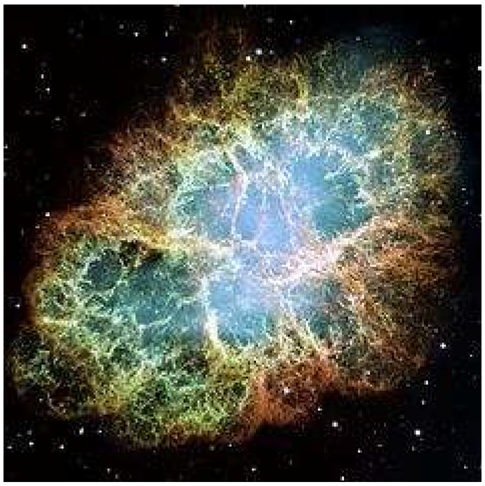
Tuesday 2nd May 2017: "Nuclear Astrophysics" - Prof. Alex Murphy

Supernovae are some of the biggest and most energetic explosions in the universe, marking the transition from the star burning its fuel during its lifetime to the star's dramatic death. Core collapse supernovae are very important as they are probably responsible for all the heavier elements in the universe beyond iron which, along with lighter elements, are spread throughout space during their explosive deaths. These elements then go on to make planets and ultimately, us.

1)



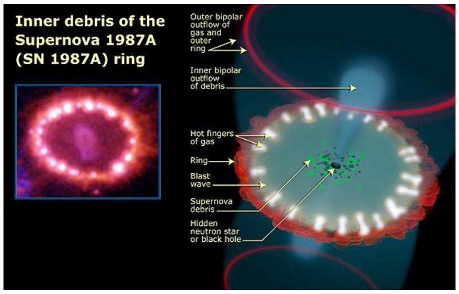
There have been between seven and eleven supernovae recorded as seen by mankind. They are thought to occur once every 30-50 years in our Galaxy. There may be more that are not seen because they are too far away and/or obscured by dust. We were then shown images of a few supernova remnants, many of which have pulsars in the centre. The Crab Nebula (1) has a pulsar at its centre.

2)

Supernova 1987A occurred in the Large Magellanic Cloud and was originally a 20 solar mass blue supergiant. This is the nearest supernova since the invention of telescopes. (2)

The Hubble Space Telescope took many photos as 1987A evolved. Material had been thrown off near the end of its life and then, after the explosion, the shock wave slammed into this material and lit it up as the "ring of fire". (3).

3)



When the star runs out of hydrogen in the core, it will contract and heat up and will then begin to fuse helium to carbon and oxygen. Once helium has been used up, contraction occurs again with a subsequent rise in temperature and carbon starts fusing to neon and magnesium. This continues with each element being used up faster than the last one. Eventually the core consists of iron with layers of other elements around it like an onion.

Iron cannot be fused as energy needs to be put into the system to achieve its fusion, so the core of the star, now several thousands of kilometres thick, collapses under gravity at a third of the speed of light in about 1/40th of a second, producing as much energy as our Sun in its entire lifetime.

As the density of the material reaches that of nuclei, it can’t collapse any further so the material bounces off the core. The shockwave moves through the outer layers of the star and the enormous heat and energy produced during the explosion creates the heavier elements. The collapse happens so fast that the outer layers of the star don’t know about it until they are thrown out into space by the shock wave.

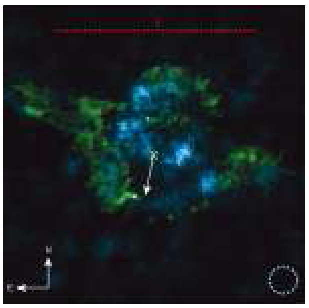
Material tends to continue falling onto this dense hard core generating heat and radiation, but at the same time the shockwave radiates outwards giving rise to some interesting physics which are so extreme that it is not possible to reproduce them in the laboratory.

How can we make progress? We need a probe that can tell us about the underlying physics thousands of km deep under the surface of the star. The probe must be something we can measure. The probe that can be used is an isotope of Titanium called Ti 44, which is an unstable form and has a half-life of about 60 years, and we can see this isotope in the latter stages of the light curve.

It is one of the nuclei produced in supernova ejecta and requires very high temperatures to make it so it must be produced in the deepest layers near the ‘mass-cut’ that separates the remnant (material that gets stuck inside the star) from the ejecta (material that bounces outwards in the explosion – the shockwave). The Ti 44 is produced in the region of the mass-cut so some gets stuck inside the star and some is thrown out of the star. If there is a more energetic explosion then more Ti 44 gets thrown out and vice versa. Ti 44 also emits gamma rays as it decays which can be detected by space telescopes such as the Integral satellite which replaced the Compton in 2002 then the NUSTAR which was launched in 2012.

The best data we have comes from Cassiopeia A and 1987A and the amount of Ti 44 produced in a supernova is around 1.4 - 1.5 x 10^{-4} solar masses. NUSTAR can also image supernovae remnants. This is Cassiopeia A (4) – the blue shows radioactive Ti 44 and can give a more direct look at the heart of the explosion. The green shows silicon and magnesium in X-rays as seen by Chandra. It was thought the blue and green should have been correlated but they are not – this was a surprise.

4)



The amount of Ti 44 measured in observations has shown much more Ti 44 than the best models predict. To find out why there is this difference, it is important to measure the amount of Ti 44 destroyed during the supernova explosion by looking at its decay product of Vanadium 45 after it has fused with an alpha particle.

To do this, they had to go to the Paul Scherrer Institute in Switzerland for radioactive waste from particle accelerators, which contained enough Ti 44, which after extraction enabled them to run an experiment in the Isolde accelerator at Cern. They fired a beam of Ti 44 into a helium filled gas chamber to recreate the explosive energy of a supernova to see how quickly Ti 44 is destroyed. They didn't actually find anything to measure, but it still proved very interesting because the limit that they put on this is much smaller than the rate was thought to be – less Ti 44 was destroyed, which means more was left over.

The result therefore is in line with what the observations show and brings it into closer agreement with the models once the new figures have been taken into account. Prof Murphy says this is a convoluted way of saying that a non-measurement in a very complicated scenario helps to explain the observations that are seen in astrophysics.

It is still a mystery as to why core collapse supernovae occur; why do they explode? A chap from Aberdeen who works in quantum gravity has a theory, which suggests that in very dense environments (as in the beginning of the universe) a new particle might exist which undergoes a phase transition of potential energy that releases energy. Prof Murphy also wondered if the theory could also apply to supernovae, which are also dense environments. A new particle, like another kind of Higgs Boson, could solve inflation, provide a late universe explanation of dark energy and provide an extra energy boost for incredibly dense environments like supernovae.

LIGO will be releasing new information in two to three weeks time which will include five or ten more observations of gravitational waves, one of which quite possibly could be from a core collapse supernova. Thank you Prof Murphy for a stimulating and challenging talk about your work with Ti 44 and its importance in helping to understand why core collapse supernovae explode.