Calculation of the Mass of a ‘Full Stop’ made of Neutron Star Material

The density of neutron star material is 100 000 000 000 000 000 kg/m³. Estimate the volume of ink in a full stop on this page and calculate its ‘neutron material’ mass.

$$\text{Volume of a cylinder} = \pi \times r^2 \times h$$

$$\text{Mass of cylinder} = \text{Volume} \times \text{Density}$$

+++++

$$\text{Volume of a cylinder} = \pi \times r^2 \times h$$

$$= \pi \times (0.25 \times 10^{-3})^2 \times 2.0 \times 10^{-6}$$

$$= 3.93 \times 10^{-13} \text{ m}^3$$

$$\text{Mass of cylinder} = \text{Volume} \times \text{Density}$$

$$= 3.93 \times 10^{-13} \times 1.0 \times 10^{17}$$

$$= 3.93 \times 10^4 \text{ kg}$$

$$= 3.93 \times 10^1 \text{ tonnes}$$

$$= 39.3 \text{ tonnes.}$$

Other Observations

Tycho's Supernova Remnant in Cassiopeia is of Type 1a. It is visible in a small telescope. The explosion was caused by hydrogen falling onto a white dwarf star from its red giant companion. Eventually there was too much mass for the white dwarf to support and it collapsed, converting a large part of its mass into energy. The light from the explosion was so bright that it will be visible across the Universe.

Acknowledgements:

The author gratefully acknowledges the useful discussions he had with Rainer Gaitzch, Teacher's Academy of Bavaria (Germany) and Alexandre Costa, Escola Secundária de Loulé and Centro Ciência Viva do Algarve (Portugal) in the creation of this workshop.

References:

Universe (6th Edition). William J Kaufmann & Roger A Freedman. Freeman Press. ISBN 0716746476.

Space Encyclopedia. Heather Couper & Nigel Henbest. DK Publishing. ISBN 0789447088.

SEDS Web Site – Full of useful data – www.seds.org

Equipment:



Project Star Spectroscope (PS-14/Plastic) \$33 + p&p.



Sunspotter – The Safer Solar Telescope (LT-70) \$475 + p&p.

Available from www.astrosociety.org.

Updated January 2018.