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SUPERNOVA 1987A

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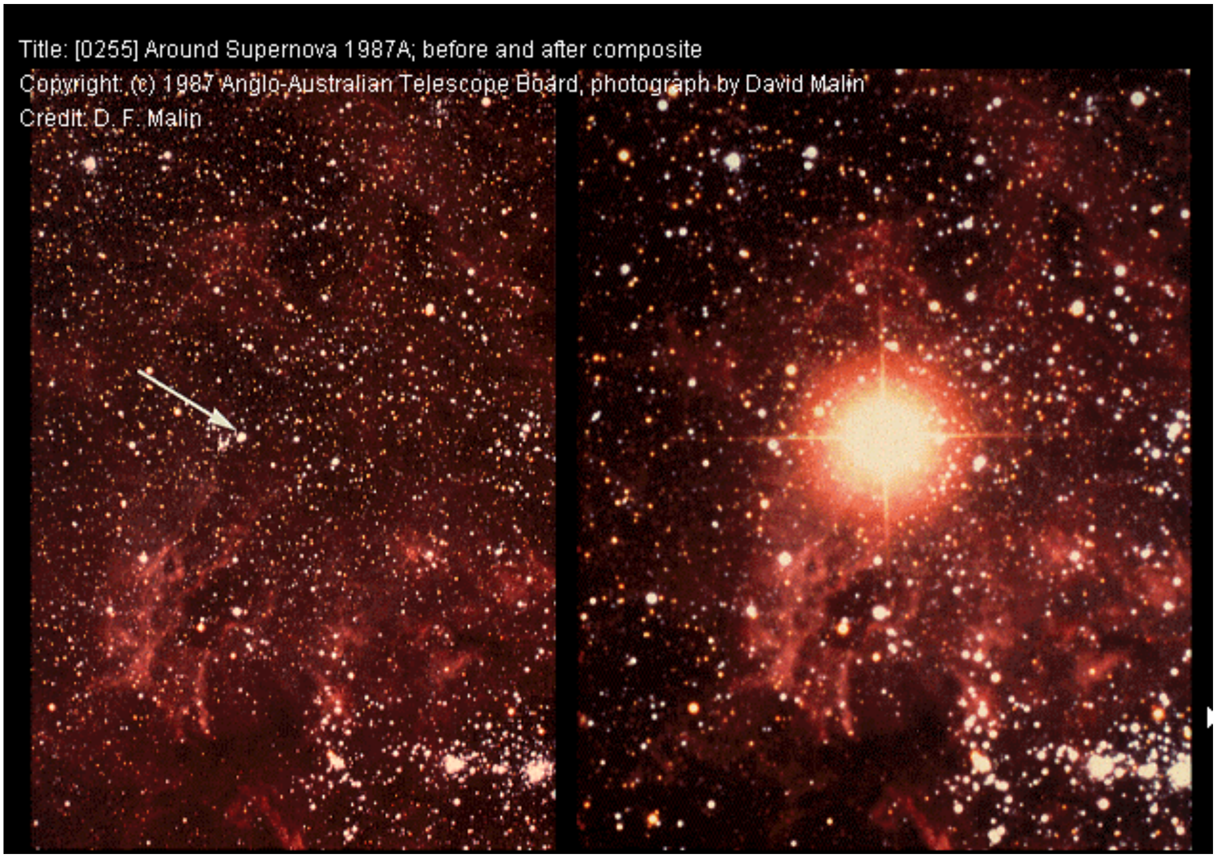
Introduction

On the night of February 23rd 1987, Ian Shelton of the Las Camponas Observatory in Chile observed a very bright star in the constellation of Dorado; part of the Large Magellanic Cloud. What he discovered and was very soon verified by astronomers around the world was a Type II supernovae. This discovery as it stands was very important to astrophysics due to its brightness and near proximity. The timing was also significant because it could be observed in a number of wavelength regimes such as Infra Red, Ultra Violet, visual, radio, x-ray and gamma ray. The last supernovae visible to the unaided eye was in 1604 which was a Type I supernova and appeared four years before the invention of the telescope. SN 1987A as it became designated could be studied like no other supernova before and astrophysicists have achieved remarkable results which have supported as well as opposed the common models about such events.

Although the official discoverer was Shelton, other astronomers can also stake a claim to be discoverer. Richard McNaught of Siding Spring, Australia observed the LMC only the night before but did not process his photographic plates until the 23rd. When he did so, what he saw was a new star of magnitude 6 where the previous night there was nothing to note. An amateur astronomer called Albert Jones located in New Zealand, saw the new star only a few hours after Shelton had photographed it, but what makes him a more important piece in the jigsaw was what he didn't see on the 23rd. His failure to notice anything untoward had occurred in the LMC places a limit to the brightness of the supernovae on that day.



THESE TWO IMAGES SHOW THE LOCATION OF SN 1987A BEFORE AND AFTER THE EXPLOSION.

The Pre Supernovae Star

Soon after its' discovery, astronomers around the world examined their photographic plates to see which star had exploded. What they found was a blue super giant star named Sk -69° 202, that is star 202 in Nicholas Sanduleaks' list of bright blue stars. The -69° comes from its' declination on the sky.

The Radius Of Sk -69°202

The radius of the star can be estimated by using some simple methods.

The distance to the Large Magellanic Cloud is thought to be 52,122 Parsecs which gives a distance modulus of 18.85. The apparent magnitude was estimated from photographic plates taken before the star turned supernova and is estimated to be m_v=12.24. This gives an absolute magnitude of M_v=-6.34. So applying a bolometric correction of 1.26 gives M_{BOL}=-7.6

Now:-

$$M_{\oplus} - M_{*} = 2.5 \, \mathrm{Log} \, \frac{L*}{L\oplus}$$

$$4.64 - -7.6 = 2.5 \, \mathrm{Log} \, \frac{L*}{L\oplus}$$

$$\therefore \; 4.896 = \mathrm{Log} \, \frac{L*}{L\oplus}$$

$$\therefore \; \frac{L*}{L\oplus} = 78{,}704.5$$

$$\therefore \; L* = 2.98 \times 10^{31}$$

$L = 4\pi R^2 \sigma T_e^4$ Where T_e is 15,200 for a B3I supergiant.

$$\therefore \; R = 2.8 \times 10^{10} m$$

The Mass Of Sk -69°202

As seen above, it is quite easy to determine the radius of the progenitor, however determining its' mass is not so easy. The mass can only be estimated, as its' position on the Hertzsprung-Russell diagram is only loosely constrained. To make the definition more difficult, there are large uncertainties in the amount of mass lost during the stars lifetime. However calculations by Stanford Woosley have shown the mass to be around 15 times the solar mass. This was determined by using the flux of neutrinos detected by the Kamiokande and IMB neutrino detectors. It is estimated that the flux at Earth was approximately 50 billion neutrinos per square centimetre. This flux obeys an inverse square law of the form 1/r2, which gives a signal of between 2 to $3*10^{53}$ ergs when using the distance of the LMC of 160,000 light years. Now it has been calculated that when 0.1 solar mass of iron is broken down in to protons and neutrons, $1.7*10^{51}$ ergs is carried away in neutrinos. 99% of the binding energy in this process is carried away by neutrinos, so the mass can be estimated as follows:-

$$\frac{2\times10^{53} ergs}{1.7\times10^{51} ergs} = 117.64$$

Multiplied by 0.1 solar masses gives 11.76 times the solar mass.

And $$\frac{3\times10^{53} ergs}{1.7\times10^{51} ergs} = 176.57$$

Multiplied by 0.1 solar masses gives 17.64 times the solar mass.

So the estimated mass lies between 11 solar masses and 17 solar masses. Or around 15 solar masses.

The Optical Light Curve Of SN 1987A

Hydrodynamical Time

The effective temperature of the progenitor governs how much energy is emitted in photons and at what wavelength. The hydrodynamical time is the time it takes for the star to cool so that the photons are emitted in the visual regime of the electromagnetic spectrum. The reason why this time is important is because it gives the optical rise time.

$$t_h \approx 10^4 \times \left(\frac{M}{15M\oplus}\right)^{\frac{1}{2}} \left(\frac{E}{10^{51} erg}\right)^{-\frac{1}{2}} \left(\frac{R}{3\times10^{12} cm}\right) \text{ seconds}$$

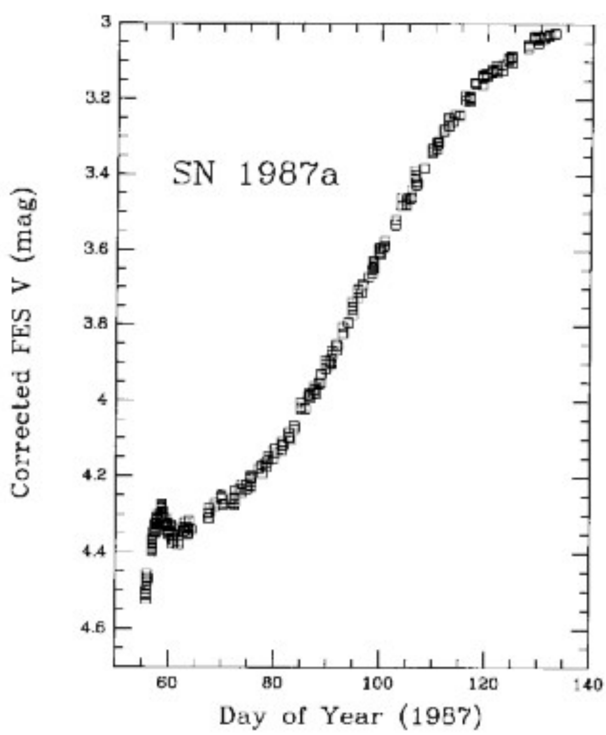
This gives a very short time for the Sk -69° 202 parameters, which is why the visual decay occurred only hours after the neutrino burst was recorded at Kamiokande and IMB. A typical SN II progenitor has a radius of around 10^{14} cm which gives a rise time for them about 10 days.

Luminosity Of SN 1987A

The relatively small radius of Sk -69° 202 is responsible for the low luminosity of SN 1987A and is governed by the relation:-

$$L_{SN1987A} = 4\pi R^2 \sigma T^4$$

As can be seen from the ultraviolet luminosity of SN 1987A taken by the International Ultraviolet Explorer Satellite, there is a rapid rise to a maximum, then a sudden decline within 15 days from core collapse. This can be explained by adiabatic cooling of the photosphere, the colour of the star quickly moved from blue to red. This occurred comparatively quickly for SN 1987A due again to its' small radius.

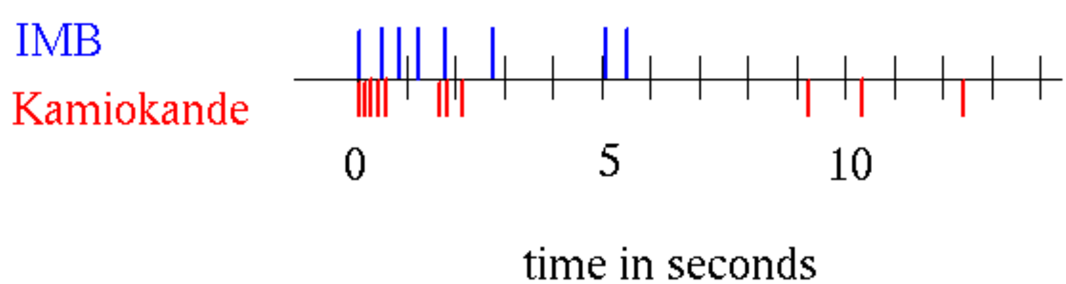


THE ULTRAVIOLET LUMINOSTY FOR SN 1987A FROM DAY 50 TO DAY 140

The Neutrino Burst

One of the amazing things about SN 1987A was the fact that it was detected by two neutrino instruments only hours before it was discovered visually. The two neutrino detectors in question are the Kamiokande in Japan and the IMB in Ohio, USA. Both these detectors are of the same basic design. They consist of a large tank of very pure water with 2,000 light sensors immersed in it. When a neutrino enters the tank and hits a proton or electron in the water, Cerenkov radiation is emitted which is then picked up by the light sensors. Because neutrinos are very light, they very rarely interact with particles. It was typical to detect an extra solar neutrino once in every five days.

However on the 23rd of February 1987, eight neutrinos were detected by the IMB at the same time as the Kamiokande registered 11 neutrinos. This time which was recorded by computer is thought to result from the neutrino burst from SN 1987A as its' core collapsed. These two large detectors were not the only ones on Earth to register something that day. The Mont Blanc detector underneath the Alps recorded several events, but at a different time to the Kamiokande and IMB detectors, it is still unknown what significance this has to neutrino astronomy and SN 1987A in particular. The other detector called the Baksan Detector underneath the Caucasus mountains also recorded neutrino events, but as they were received just below its' working threshold, this data was ignored by the astrophysicists. It was these detectors that helped put a limit on the mass of the neutrino and so may help explain some of the missing mass in the universe.



THIS DIAGRAM SHOWS THE NEUTRINO EVENTS FOR THE KAMIOKANDE AND IMB DETECTORS OVER A PERIOD OF 14 SECONDS

The Life Of A 20 Solar Mass Star

The progenitor star Sk -69° 202 was formed around 10 million years ago and lived the past 9 million years like other stars; fusing hydrogen into helium to produce energy. After the hydrogen had been consumed, a helium core of 6 solar masses was left. The central regions contracted, heating up as it did so. Hydrogen fusion continued in a thick shell around the core while the stars outer layers expanded. When the central core reached a temperature of 170 million degrees Kelvin, helium began to fuse to produce more energy. The radius of the star was now around 10^8 km while the luminosity was about 100,000 times our suns'. The star had now entered its' red supergiant phase.

Helium fusion lasted about a million years producing a 4 solar mass core of carbon and oxygen. It was at this stage of the stars life that it lost a large amount of material in the form of a stellar wind. Eventually, the helium fusion ceased at the core and again the star contracted. The luminosity diminished by such an amount that the outer red giant envelope could not be supported and so was lost to outer space. The central part of the star contracted by a factor of 10 heating up so much, it entered its' blue phase. The central core had now reached 700 million degrees Kelvin and a new process of fusion began.

Over a period of 1000 years, the carbon within the core fused together to produce neon, sodium and magnesium. It was at this stage that electrons and positrons collided to produce neutrino-antineutrino pairs. These neutrinos escaped very easily and so took away more energy than radiation from the surface. The next stage called neon burning occurred when the carbon had been exhausted. Neon fused together at a temperature of 1.5 billion degrees Kelvin to produce oxygen and magnesium. This phase only lasted a few years and was followed by oxygen burning which created silicon and sulphur at temperatures of about 2.1 billion degrees Kelvin.

The final stages of the stars life lasted only a matter of days and is called silicon burning. Because silicon and sulphur cannot fuse together to produce heavier elements, at a temperature of 3.5 billion degrees, a small amount of silicon melted in to the area of free helium nuclei, neutrons and protons. These particles then added on to the silicon and sulphur nuclei to produce elements of the iron group, mainly ^{54}Fe and ^{56}Fe. When the silicon burning was completed, the star had reached the end of its' evolutionary life. No more energy could be produced by the fusion process.

Throughout its' life, gravity had got stronger and stronger with every contraction of the star and that continued here. The core contracted and heated up, aided by two other processes; electron capture and photodisintigration. Because most of the pressure supporting the star came from electrons, removal of these electrons allowed the star to contract. These electrons were lost because they combined with protons inside heavy iron nuclei. Photodisintigration involved the breaking up of nuclei by high energy radiation. But this process took away a large amount of energy that would otherwise be used to provide heat and pressure. The outcome again was more contraction of the stars' core. Due to these two processes, the core collapsed very fast.

Why Was Sk -69°202, Blue?

It was soon realised that the star that exploded was a blue giant as opposed to a red giant so typical of a Type II supernova. One possible answer is that before it exploded, Sk -69° 202 had lost so much matter as a stellar wind that all that was left was a helium core contracted so much that it glowed a hot blue colour. Another possibility is the composition of stars in the Large Magellanic Cloud. These stars have a tendency to be low in metalicity and so Sk -69° 202 may have evolved through its' life differently to a typical galactic star that consists of mainly hydrogen and helium.

Explosion Mechanisms

The Prompt Hydrodynamical Explosion

The core collapses in only a few tenths of a second, while the density rises to about 1million times its' previous amount. The outer layers, that is the neon, carbon, helium and hydrogen shells, do not collapse inward, but instead hang suspended. When the density in the core reaches a certain point, the nuclear forces which usually hold the atoms together, changes sign and becomes repulsive. The resistance to further compression is too great and so the stars' collapse halts. About half of the iron core (0.7 solar masses) springs back, blocking the infalling matter from the outer layers. A shock wave is created at this intersection of iron core and supersonic infalling matter. The shock front moves on outward exciting the rest of the core with 10^{51} erg which then blasts the stars outer layers at high velocity in to space.

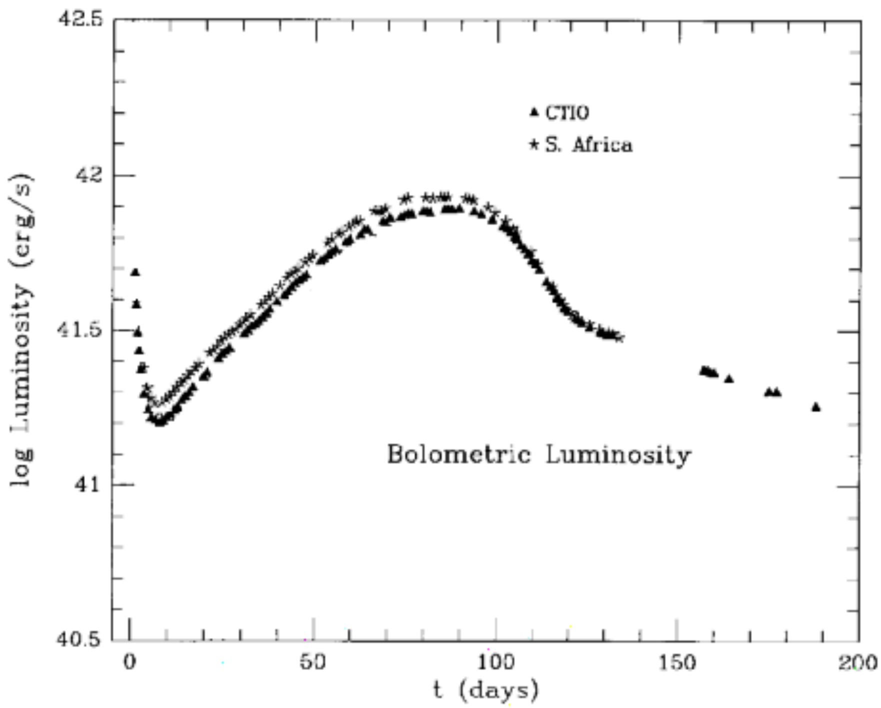
The Delayed Explosion Mechanism

Because 99% of the energy of a forming neutron star is emitted as neutrinos, it turns out the neutrino energy is 100 times more powerful than is needed to produce the shock front that creates a powerful supernovae. Some of this energy must be deposited underneath the shock front at the point where matter is accreting on to the iron core. It is in this zone that neutrinos and antineutrinos deposit energy to produce enough heat an pressure to send the shock front outwards again.

It is still unknown which method of explosion SN 1987A erupted with, because the observable properties such as velocity, light curve and spectra only give data on the energy deposited in the core and not the mechanism. However it has been found that core masses up to 1.35 solar mass favour the prompt hydronamical explosion and core masses greater than 1.35 solar mass favour the delayed mechanism. The expansion of SN 1987A will give more detail on the kinetic energy produced by the explosion and should give a better understanding of which mechanism occurred inside.

The Light Curve And The Decay Of 56Cobolt

The bolometric light curve of SN 1987A shows a sharp decrease over the first few days, then a slow increase to maximum around day 80. Then the curve decreases again and steadies out as shown in the figure below.



THE BOLOMETRIC CURVE OF SN 1987A FROM DAY 0 TO DAY 200. THE DIFFERENCE IN THE TWO CURVES ARE DUE TO THE OBSERVERS TAKING DIFFERENT AMMOUNTS OF INTERSTELLAR REDDENING IN TO ACCOUNT

The curve can effectively be split in to three regions; day 0 to day 10, day 10 to day 40 and day 40 onwards.

Day 0 To Day 10

The rapid decline of the bolometric luminosity is due to the rapid expansion of the surface of the star. This expansion caused a decrease in temperature which was also noted by a rapid colour change from blue (hot) to red (cooler).

Day 10 To Day 40

This phase of the curve saw a rapid increase in the luminosity which was mainly due to the recombination of hydrogen nuclei and electrons which were ionised when the shock wave passed through during core collapse. The temperature here levelled off to between 5,000 and 7,000 Kelvin, which is the temperature required for recombination to occur at the low density of 10^{-13} gcm^{-3}.

Day 40 Onwards

If the only source of energy in the supernovae was produced by the shock wave, then the luminosity would slowly decrease after around day 40. However it was seen that the luminosity climbed and peaked at day 85. Some of this energy was created as the shock front passed through, but as can be seen from the graph, it decreases linearly through to day 200. There are two possibilities about what was creating the energy in this phase. One is energy that is created from a rapidly spinning pulsar that was formed when Sk -69° 202 went supernova. The second is radioactivity from the decay of ^{56}Cobalt which was synthesised in the initial explosion.

The Decay Of 56Cobalt

As can be seen here from the process of decay from ^{56}Nikel to ^{56}Cobalt and ^{56}Cobalt to ^{56}Iron, the decrease of the bolometric curve (if powered from ^{56}Cobalt decay) should follow a similar path to the half life of the decay.

$$^{56}\mathrm{Ni} \Rightarrow {}^{56}\mathrm{Co} + e^{+} + \nu_e + \gamma$$

$$^{56}\mathrm{Co} \Rightarrow {}^{56}\mathrm{Fe} + e^{+} + \nu_e + \gamma$$

$$\frac{dN}{dt} = -\lambda N$$

$$N(t) = N_0 e^{-\lambda t}$$

$$\therefore \quad \lambda = \frac{\ln 2}{t^{\frac{1}{2}}}$$

So $$\frac{d\mathrm{Log}_{10} L}{dt} = -0.434\,\lambda$$

Or $$\frac{dM_{BOL} L}{dt} = 1.086\,\lambda$$

$$\therefore \quad \lambda = \frac{\ln 2}{t^{\frac{1}{2}}} = \frac{\ln 2}{77.1} = 0.00899$$

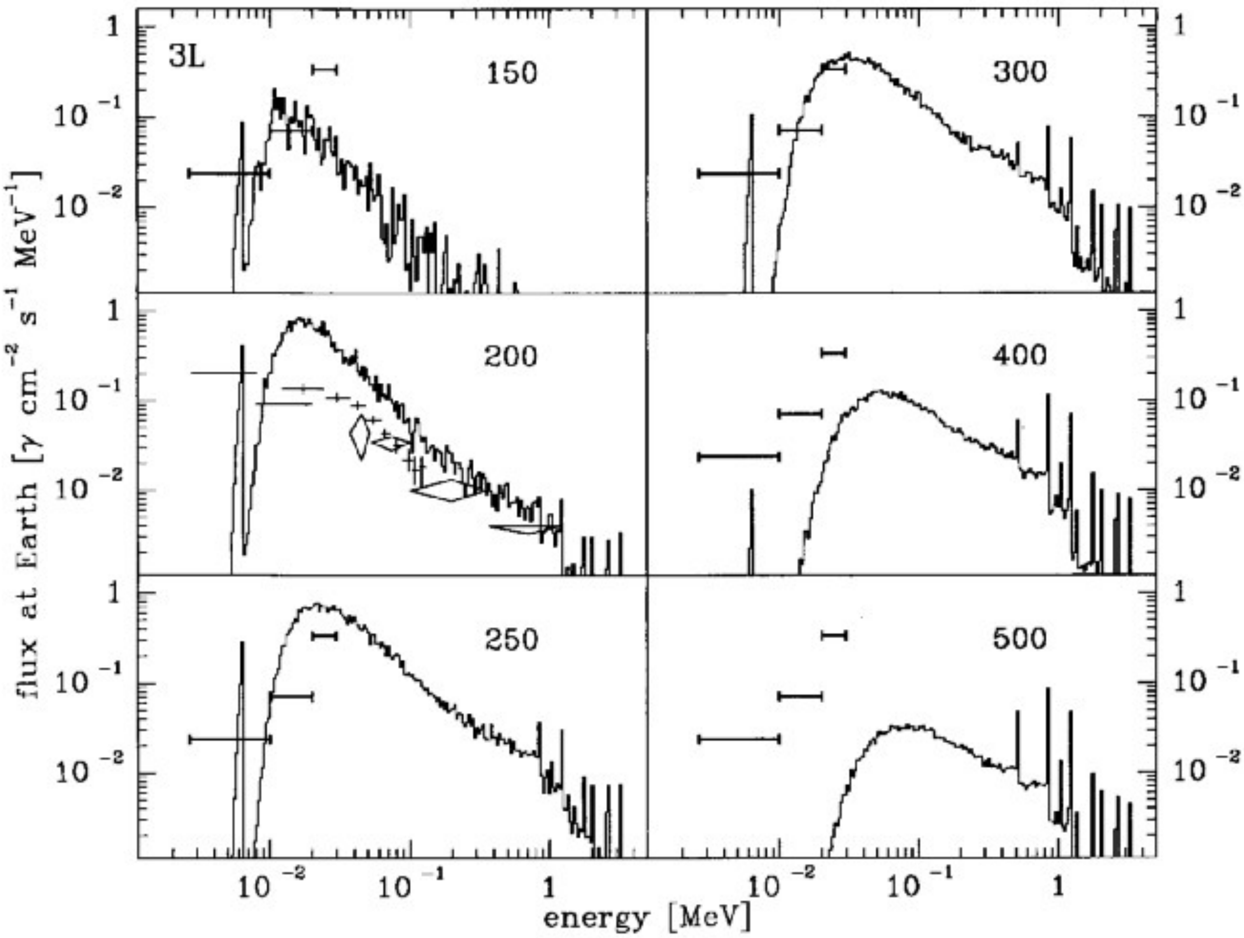
Where the half life of ^{56}Cobalt is 77.1 days.

So $$\frac{dM_{BOL}}{dt} = 0.01 \text{ magnitudes per day}$$

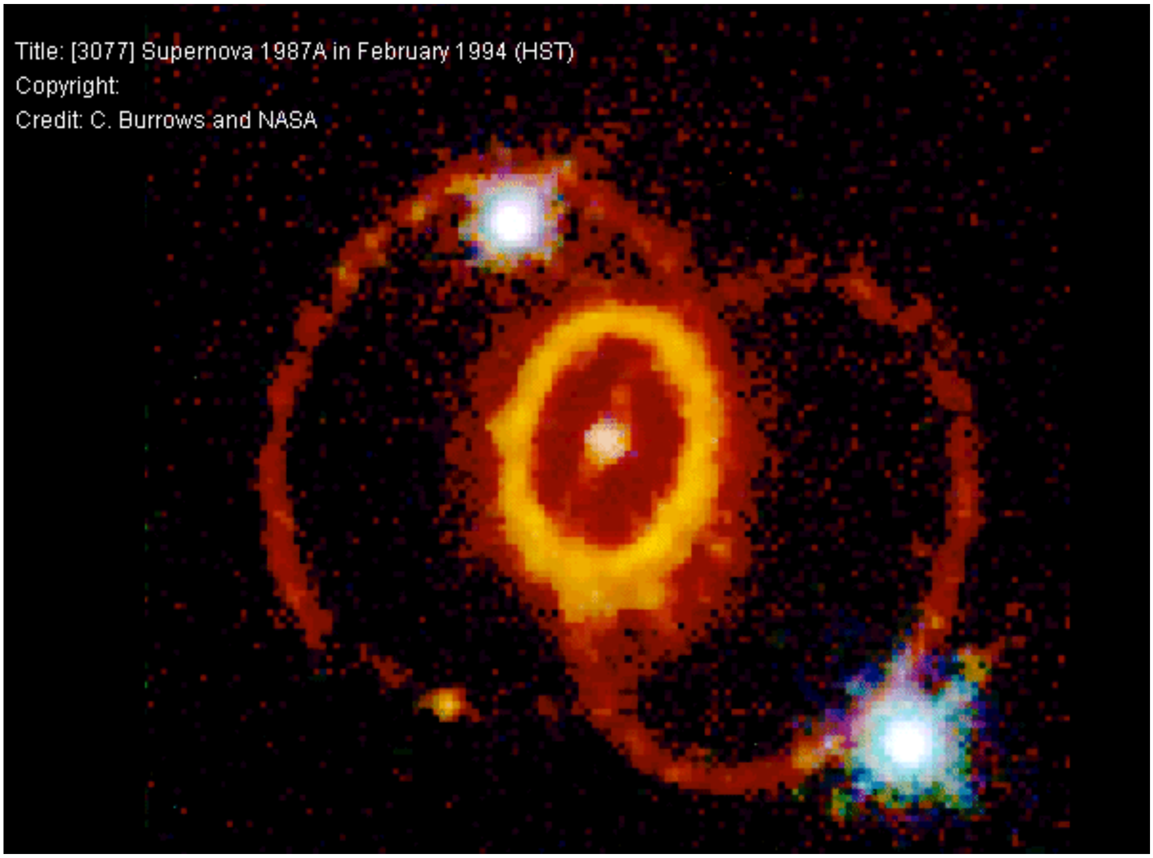
This decrease of 0.01 magnitudes per day is exactly what is seen on the graph from day 130 onwards. The decay of ^{56}Cobalt produces gamma rays with energies of 847, 1238 and 2599 kev. The delay in the creation of these gamma rays and their detection is because they had previously been trapped inside the expanding shell around the supernova. It was not until day 150 since core collapse that the shell expanded to such an extent that the energy could escape. Firstly hard x-rays were detected, which was due to the energy decrease from collisions of the gamma rays and particles in the envelope. Finally gamma rays of 847 and 1238 kev were detected by the solar maximum mission in August of 1987 proving that ^{56}Cobalt was present in the supernova and had decayed to ^{56}Iron.

Models Of The Supernova By Pinto And Woosley

Stanford Woosley from the University of California has for many years developed models of supernova explosions using computer simulations. But it was his teaming up with Philip Pinto that created ground braking ideas. In their simulations, the parameters of the star are inputted such as mass, density, gas pressure, energy release and opacity. The outcome is a model of how that particular supernova should behave at various wavelengths. Shown below are a couple of model spectra. One for a 3 solar mass hydrogen envelope that surrounds a 6 solar mass helium core and an explosive energy of $6.5*10^{50}$ ergs. The other a 5 solar mass hydrogen envelope that surrounds a 6 solar mass helium core and the same energy output. The first model, called 3L, obeys the observed x-ray spectra very well up to day 300 where it clearly decreases in flux whereas the observations do not. The second model, called 5LM obeys the observations well. An extra parameter concerning the amount of mixing between the hydrogen envelope and the helium core was inserted in this model, but does not prove that it actually happened in SN 1987A. It is thought that the real model of SN 1987A lies between these two described above.



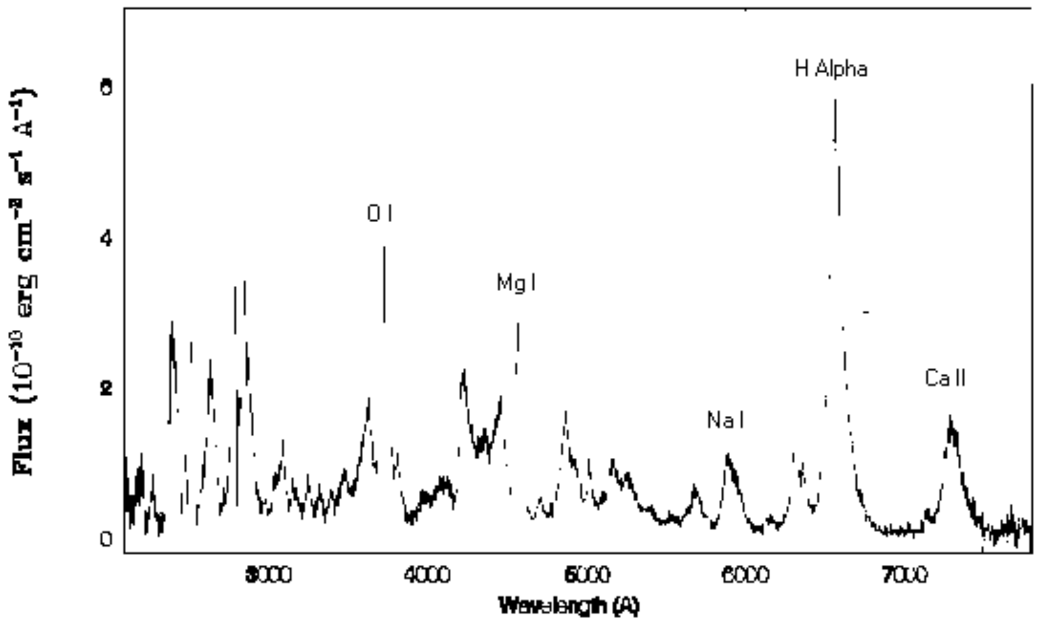
THE MODEL SPECTRA FOR THE PINTO AND WOOSLEY MODEL 3L. THE BARS ON THE GRAPHS ARE OBSERVED FLUXES WHILE THE BACKGROUND IS THE CALCULATED SPECTRUM



HUBBLE SPACE TELESCOPE IMAGE OF SN 1987A SHOEING THE THREE RING STRUCTURE.

The Spectra Of SN 1987A

At an age of eight years, astronomers used the Hubble Space Telescope Faint Object Spectrograph (FOS) to obtain spectra of the material that now makes up the supernova remnant. It is clear from the diagram that it is dominated by Hydrogen alpha (6568 Angstroms), oxygen (3734 Angstroms), magnesium (4563 Angstroms), sodium (5889 Angstroms) and calcium (7306 Angstroms). It seems the supernova has now taken a nebular appearance as opposed to its' P Cygni profile it portrayed shortly after core collapse.



SPECTRUM OF SNR 1987A SHOWING THE PEAKS OF VARIOUS ELEMENTS PRESENT

Conclusion

A wealth of data has been gatherred on this particular star and its' supernova event. Many theories have been backed up not for just this event, but also for other supernova. Also a grater understanding of the evolution of stars has been achieved for stars such as Sk -69° 202 which before this event was only postulated wether they could turn supernova. The process of neutrino creation has been closely examined by astronomers, both in theory and by observation, streangthening the understanding of these strange particles. Perhaps one of the forgotten achievments SN 1987A is the fact that since Februrary 1987, more supernova have been observed in other galaxies than ever before, not just by professional astronomers, but by amateurs aswell. Although it has been 12 years since Sk -69° 202 turned supernova there is still a lot to understand about such events, this is partly due to the fact that SNR 1987A is continously changing, showing aspects of its' personality that in 1987 were not even thought of. Because of these changes, it will be a long time yet untill astronomers fully understand these events and the implications they have on the universe as a whole.

Bibliography

Borkowski, K.J and Blondin, J.M (1996) X-Ray and Ultraviolet Line Emmission From SNR 1987A.

The Astrophysical Journal, 476: L31-L34. 1997 Feb 10.

Carroll, B.W and Ostlie, D.A (1996) An Introduction To Modern Astrophysics. Addison-Wesley Publishing Co. pp 510-528.

Chujai, N.N, Chevalier, R.A, Kirshner, P and Challis, P.M (1996) Hubble Space Telescope Spectrum Of SN 1987A At An Age Of Eight Years: Radioactive Luminescence Of Cool Gas. The Astrophysical Journal, 483: 925-940, 1997 July 10.

Clarke, D and Roy, A.E (1989) Astronomy Structure Of The Universe. 3rd Ed. Adam Hilger, New York. Pp 122-123.

Goldsmith, D (1990) Supernova The Violent Death Of A Star. Oxford University Press.

Hasinger, G, Aschenbach, B and Trumper, N (1996) The X-Ray Light Curve Of SN 1987A. Astronomy And Astrophysics. 312, L9-L12 (1996).

Kirshner, R.P, Sonnerborn, G et al (1987) Ultraviolet Observations Of SN 1987A. The Astrophysical Journal, 320: 602-608, (1987) Sep 15

Michael, E et al (1998) New Hubble Space Telescope Observations Of High Velocity Lya And Ha In SNR 1987A. The Astrophysical Journal, 509: L117-L120 (1998) December 20.

Phillips, M.M and Woosley, S.E (1998) Supernova 1987A! Science. Vol 240 pp 750-759.

Pinto, P.A and Woosley, S.E (1987) X-Ray And Gamma Ray Emmissions From Supernova 1987A! The Astrophysical Journal, 329: 820-830, (1988) June 15.

Schaeffer, R, Casse, M, Mochkovitch, R and Cohen, S (1987) The Light Curve Of SN 1987A. Astronomy And Astrophysics, 184, L1-L4 (1987).