Supernovae – the biggest bangs since the Big Bang

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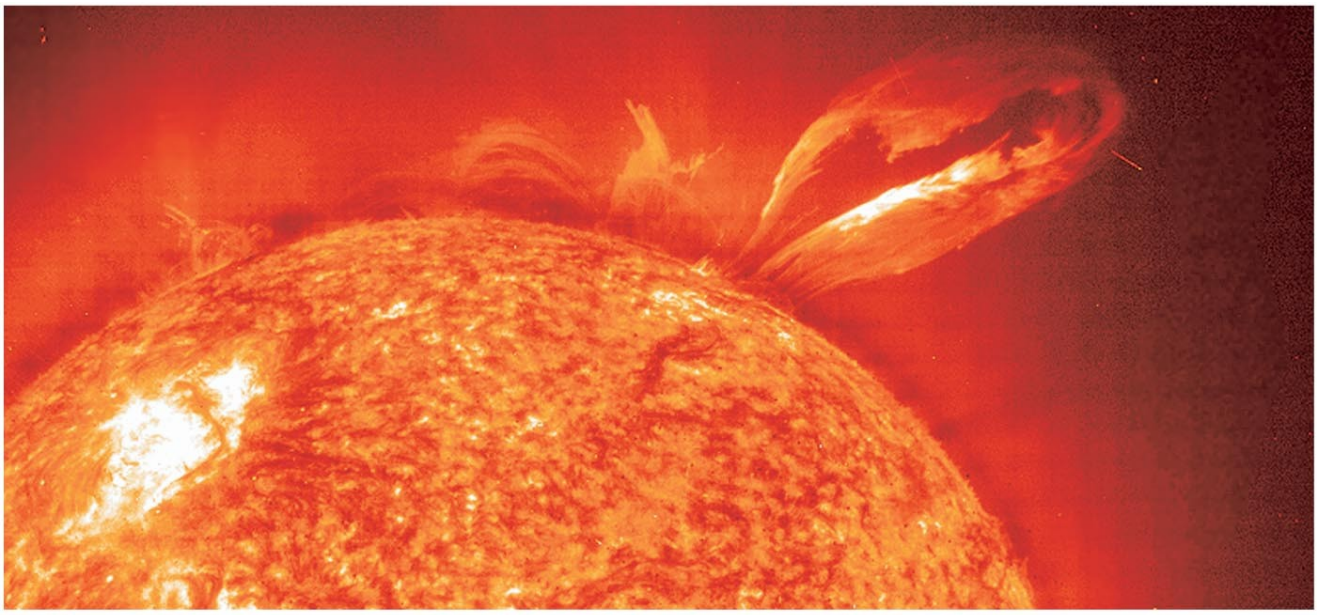
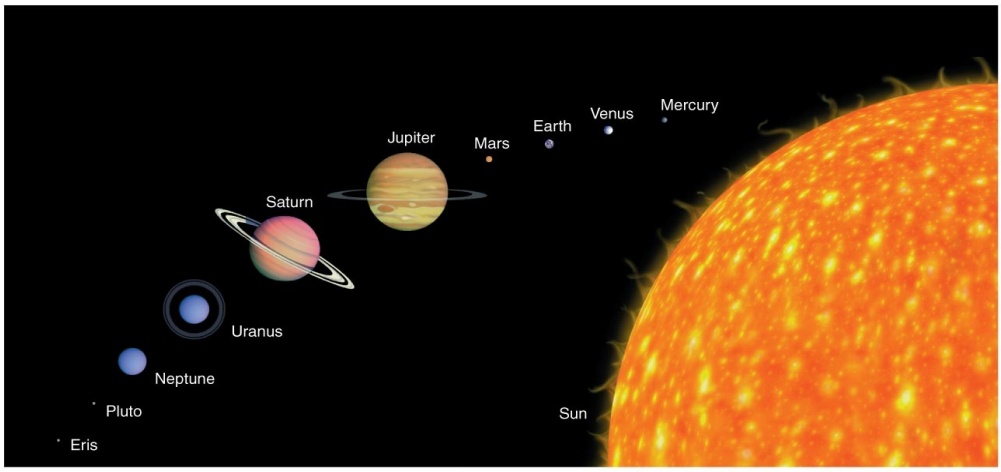
A supernova is a star that ends its life in a fiery explosion.

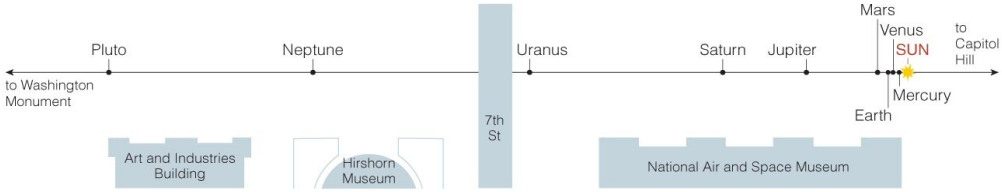
There are different kinds of supernovae. Some are very massive stars, as if we packed 20 stars like the Sun into a single star. Other supernovae are members of close double star pairs, like the home stars of the planet Tatooine in the *Star Wars* movie series.



Our Sun will *not* end its life as a supernova. This we know for certain.



a This painting shows the Sun, the planets, and the two largest known "dwarf planets." (Distances are not to scale in this painting.)



b This map shows the locations of the Sun and planets in the Voyage model; the distance from the Sun to Pluto is about 600 meters (1/3 mile). Planets are lined up in the model, but in reality each planet orbits the Sun independently and a perfect alignment essentially never occurs.

The Earth is about 8000 miles in diameter, and the Sun is a little over 100 times the size of the Earth.

The center of the Sun is a *nuclear fusion reactor*. For the past 4.5 billion years it has been transforming hydrogen into helium by means of nuclear reactions.

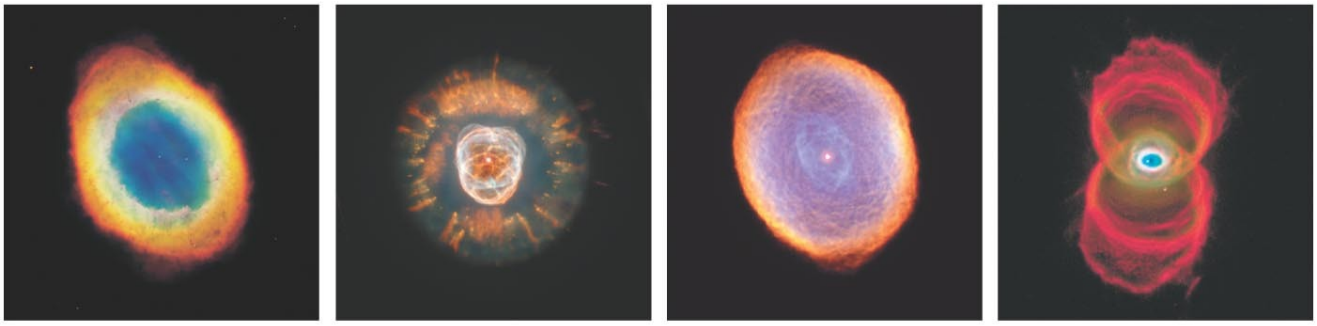
Four hydrogen nuclei are fused into one helium nucleus. It turns out that one helium nucleus has 0.7 percent less mass than one four hydrogen nuclei. The mass is converted into energy according to Einstein's famous formula $E = mc^2$. For a little bit of mass, you get a *lot* of energy.

The Sun will continue converting hydrogen into helium in its core until it is 10 billion years old.

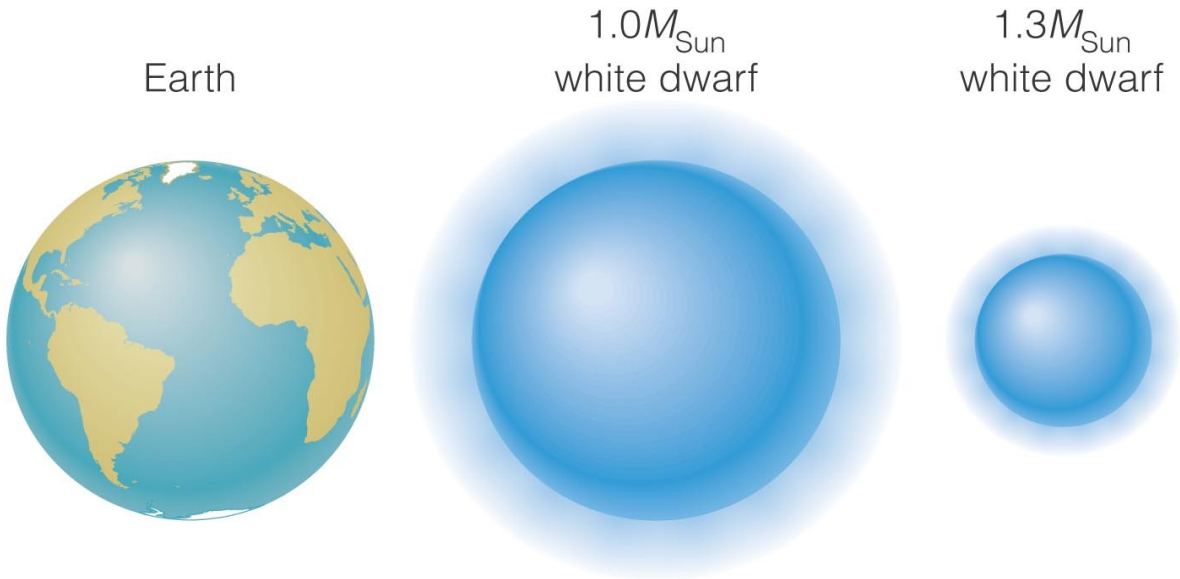
When the Sun has used up the hydrogen in its core, it will swell up to become a *red giant star*. It will become a few dozen times its present size. This will result in the end of life as we know it on the Earth. The oceans will evaporate and the Earth will be much too hot to sustain life as we know it. But don't worry. That is roughly 6 billion years into the future.

At the end of the Sun's red giant phase, it will exhale most of its atmosphere and produce what is known as a planetary nebula. This will leave a very small, hot star in the middle – a *white dwarf star*. (In a small telescope a planetary nebula might look like a planet. The name is not quite right. We use it for historical reasons.)

The “Southern Crab Nebula” (left) and four other planetary nebulae.



a Ring Nebula **b** Eskimo Nebula **c** Spirograph Nebula **d** Hourglass Nebula

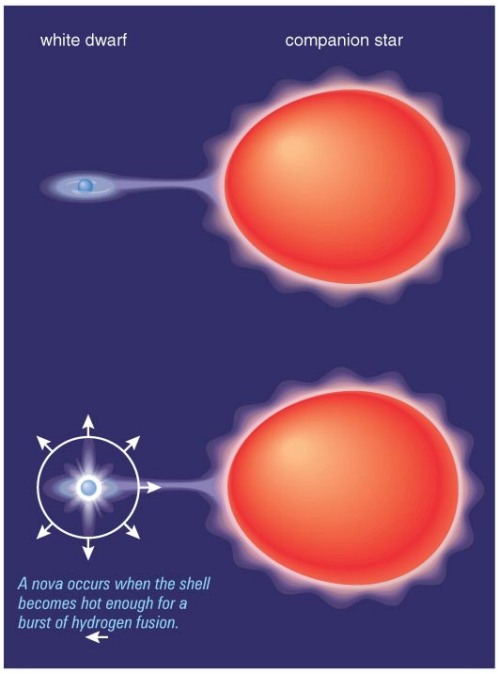


About 7 billion years from now the Sun will be a hot, dense stellar remnant no bigger than the Earth. A white dwarf star is a million times denser than water! It is made up mostly of carbon and oxygen.

Once the Sun becomes a white dwarf star, that will be its end state. All it will be able to do then is slowly cool down, forever.

But what if a star like the Sun had a close companion star? Something quite different could occur.

Imagine a star exactly like the Sun, with a close companion that is slightly less massive. It turns out that the less massive star uses up its nuclear fuel more slowly – it is a lower power nuclear reactor, but that phase of its life can last longer.



a Diagram of the nova process.

Eventually, the companion star swells up too, and it can pass matter (mostly hydrogen) to the white dwarf star. This hydrogen could be converted into helium on the surface of the white dwarf star. Then we'd observe a relatively small explosion.

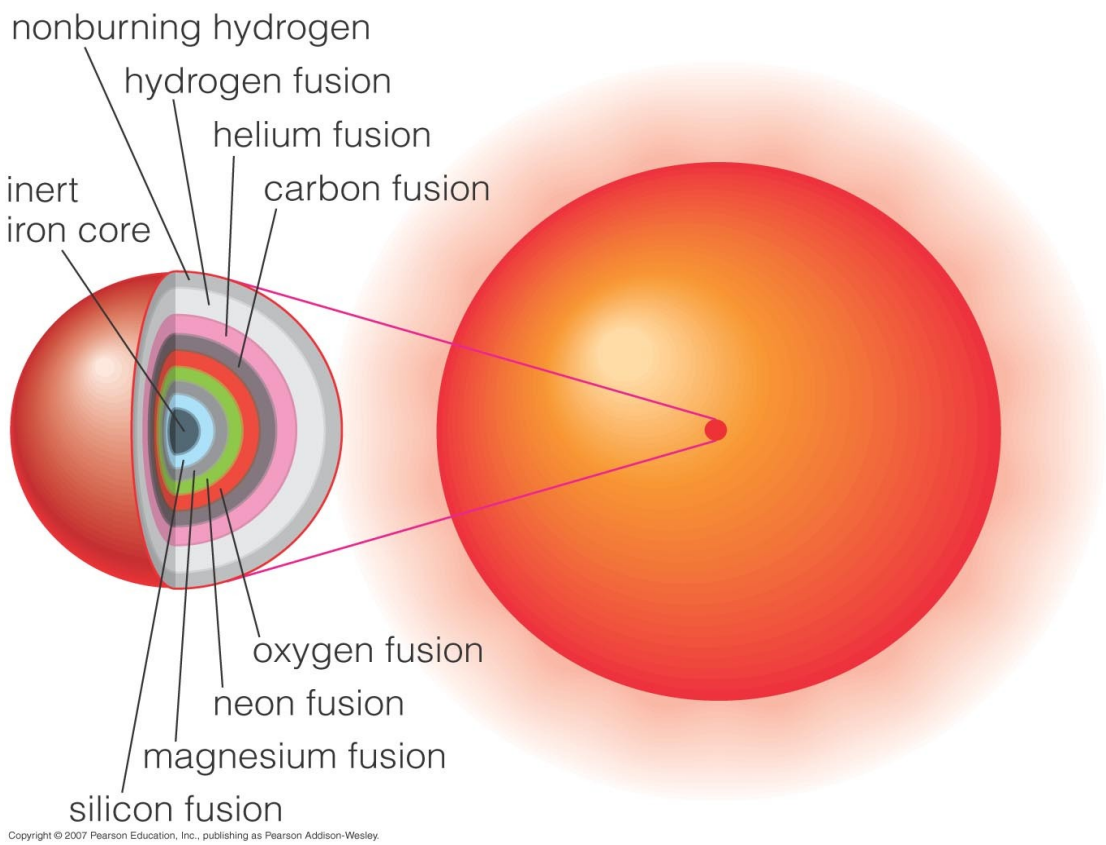
However, if matter passes to the white dwarf star and it becomes more than 40 percent "heavier" than the Sun, it will make a huge explosion. The entire white dwarf will explode with the energy of four billion Suns. This is called a "white dwarf supernova" (also known as a "Type Ia supernova").

Imagine you made a series of bombs, each with the same amount of the same material. The bombs would all have about the same power, right? The same is true of white dwarf supernovae. If each one is the explosion of 1.4 solar masses of mostly carbon and oxygen, each one gives us just about the same amount of energy. This means that they all have about the same intrinsic brightness, like a 100 Watt light bulb, only much, much brighter.

Another way to blow up a star is to consider the evolution of a star with 8 times the mass of the Sun (or more). These stars are very rare. Only one in a thousand stars formed has this much mass.

An 8 solar mass star will not live for 10 billion years converting hydrogen into helium in its core. It is hot enough in its core to convert hydrogen into helium, then helium into carbon, carbon into oxygen, oxygen into neon, neon into magnesium, magnesium into silicon, and eventually the core is made of iron.

Furthermore, all this takes place in 50 million years or less – a tiny fraction of the lifetime of the Sun.



Onion-like model of a massive star just before it explodes.

All the nuclear reactions in the core and shells of the massive star result in the conversion of some small fraction of the material into energy according to Einstein's formula $E = mc^2$. Once you end up with an iron core, any subsequent nuclear reactions would use up more energy than they produce.

The net result is that the light streaming from the core of the massive star can no longer hold up the layers of the star above the core.

If the bottom layer cannot hold up what is above it, the whole structure collapses.

A massive star with an iron core lives for less than one day. The outer layers squeeze down on the core and it explodes. Astronomers call this a "Type II supernova".

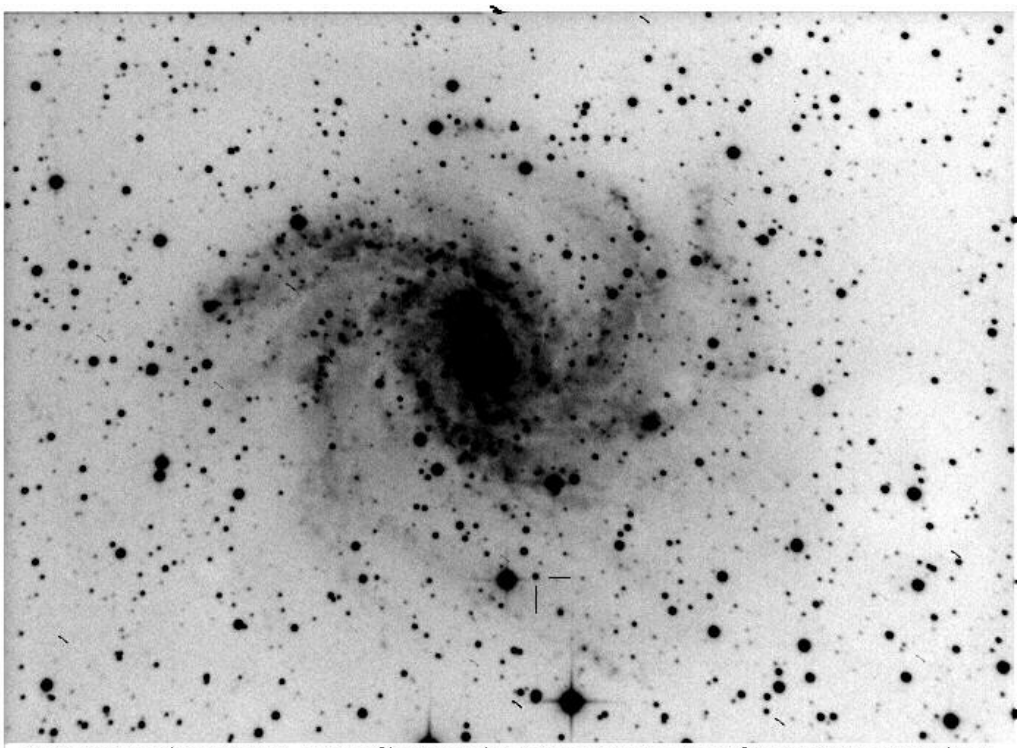
Stars that end as Type II supernovae range in mass from 8 to (maybe) 100 times that of the Sun. Because the amount of material that explodes varies from object to object, these supernovae do *not* produce an accurately predictable amount of light.

Another difference compared to "white dwarf supernovae" is that the single, massive stars that explode are *not* completely obliterated. They leave behind rapidly spinning neutron stars (pulsars), or black holes.

There have only been 8 *bona fide* supernovae observed in our Galaxy, the Milky Way. All of these supernovae were seen before the invention of the telescope! They were observed in 185 AD, 386, 393, 1006, 1054, 1181, 1572, and 1604. Most were only observed in China.

In the past century the galaxy NGC 6946 has hosted 9 supernovae. They have been designated 1917A, 1939C, 1948B, 1968D, 1969P, 1980K, 2002hh, 2004et, and the recent SN 2008S.

If some galaxies produce 9 supernovae per century, and it's been over 400 years since we had one in our Galaxy, don't you think we're overdue?

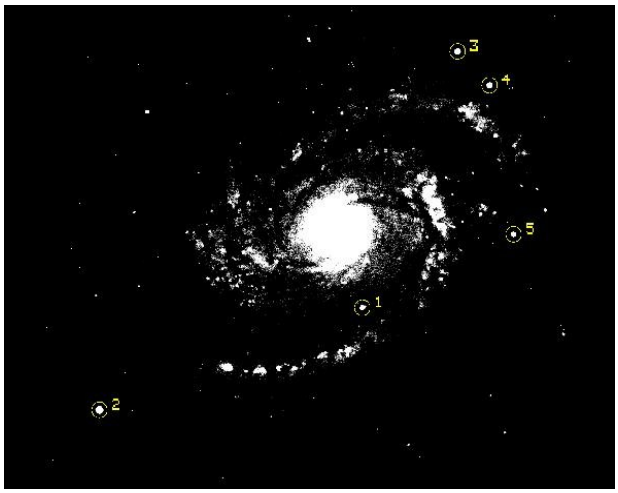


SN 2008S - Feb.6.783 U.T. - 40cm f/5 Newtonian + SXV-H9 - Average of 11 30 secs - Ron Arbour

The two black tick marks indicate the location of SN 2008S.

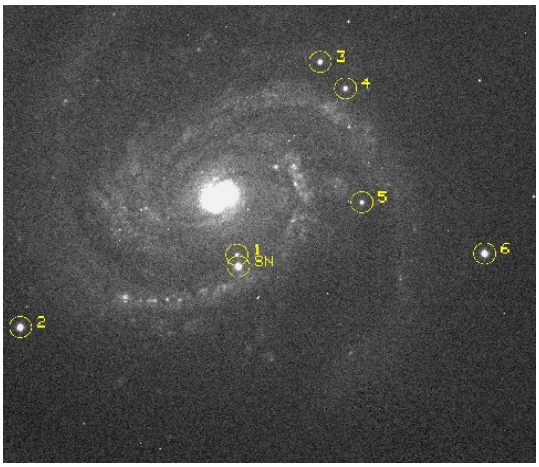
Now, when you take an image of some galaxy with a telescope, in between you and that galaxy are also a lot of stars in *our* Galaxy.

To discover supernovae you need to image the same place on the sky again and again. Using a reference image, you can determine if a new star-like image is an asteroid that just happens to be crossing the field of view. Or maybe the new object is a variable star in our Galaxy along the line of sight. Or maybe it is a supernova in the galaxy.

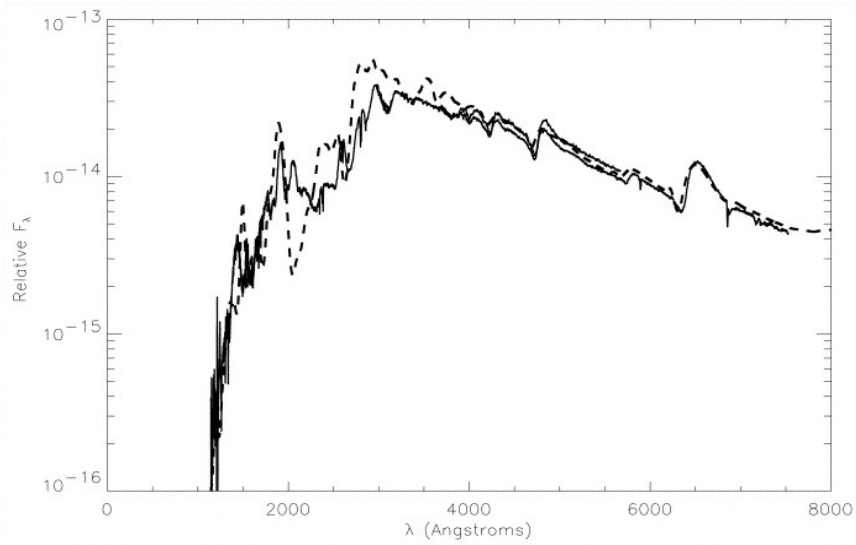


The galaxy M 100, as imaged in April of 2000 (left). The numbered stars are in our Milky Way galaxy in the same direction as M 100.

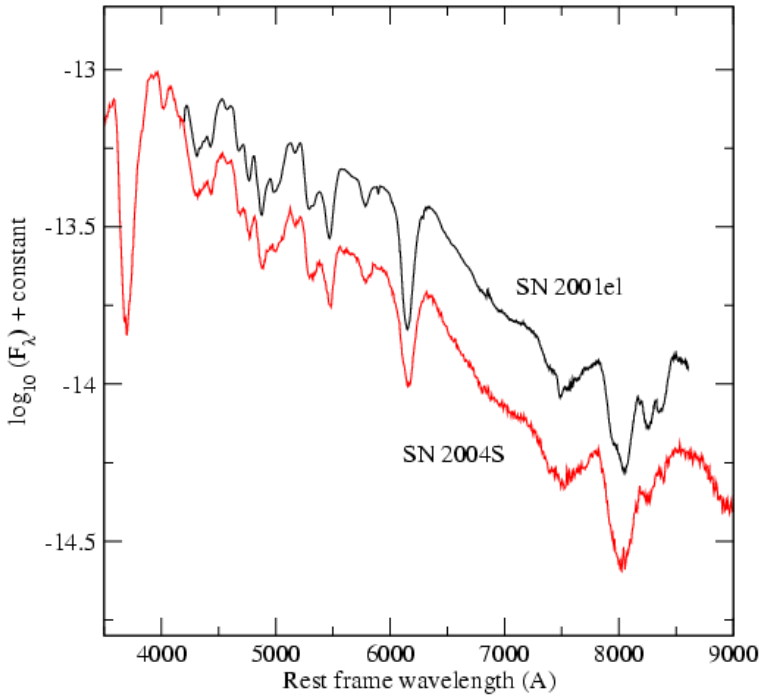
The same galaxy in early 2006. SN 2006X has appeared near star 1.



Baron et al. (2000)



The spectrum of SN 1999em obtained with the Hubble Space Telescope and with a ground-based telescope. The bump at 6563 A is due to atomic hydrogen. This was a Type II supernova.



Spectra of two very similar Type Ia supernovae.

The dip at 6150 A is due to singly ionized silicon. This is the prime signature of a Type Ia supernova.

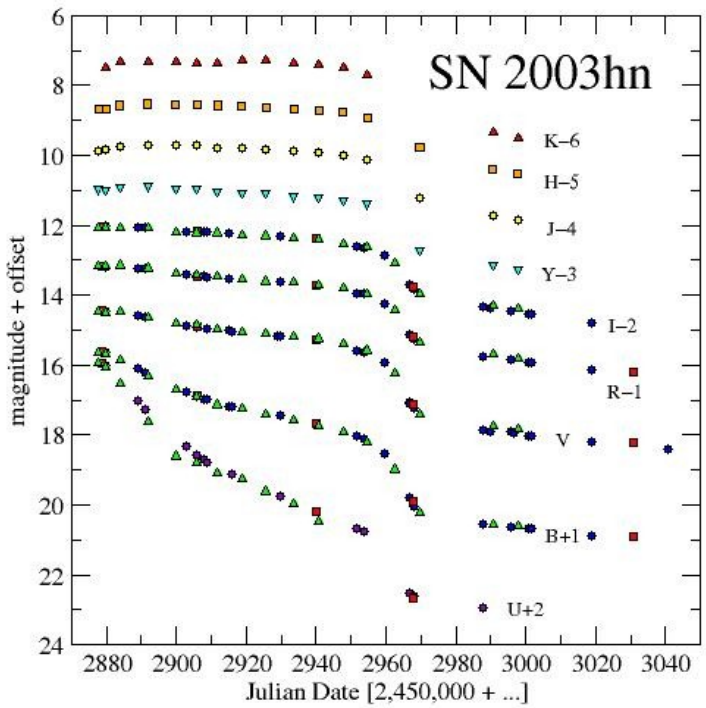
Krisciunas et al. (2007)

When a white dwarf supernova explodes the prime product of the explosion is radioactive Nickel-56, which decays into Cobalt-56, then into Iron-56. (The number of protons plus the number of neutrons in the nuclei is 56.) Other, lighter atoms are distributed to interstellar space too.

In a Type II supernova all the heavy elements up to uranium are produced. All the gold and silver in your jewelry or in the fillings in your teeth was produced in Type II supernova explosions! We are literally "star stuff". The single-star supernova also produce a huge number of particles called *neutrinos*. We detected such particles from the SN 1987A, which occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way.

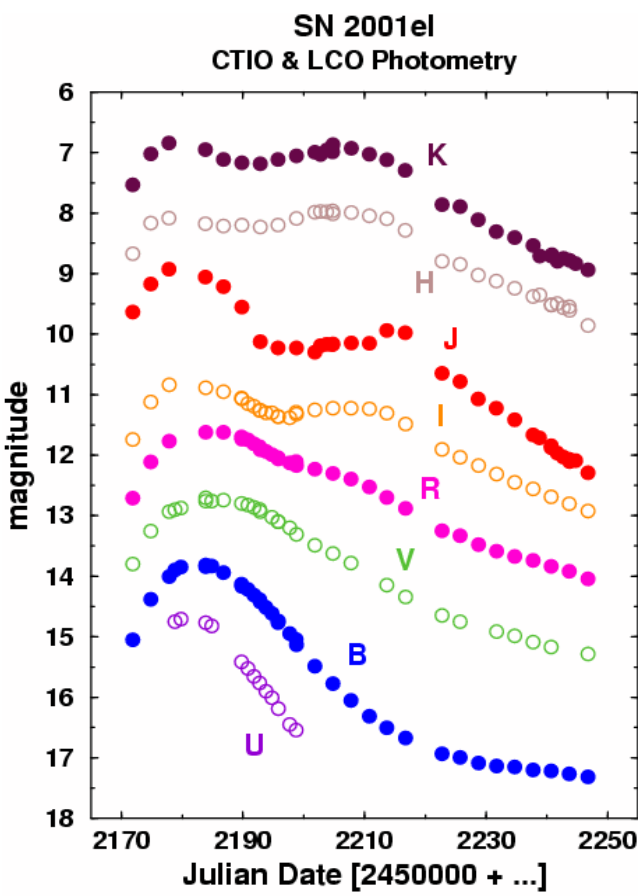
We have now described the two basic types supernovae. Some are explosions of white dwarf stars that have been fed by companion stars until they exploded. Others are single, massive, stars that blow up on their own because they could not longer hold up all the layers of the star.

The identification of a supernova is accomplished by spreading out the light of the former star with a spectroscope, like spreading out a beam of sunlight with a prism. We can also glean information about the supernovae from plots of their brightness vs. time. Such measurements are made through certain specially colored filters.



This Type II supernova was quite constant in brightness for 3 months before it began to fade

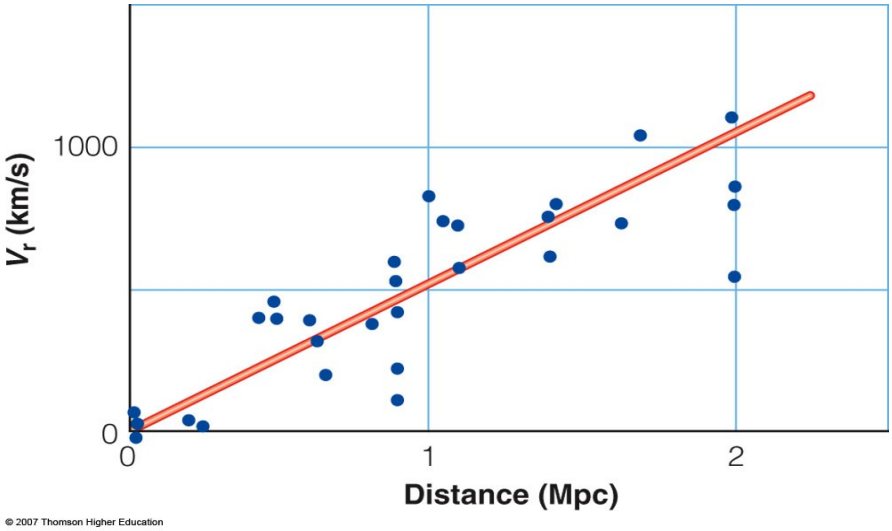
Krisciunas et al. (2008)

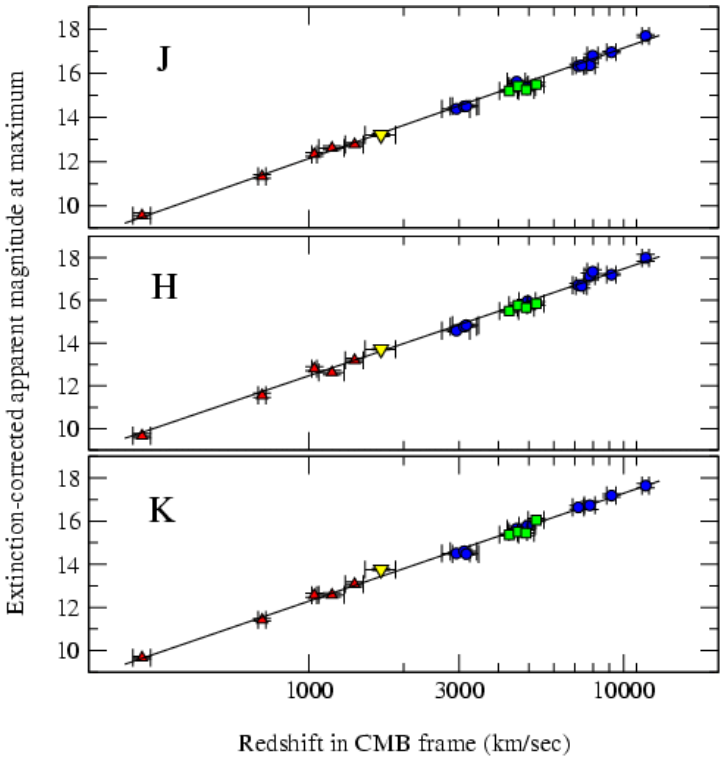


This white dwarf supernova was observed in five optical bands (UBVRI) and in three infrared bands (JHK). The individual light curves have been offset for display purposes. Note the secondary hump in the IJHK light curves.

Krisciunas et al. (2003)

In 1929 Edwin Hubble discovered that the universe was expanding. Galaxies on average recede from us at a speed proportional to distance. His first "Hubble diagram" was not particularly convincing, but we have observed much more distance objects since then.





These diagrams show the infrared brightness of white dwarf super-novae as a function of velocity of recession. There is very little scatter about the line. White dwarf supernovae are very useful "standard candles".

Krisciunas et al. (2004)

If you know the apparent brightness of a star and you know the intrinsic brightness of the star, you can determine how far away the star is.

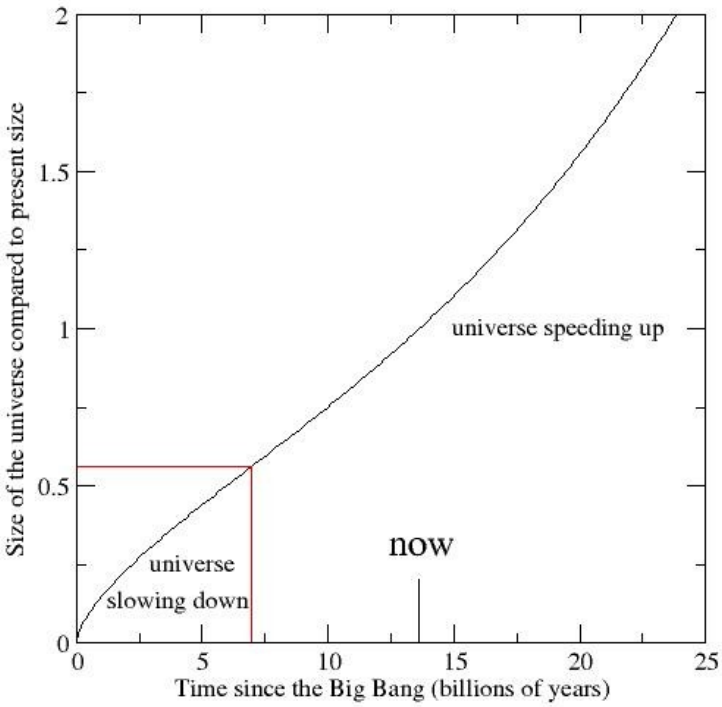
During the 1990's two groups of astronomers endeavored to discover Type Ia supernovae as far away as possible. They found some objects so far away that their light has been streaming towards us for 7 billion years. To observe such objects now is to look 7 billion years into the past. (A telescope is a time machine, in effect.)

Under the assumption that the far away supernovae were just like nearby ones of the same type, these two groups of astronomers sought to confirm the rate of expansion of the universe and the extent to which the expansion was *slowing down.*

All galaxies in the universe attract each other by means of the gravitational force. It made sense to think that the sum total of all this gravitational attraction would be causing the expansion of the universe to slow down.

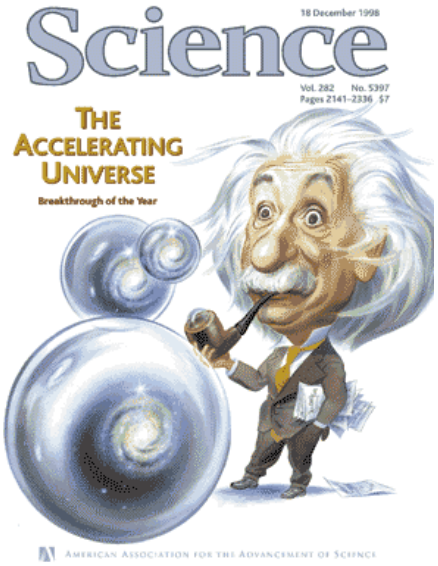
However, when astronomers determined the distances to faraway Type Ia supernovae, they found that on average they were *too far away* for their velocities of recession. Some mysterious force was causing an *acceleration* of the universe. We now refer to the cause of this acceleration as Dark Energy. It appears to be a property of the vacuum of empty space.

The universe is not slowing down. It is speeding up!



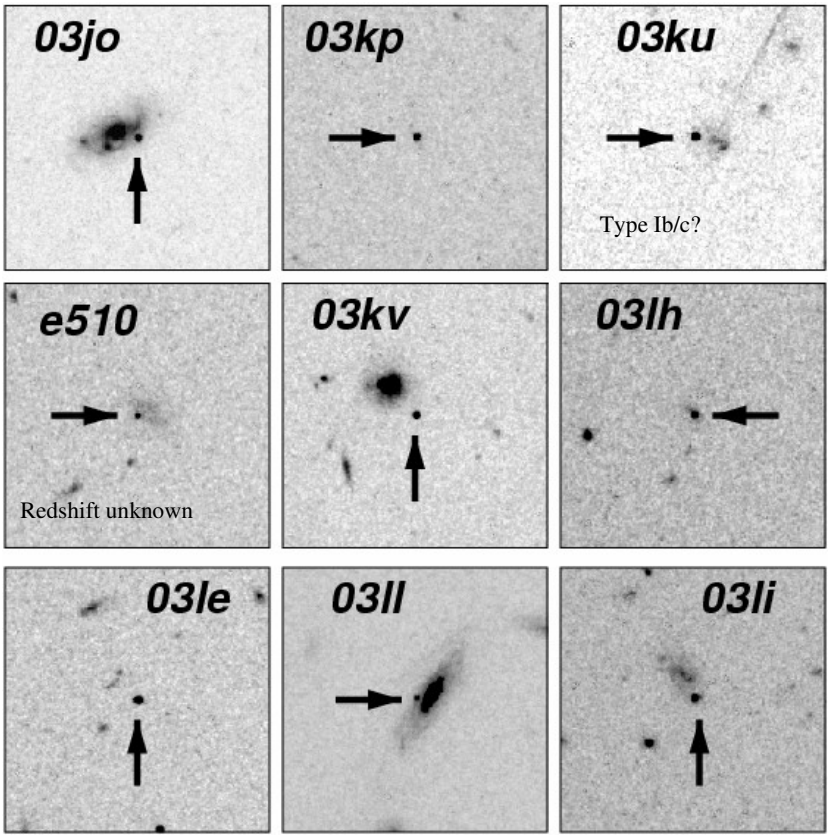
The attraction of the galaxies to each other caused the universe to be slowing down for a while, but the Dark Energy eventually took over. Now the universe is accelerating.

Riess et al. (1998) and Perlmutter et al. (1999) provided evidence from Type Ia supernovae that the expansion of the universe was accelerating. *Science* rated this the "discovery of the year".



We have just finished taking 6 seasons of observations with a 4-m telescope situated at Cerro Tololo Inter-American Observatory in northern Chile. We discovered over 200 Type Ia supernovae, some as far away as 7 billion light-years.

Some of these objects have also been observed with the Hubble Space Telescope and the Spitzer Space Telescope.

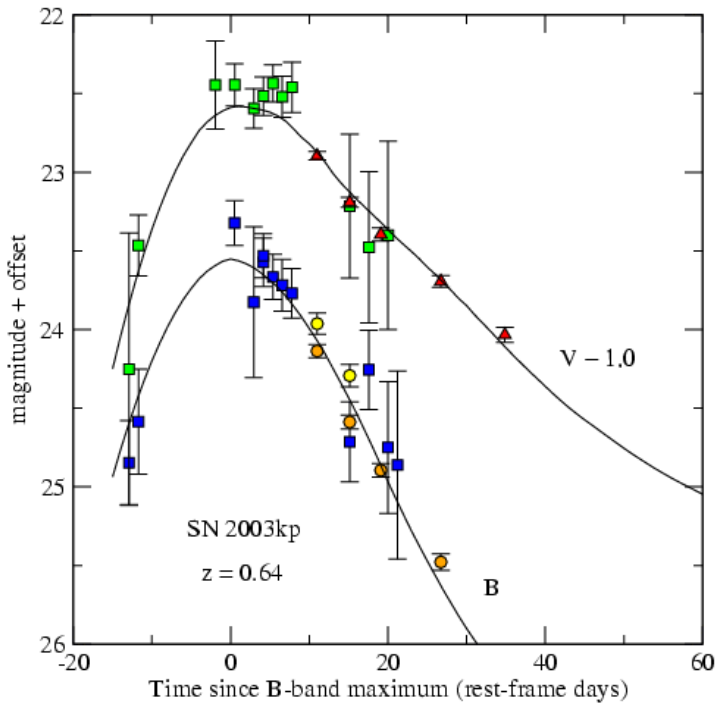


9 ESSENCE SN-e discovered in 2003 and observed with HST.

Redshifts from 0.53 to 0.79

Why do so many of these have such faint hosts?

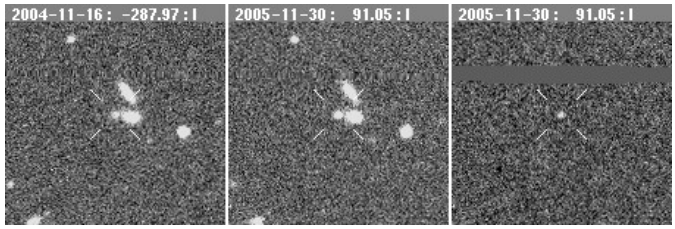
Krisciunas et al. (2005)



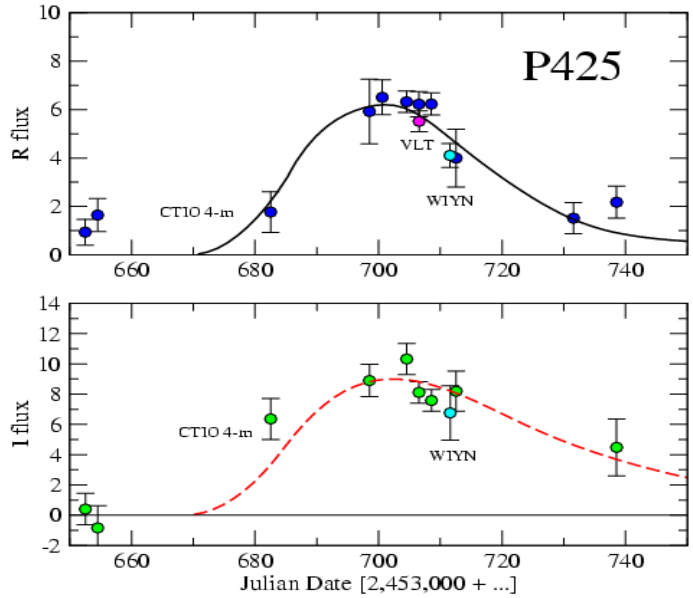
Squares = ground-based data (larger error bars)

Triangles and dots = HST data

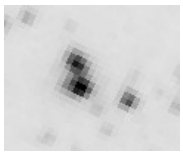
Krisciunas et al. (2005)



Redshift 0.458 SN discovered in Dec. of 2005.



Was also observed with Spitzer Space Telescope.



The evidence so far indicates that the universe will expand forever. Many billions of years from now, when all the gas and dust in the galaxies has been used up to form stars, and those stars have become white dwarfs or exploded as Type II supernovae, the universe will consist of many faint galaxies that contain nothing but dim stars.

Right now, however, the universe is still processing its raw material into stars. Some of those stars end their lives in spectacular fashion. In one sense these explosions bring death. In another sense they bring life. All the heavy atoms such as the calcium in your bones and the iron in your blood were processed by stars billions of years ago.