The Universe in my pocket

Supernovae: these exploding stars

TUIMP – The Universe in my pocket – No 44

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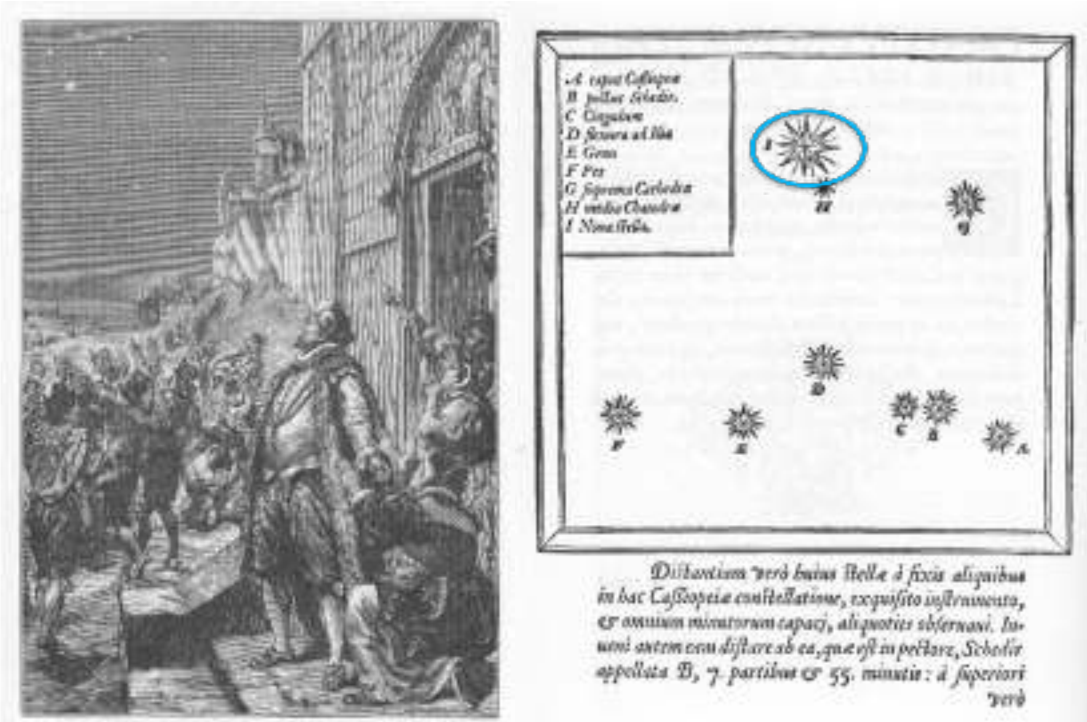
The remnant of the supernova of 1054: the Crab Nebula. Discovered by Charles Messier in 1758, it is number 1 in his catalog of nebulae and galaxies.



Tycho Brahé observing the supernova of 1572 and the drawing he made of it, showing the position of the star in the constellation Cassiopeia (the object is circled in blue).

Historical supernovae

Supernovae are exploding stars. When a star explodes as a supernova, it becomes so bright that, even from its great distance, it can become visible to the naked eye. This happened six times during the last millennium, in 1006, 1054, 1181, 1572, 1604 and 1987

The supernova of 1054 in the constellation Taurus was visible in broad daylight for two years! Today we can use telescopes to observe the remains of this explosion, the famous Crab Nebula (see tuimp 10).

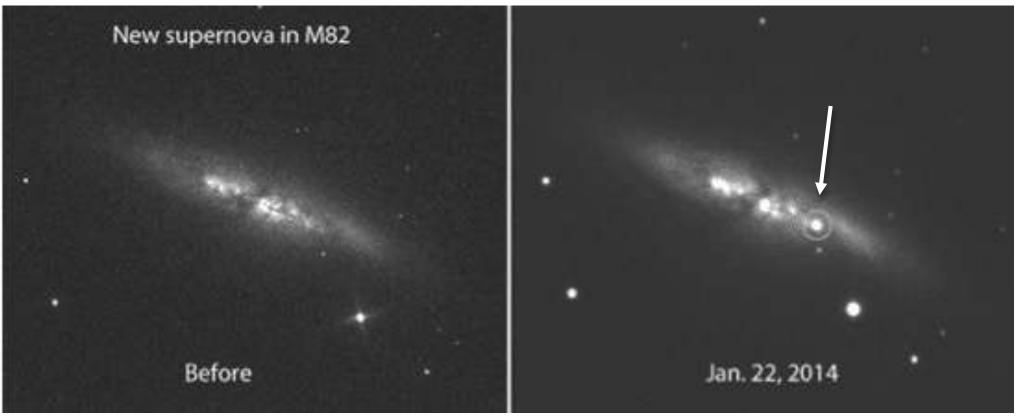
During the Renaissance, two supernovae were discovered, in 1572 and 1604, by astronomers Tycho Brahé and Johannes Kepler.

It was not until 1987 that a supernova visible to the naked eye appeared again (cover image). This one exploded in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way, while the first five occurred in the Milky Way.

The Mount Wilson telescope was commissioned in 1917. At the time, it was the largest telescope in the world, with its 2.5 m diameter mirror.

Fritz Zwicky

Walter Baade



A supernova that appeared in the galaxy M82.

Novae and supernovae

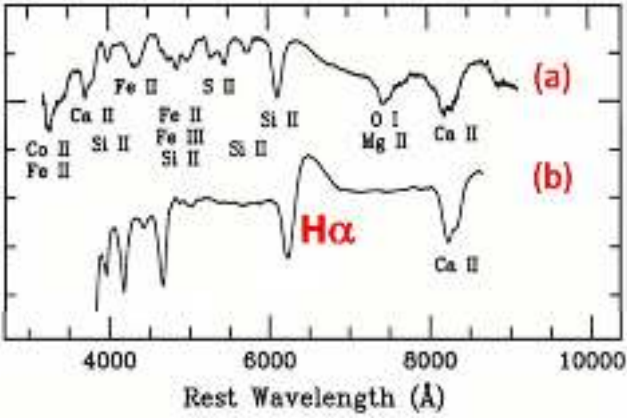
In 1885 an apparently 'new star', or 'nova' , was found in the Andromeda nebula. It was just below the limit of visibility to the naked eye.

From the mid-1920s onwards, it gradually became clear that some 'nebulae' are in fact galaxies, external to our Milky Way (see tuimp 15). The Andromeda nebula thus became the Andromeda galaxy, located more than two million light-years away. As a result, the luminosity of the 1885 nova was re-evaluated to be nearly a billion times that of the Sun! Astronomers Fritz Zwicky and Walter Baade then coined the term 'supernova' to describe these extraordinary objects. Using the newly commissioned Mount Wilson telescope, they promptly observed several other supernovae.

Today, several hundred supernovae are discovered each year, some at distances exceeding one billion light-years!

Spectra:

(a) Type I: no hydrogen line; but lines of silicon, iron, magnesium, and calcium are present.

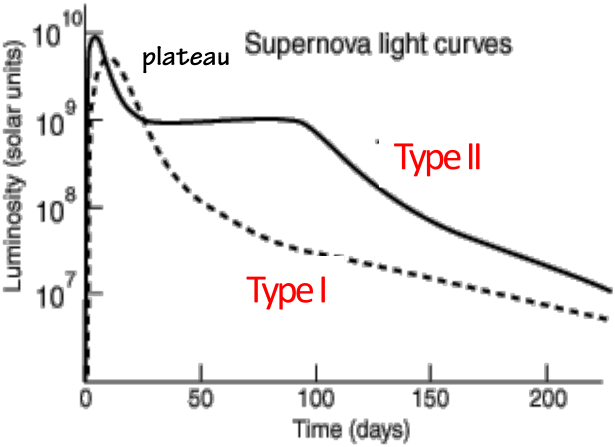


(b) Type II: hydrogen lines (in particular the Hα line, around 6500 Å) and calcium lines are present.

Light curves (luminosity as a function of time):

Type I: very similar from one event to another (which is very useful for measuring distances in the Universe and studying its expansion).

Type II: great diversity of behavior with time (the plateau is not always present).



Figures adapted from Chaisson and McMillan.

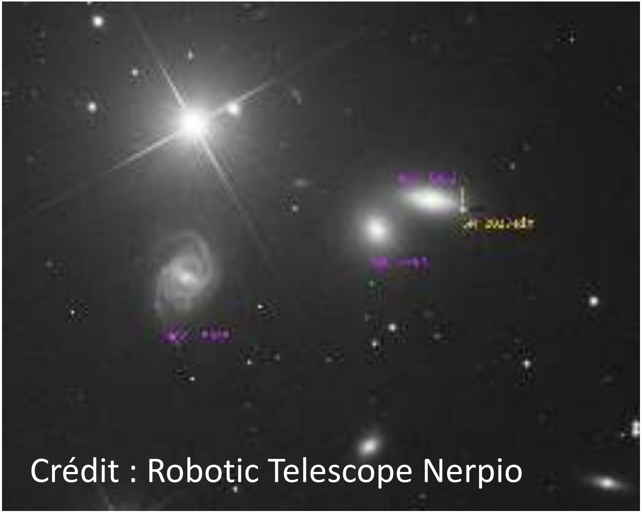
Two types of supernovae

Using spectroscopy, two main types of supernovae are distinguished:

- Type I supernovae (SN I) whose spectra show no hydrogen line. This is striking because hydrogen is the most abundant element in the Universe. The main lines present are those of silicon, calcium, oxygen, iron.
- Type II supernovae (SN II) whose spectra are dominated by hydrogen lines.

The light curves of the two types are different as well:

- SN Is are characterized by a great uniformity of their light curves, which are very similar from one event to another.
- SN IIs show great diversity in their light curves, often with a plateau of brightness, following an initial decline.



Two **type I** supernovae: on the left in an elliptical galaxy; on the right in the spiral galaxy M101.

Two **type II** supernovae in nearby spiral galaxies: on the left in the Hunting Dogs galaxy M51; on the right, again in M101.

In M101, the type I supernova was observed in 2011 and the type II supernova in 2023.

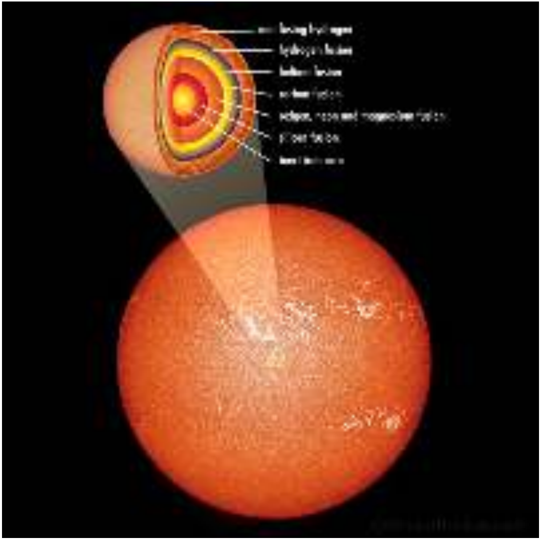
Which stars explode?

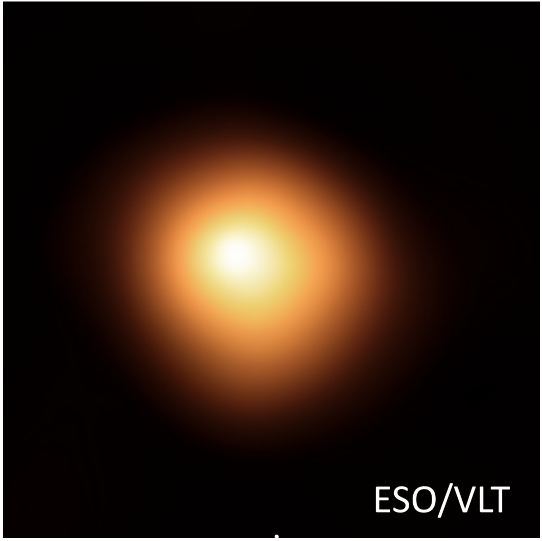
A first indication about the nature of stars that explode as supernovae comes from the type of galaxies in which they are found.

SN IIs are always seen in galaxies that are forming stars (spiral or irregular galaxies) but never in galaxies where star formation has ended for billions of years (elliptical galaxies). This leads to the idea that SN IIs correspond to the explosion of massive stars, whose lifespan is only a few million years.

SN Is, on the other hand, are observed in all types of galaxies, including elliptical ones. This suggests that they arise from low-mass stars, which can explode billions of years after they were formed.

The explosion mechanisms of the two types of supernovae are very different. They are very complex and are actively studied.





Left: diagram of a red supergiant star about to explode.
Attention! The scales are not respected: if we represent the iron core by a pinhead, the layers up to helium would be contained in a sphere one meter in diameter, while the hydrogen envelope would have a radius exceeding one hundred meters!
Credit: Pablo Carlos Budass

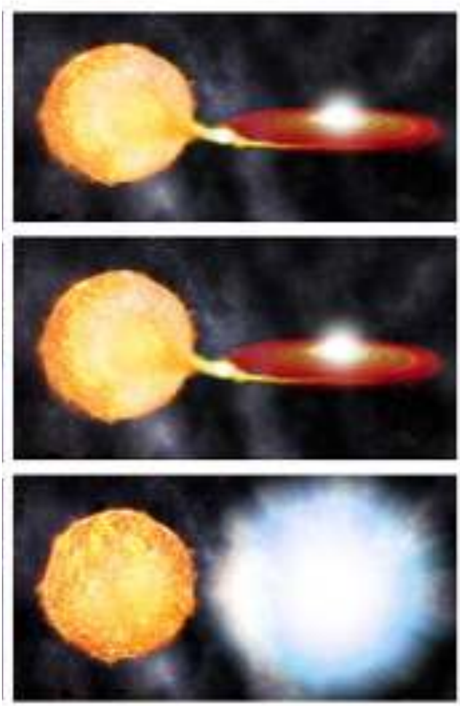
Right: image of Betelgeuse (a red supergiant) obtained with the SPHERE instrument installed on the European VLT telescope (8.20 m in diameter). With a mass of 10 to 20 times that of the Sun and a radius almost a thousand times larger, Betelgeuse has entered its last few million years of life, but a precise date for its explosion is difficult to predict.

How do SN IIs explode?

During its lifetime, a star more than ten times the mass of the Sun carries out a series of nuclear combustions, forming increasingly heavy elements. Thus, when it explodes, it consists of an iron core, surrounded by layers of silicon, oxygen, carbon and helium, all immersed in a large hydrogen envelope.

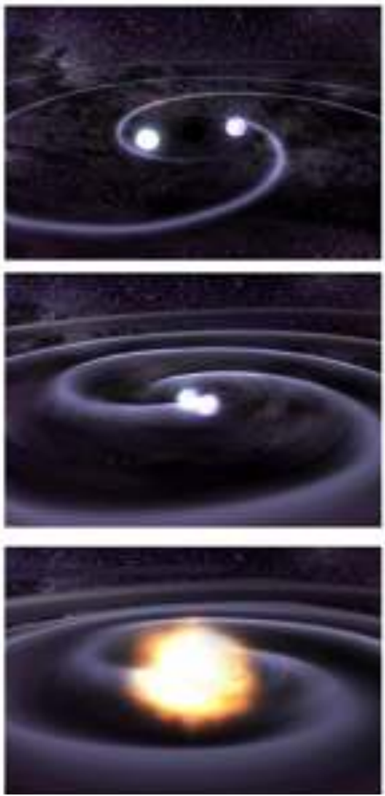
The iron core is so dense (a thousand tons per cm^3) that it obeys particular physical laws. It cannot exceed a critical mass, close to 1.4 times the mass of the Sun. However, its mass increases because the combustion of silicon at its periphery produces iron. When it exceeds the critical mass, it becomes unstable and collapses until it reaches a density of 100 million tons per cm^3! The matter then refuses to compress further and the core bounces back on itself, giving rise to a shock wave that causes the star to explode. The deep, ultra-dense core then becomes a neutron star or a black hole, depending on the remaining mass.

Two scenarios leading to the explosion of a type I supernova:



A white dwarf accumulates matter from a companion star. The mass transfer takes place via an 'accretion disk'. The explosion occurs when the white dwarf approaches the critical mass of 1.4 solar masses. It then explodes as a supernova.

Credit: NASA/CXC/M.Weiss



Two white dwarfs in a binary system gradually approach each other until they collide, which causes the explosion.

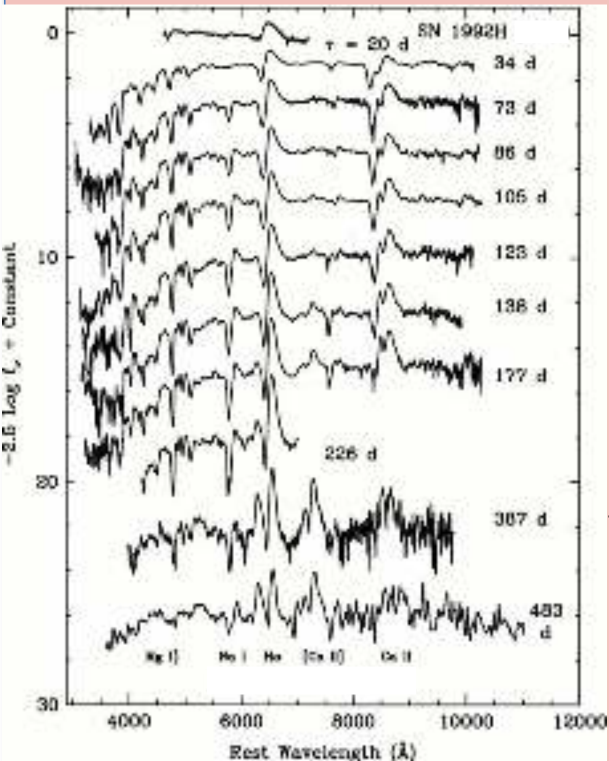
Credit: GSFC/D.Berry

How do SN Is explode?

The SN I mechanism is completely different from that of SN IIs, although the critical mass of 1.4 solar masses again plays an important role. The star that explodes is a 'white dwarf', the residue from the evolution of a star of a few solar masses. It is made of carbon and oxygen and is 'degenerate', like the iron core of massive stars, but its mass is less than 1.4 solar masses.

However, in a binary system, the mass of the white dwarf can increase by 'accretion' from a companion or by coalescence with another white dwarf. It then contracts and heats up. New nuclear reactions can thus start in its center and ignite the entire star. A combustion front propagates outwards and transforms carbon and oxygen first into nickel, cobalt and iron, then into silicon and magnesium. The white dwarf is destroyed and its matter dispersed.

QUIZ



1) Here is a series of spectra of supernova 1992H at different times after maximum brightness.

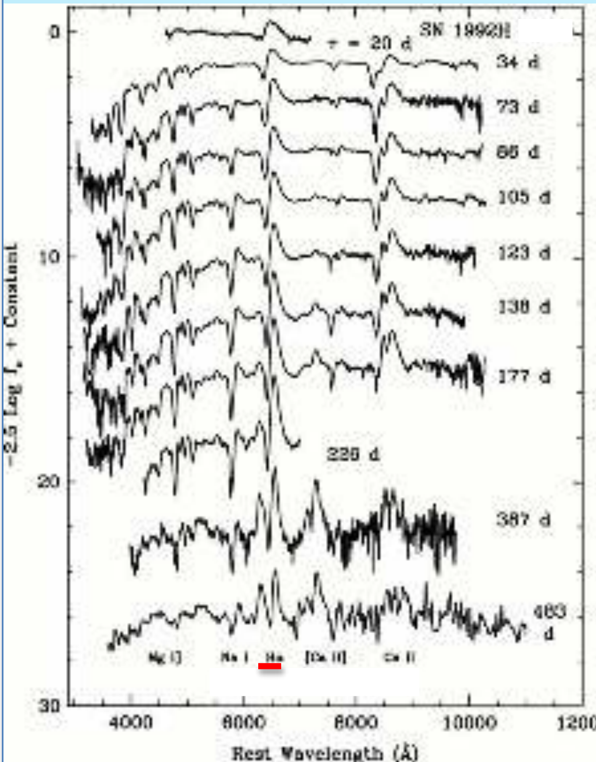
Was it type I or type II?

2) Here are three supernovae observed simultaneously (in January 2022) in the same spiral galaxy!

Were there really three explosions so close in time?

3) When will the next supernova visible to the naked eye occur in our galaxy, the Milky Way?

ANSWERS



1) We note the presence of the Hα line of hydrogen; therefore it is a type II supernova

2) NO! A galaxy is a very large object! Depending on their position in the galaxy, the distance between us and these supernovae may differ by several thousand light-years. The travel time difference was just compensated here by the difference between the explosion times, which is a remarkable coincidence.

3) We don't know! In 1, 10, 100 or 300 years (or maybe tonight?). We've been waiting for this since 1604... (The 1987 supernova exploded in the Large Magellanic Cloud).

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This booklet was written in 2025 by Robert Mochkovitch of the Institute of Astrophysics of Paris (IAP) and reviewed by Grażyna Stasińska of the Paris Observatory and Stan Kurtz (IRyA, Morelia, Mexico).

Cover image: On the left, Supernova 1987A just after its explosion in February 1987 in the Large Magellanic Cloud, and on the right, a photo of the same area taken before the explosion.
Credit: David Malin / Australian Astronomical Observatory

To learn more about this series and the themes covered in this booklet, visit http://www.tuimp.org

Translation: Stan Kurtz