

Star Clusters & Supernova



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{Abstract – In this segment of our “How far away is it” video book, we cover star clusters and Supernova.

We begin by pointing out that there are two primary kinds of star clusters: open cluster and globular cluster. We visit some very beautiful open clusters including: the Pleiades, the Jewel Box (NGC 4755), Pismis 24 in NGC 6357, and NGC 6791. And then we visit some spectacular globular clusters including: 47 Tucanae, Omega Centauri, the Quintuplet, and Arches cluster with the Pistol Star, and M30.

As we start Supernovas, we review the magnitude of a nova that created the Helix Planetary Nebula with the explosion that created the Crab Nebula. We take the opportunity to describe the size and densities of White Dwarfs as compared to Neutron Stars. We also take a look at what the daytime sky might look like if Betelgeuse were to supernova.

We then explain what a Type 1a Supernova is and how it works as a critically important standard candle. We show binary star matter flowing through the L1 Lagrange point, and mention Subrahmanyan Chandrasekhar’s solution to Einstein’s equations. We then take a look at the amazing remnants of past supernova explosions scattered across our galaxy including: Veil Nebula (NGC 6995), Cygnus Loop, Crab Nebula, SN 1006, RCW 86, Tycho Supernova SN 1572, Cassiopeia A, RCW 103, Kepler’s supernova SN 1604, N 63A, and Supernova 1987A. For RCW 103, we illustrate the impact on the Earth if it were Capella that went supernova. For Cassiopeia A, we illustrate ‘light echoes’.

We conclude by adding brightest globular clusters and Type 1a Supernova as key standard candle rungs on our distance ladder.}

Introduction

[Music: Johann Sebastian Bach – “Air” – Again, “Air” is perfect for these majestic and beautiful star clusters.]

Welcome to our segment on star clusters and supernova. These are two very important items for our distance ladder, and there’re strikingly beautiful. We’ll start off with star clusters, move into supernova, and then cover the significant addition to our distance ladder that these objects have made.

There are two kinds of clusters:

- **Open clusters:** usually a few hundred young stars lightly bound by gravity.
- And **Globular clusters:** like this one, hundreds, sometimes hundreds of thousands of older stars tightly bound by gravity.



[Additional info: A few of the nearest clusters such as Pleiades are close enough for their distances to be measured using parallax. A Hertzsprung–Russell Diagram can be plotted for these clusters which has absolute values known on the luminosity axis. Then, when a similar diagram is plotted for a cluster whose distance is not known, the position of the main sequence can be compared to that of the first cluster and the distance estimated. This can then be compared to Cepheid variables found in the cluster to improve the accuracy of the H-R diagram process itself.]

Pleiades - 456 light years

The Pleiades or Seven Sisters is a cluster of extremely luminous blue stars. The Pleiades is an open cluster and it is one of the nearest star clusters to Earth. It is one of only a few open clusters whose distance can be measured via parallax.



Jewel Box – 6,500 light years

This image is a "close-up" view of the Jewel Box cluster taken by Hubble.



Several very bright, pale blue supergiant stars, a solitary ruby-red supergiant and a variety of other brilliantly colored stars are visible in the image, as well as many much fainter ones, often with intriguing colors. The huge variety in brightness exists because the brighter stars are 15 to 20 times the mass of the Sun, while the dimmest stars are less than half the mass of the Sun.

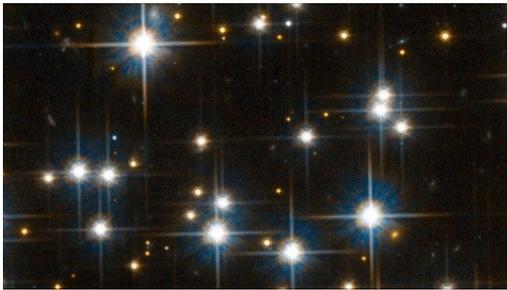
Pismis 24 - 8,000 light-years

The small open star cluster Pismis 24 lies in the core of the large emission nebula NGC 6357. We'll cover emission nebula in another segment on the Milky Way. The brightest object in the picture is designated Pismis 24-1. It was once thought to weigh as much as 200 times the mass of the sun. However, the high-resolution Hubble Space Telescope images of the star show that it is really two stars orbiting one another.





NGC 6791 – 13,300 light years



NGC 6791 is one of the oldest and largest open clusters known. It is 10 times larger than most open clusters and contains roughly 10,000 stars.

[It is unusual in that it contains a large number of White Dwarf binary star systems.]

47 Tucanae – 15,000 light years

47 Tucanae is one of the densest globular clusters in the Southern Hemisphere containing around a million stars.

Multiple Hubble photos of this region allowed astronomers to track the "beehive swarm" motion of stars. Using Doppler shifts and proper motion measurements, precise velocities were obtained for nearly 15,000 stars in this cluster.



This has provided astronomers with the best observational evidence to date that globular clusters sort out stars according to their mass, governed by a gravitational billiard ball game between stars. Heavier stars slow down and sink to the cluster's core, while lighter stars pick up speed and move across the cluster to its periphery.

Omega Centauri - 16,000 light-years



Omega Centauri is among the biggest and most massive of some 200 globular clusters in the Milky Way. Hubble snapped this panoramic view of a colorful assortment of 100,000 stars residing in the crowded core of a giant star cluster that contains nearly 10 million stars.

All of the stars in the image are cozy neighbors. The average distance between any two stars in the cluster's crowded core is only about a third of a light-year, roughly 13 times closer than our Sun's nearest stellar neighbor, Alpha Centauri.

Arches Cluster & Quintuplet Cluster - 25,000 light-years

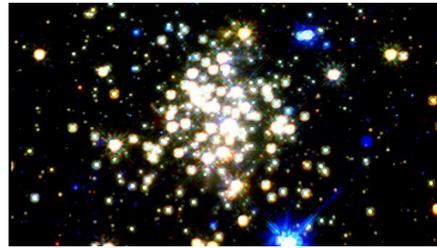
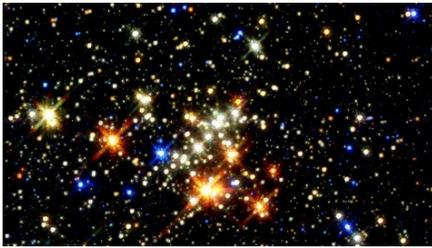
Penetrating 25,000 light-years of obscuring dust and stars, Hubble uses infrared to provide the clearest view yet of a pair of the largest young clusters of stars in our Milky Way galaxy.

They are located less than 100 light-years from the very center of the Galaxy.

Having the equivalent mass greater than 10,000 stars like our sun, the monster clusters are ten times larger than typical young star clusters scattered throughout the galaxy.



Arches cluster is so dense, over 100,000 of its stars would fill a spherical region that only contains 5 stars in our local neighborhood.



The Quintuplet cluster is home for the brightest star in the Galaxy, called the Pistol star.

Globular Cluster M30 - 28,000 light-years

Here we are zooming into our final and most distant cluster, M30. Globular cluster M 30 is a



dense swarm of several hundred thousand stars. It's about 90 light-years across.

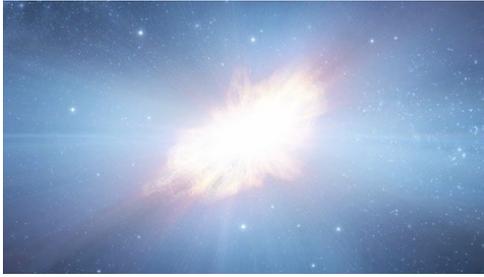
Supernova

[Music: Sergei Rachmaninoff – “Rhapsody on a Theme of Paganini” – Paganini's capriccios were fairly free in form and lively in character. His 24th, written around 1807, is widely considered one of the most difficult pieces ever written for the solo violin. As with the study of Supernova Remnants, it requires many highly advanced techniques. Rachmaninoff's 1934 rendition for violin and orchestra is my favorite and fits our examination of Supernova very well.]

Here's the Helix Planetary Nebula creation clip. You'll recall that Planetary Nebulae are the result of a Main Sequence star exploding at the end of its life. This is called a nova and it is the expected end for the Sun and most stars less than 5 times the mass of the Sun.



The star left behind at the end is called a white dwarf. The typical white dwarf is around the mass of the Sun but packed into a star about the size of the Earth. It's so dense that a spoonful of it would weigh several tons here on Earth.



For massive red supergiant stars, a different end is in store. Here's a clip on what the Crab Nebula supernova may have looked like. The explosion at the end is billions of times larger. A supernova may shine with the brightness of 11 billion suns! The total energy output can be as much as the total output of the sun during its entire 13 billion year lifetime!

The star left behind at the end is called a neutron star. If the star was massive enough, the supernova could leave behind a black hole. The typical neutron star is around one and a half times the mass of the Sun but packed into a star about the size of Poway, California. It's so dense that a spoonful of it would weigh 10 million tons!

Here's what the daytime sky might look like if and when Betelgeuse supernovas. The luminosity of a supernova depends on the mass of the star.

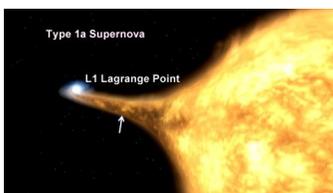


If we knew the mass, we'd have ourselves another standard candle, one that shines hundreds of thousands of times brighter than Cepheid Variables. But for most explosions across the cosmos, we don't have that information. But there is one scenario where we do. It is called a **Type 1a supernova**. It is based on a particular binary star setup, and it is recognizable via light profiles and spectral analysis.

Here's how it works:



1) A massive red giant star has a small stellar companion.



2) Mass flows from the giant to the dwarf through the L1 Lagrange point. You'll remember Lagrange points from our discussion on Jupiter in the segment on our Solar System.

3) The mass of the dwarf star increases.



4) Once the mass of the smaller star reaches a critical level, its ability to hold off collapsing under the force of gravity ends. The result is a total collapse inside a few seconds. This creates the supernova explosion that rips the smaller star to pieces.



The critical mass needed for this explosion was calculated to be 1.44 solar masses by Subrahmanyan Chandrasekhar in 1930 on a ship on the way from India to England to begin graduate study in physics at Cambridge University! The Chandra space telescope is named after this great physicist.

Because we know the mass of a Type Ia supernova, we know the luminosity. This has made them very important standard candles and one of the most reliable distance measurements. They are thought to provide a distance measurements approaching 5% accuracy over vast distances.

Let:

$$\begin{aligned} M_{\text{limit}} &= \text{Chandrasekhar limit} \\ &= 2.13 (hc/2\pi G)^{2/3} \times (1/\mu_e m_H) \\ &= 1.44 M_{\text{sun}} \end{aligned}$$

Where:

$$\begin{aligned} h &= \text{Planck's constant} \\ c &= \text{the speed of light} \\ G &= \text{Newton's gravitational constant} \\ \mu_e &= \text{average electron molecular weight} \\ m_H &= \text{mass of a Hydrogen atom} \\ M_{\text{sun}} &= \text{the mass of the Sun} \end{aligned}$$

Supernova Stars

So let's take a look at some of the fantastic celestial remnants of stars destroyed by supernovae explosions photographed by the Hubble Space Telescope.

[Music: Georges Bizet – “Entracte to Carmen Act III” – Here we replay this beautiful piece as we dance with the remnants of nearby supernova.]

Veil Nebula – 1,500 light years

A supernova releases so much light that it can outshine a whole galaxy of stars put together. The exploding star sweeps out a huge bubble in its surroundings, fringed with actual stellar debris along with material swept up by the blast wave. This glowing, brightly-colored shell of gas forms a nebula that we call a 'supernova remnant'. Such a remnant can remain visible long after the initial explosion fades away.

This Veil Nebula is the shattered remains of a supernova that exploded some 5-10,000 years ago. We are zooming into sections of the Veil Nebula photographed by Hubble. This series of images provides beautifully detailed views of the delicate, wispy structure resulting from this cosmic explosion.



Although only a few stars per century in our Galaxy will end their lives in this spectacular way, these explosions are responsible for making all chemical elements heavier than iron in the Universe.

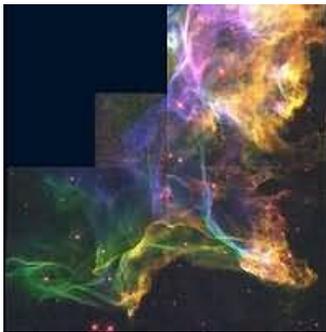


[Additional info: Many elements, such as copper, mercury, gold, iodine and lead that we see around us here on Earth today were forged in these violent events billions of years ago. The expanding shells of supernova remnants were mixed with other material in the Milky Way and became the raw material for new generations of stars and planets. That's why we are 'star dust', as Carl Sagan pointed out in his Cosmos series back in the 80s.

Cygnus Loop – 2,500 light years

The Veil Nebula is part of a larger nebula known as the Cygnus Loop.

The Cygnus Loop marks the edge of a bubble-like, expanding blast wave from a colossal stellar explosion which occurred about 15,000 years ago.



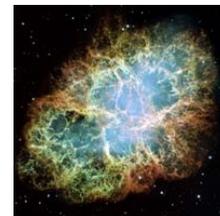
This image shows a small portion of this nebula.

[Additional info: In this image the supernova blast wave, which is moving from left to right across the field of view, has recently hit a cloud of denser than average interstellar gas. This collision drives shock waves into the cloud that heats interstellar gas, causing it to glow.]

Crab Nebula - 6,500 light-years

Japanese and Chinese astronomers recorded this violent event nearly 1,000 years ago in 1054, as did, almost certainly, Native Americans. Called the Crab Nebula, it derived its name from its appearance in a drawing made by Irish astronomer Lord Rosse [in 1844.]

The orange filaments are the tattered remains of the star and consist mostly of hydrogen. The rapidly spinning neutron star embedded in the center of the nebula is the dynamo powering the nebula's eerie interior bluish glow. The blue light comes from electrons whirling at nearly the speed of light around magnetic field lines from the neutron star.



The neutron star, like a lighthouse, ejects twin beams of radiation that appear to pulse 30 times a second due to the neutron star's rotation. This kind of Neutron star is called a **Pulsar**.

SN 1006 – 7,000 light years



Just over a thousand years ago, the stellar explosion known as supernova SN 1006 was observed. It was brighter than Venus and visible during the day for weeks. The brightest supernova ever recorded on Earth, this spectacular light show was documented in China, Japan, Europe, and the Arab world.

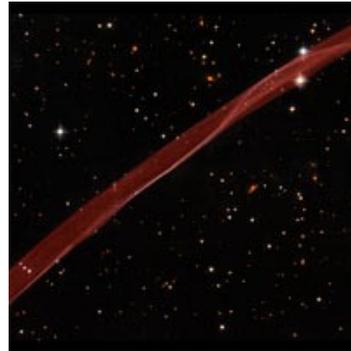


Ancient observers were treated to this celestial fireworks display without understanding its cause or implications. We now understand that SN 1006 was a Type 1a supernova.

[Music: Johann Sebastian Bach – “Air” – And again, “Air” is perfect for these wispy beautiful celestial objects.]

SN 1006 remnant – 7,000 light years

In 1976, the first detection of exceedingly faint optical emission of the supernova remnant was reported. A tiny portion of this filament is revealed in detail by this Hubble observation. The twisting ribbon of light corresponds to locations where the expanding blast wave from the supernova is now sweeping into very tenuous surrounding gas. The size of the remnant implied that the blast wave from the supernova had expanded at nearly 20 million miles per hour every hour for over 1,000 years.

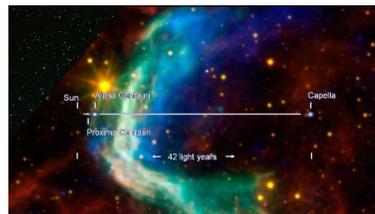


RCW 86 - 8,000 light-years



The Chinese witnessed this supernova event in 185 A.D., documenting a mysterious "guest star" that remained in the sky for eight months. This combined visible light and X-ray image shows the interstellar gas that has been heated to millions of degrees by the passage of the shock wave from the supernova.

RCW 86 is approximately 85 light-years in diameter. If it were the star Capella, the shock wave would be tearing us apart right now.

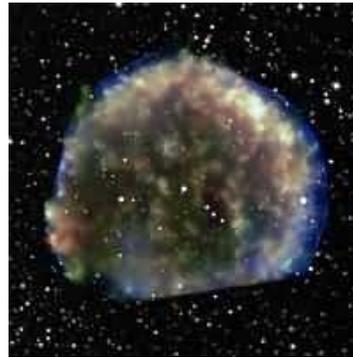




Tycho Supernova SN 1572 - 9,800 light-years

Here we are zooming into the surviving companion star to a titanic supernova explosion witnessed in the year 1572 by the great Danish astronomer Tycho Brahe.

On November 11, 1572, Tycho Brahe noticed a star in the constellation Cassiopeia that was as bright as the planet Jupiter. No such star had ever been observed at this location before. It soon equaled Venus in brightness. For about two weeks the star could be seen in daylight. At the end of November it began to fade and change color, from bright white to yellow and orange to faint reddish light, finally fading away from visibility in March 1574.



Tycho's meticulous record of the brightening and dimming of the supernova now allows us to identify its "light signature" as that of a Type 1a supernova. Tycho Brahe's supernova was very important in that it helped 16th-century astronomers abandon the idea of the immutability of the heavens.

Cassiopeia A - 10,000 light-years

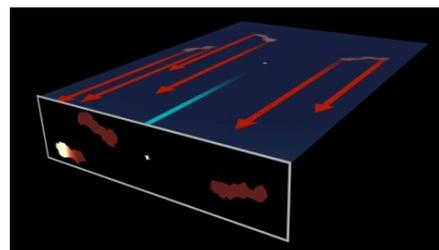
These supernova star's shredded remains are called Cassiopeia A, or "Cas A" for short. Cas A is the youngest known supernova remnant in our Milky Way Galaxy. The light from this exploding star reached Earth in the late 1600s.



This photo shows the upper rim of the supernova remnant's expanding shell. The colors highlight parts of the debris where chemical elements are glowing. The dark blue fragments, for example, are richest in oxygen; the red material is rich in sulfur. [The star that created this colorful show was a big one, about 15 to 25 times more massive than our Sun.]

These Spitzer Infrared Space Telescope images show shifting patterns of glowing dust beyond the remnant itself. These changes are so fast that they indicate motion at the speed of light!

These are **light echoes** just like what we saw with the star Monocerotis. The light from a supernova can take hundreds of years to reach surrounding dust clouds. Following the arrows of light it's clear we'll see the supernova flash first. The light echoing off of the dust clouds will arrive later - at various times, delayed by hundreds of years from the original flash.





So we're not seeing the dust move, we're seeing the light from the supernova move through the dust. It's Spitzer that can detect this brief boost in the thermal infrared glow.

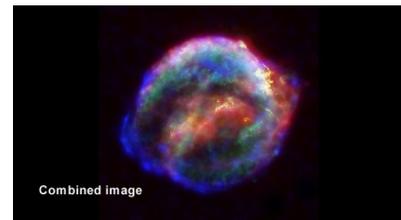
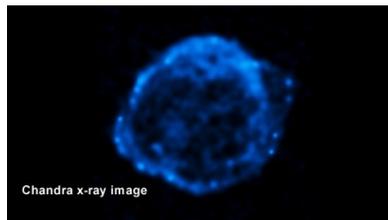
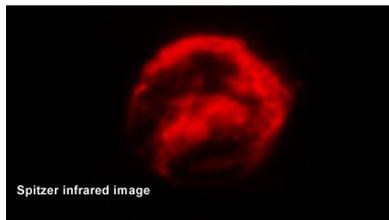
[Music: *Georges Bizet – “Entracte to Carmen Act III” – And again, we replay this beautiful piece as we dance with light echoes and the remnants of distant supernova.*]

Kepler's supernova SN 1604 - 13,000 light-years



Four hundred years ago, sky watchers, including the famous astronomer Johannes Kepler, were startled by the sudden appearance of a "new star" in the western sky, rivaling the brilliance of the nearby planets. [When a new star appeared alongside Jupiter, Mars, and Saturn on Oct. 9, 1604, observers could only use their eyes to study it. The telescope would not be invented for another four years.]

Modern-day astronomers examine the remnant in infrared radiation, visible light, and X-rays. You can see the value of going beyond visible light. Hubble's visible light image doesn't 'see' the full nature of the supernova remnant. The X-ray and infrared cameras do.



[Additional info: The combined image unveils a bubble-shaped shroud of gas and dust that is 14 light-years wide and is expanding at 4 million miles per hour. Observations from each telescope highlight distinct features of the supernova remnant, a fast-moving shell of iron-rich material from the exploded star, surrounded by an expanding shock wave that is sweeping up interstellar gas and dust at more than 22 million miles per hour, like an interstellar tsunami.

- Visible-light images from Hubble reveal where the supernova shock wave is slamming into the densest regions of surrounding gas.
- Infrared light from Spitzer shows heated microscopic dust particles that have been swept up by the supernova shock wave.
- X-rays from Chandra show regions of very hot gas.]



N 63A – 160,000 light years

A violent and chaotic-looking mass of gas and dust is seen in this Hubble Space Telescope image of a nearby supernova remnant denoted N 63A.



Many of the stars in the immediate vicinity of N 63A are extremely massive. It is estimated that the progenitor of the supernova that produced the remnant seen here was about 50 times more massive than our own Sun.

[Additional info: Such a massive star has strong stellar winds that can clear away its ambient medium, forming a wind-blown bubble. The supernova that formed N 63A is thought to have exploded inside the central cavity of such a wind-blown bubble.

Color filters were used to sample light emitted by sulfur (shown in red), oxygen (shown in blue), and hydrogen (shown in green).]

Supernova 1987A – 163,000 light years

Two decades ago, astronomers spotted one of the brightest exploding stars in more than 400 years – Supernova 1987A.



Here we have an archival photographic plate of the star before it exploded next to one where it had.

Here we zoom into a fascinating image of the asymmetric pattern of the exploding stars surroundings.

The most prominent feature in the image is a ring with dozens of bright spots. A shock wave of material unleashed by the stellar blast is slamming into regions along the ring's inner regions, heating them up, and causing them to glow.



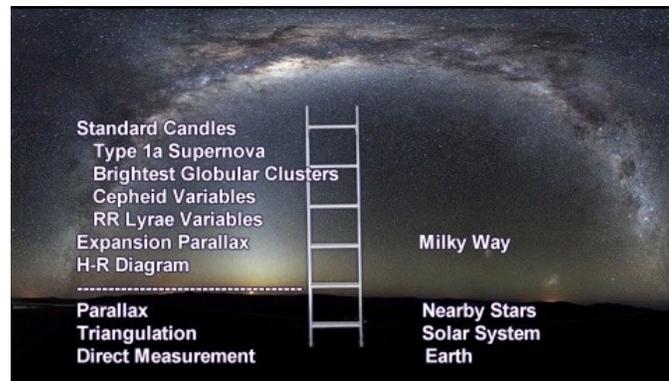
Astronomers detected the first bright spot in 1997, but now they see dozens of spots around the ring. Only Hubble can see the individual bright spots.

Distance Ladder

[Music: *Sergei Rachmaninoff – “Rhapsody on a Theme of Paganini” – We end with Rachmaninoff’s Rhapsody.*]

Although star clusters come in a variety of sizes and magnitudes, it appears that the brightest globular clusters have a similar luminosity. This makes them a good standard candle. We can also add Supernovas to our distance ladder. Type 1a supernovae provide a candle as accurate as Cepheid variables but with the advantage that they can be seen clearly at much larger distances.

How Far Away Is It – Star Clusters and Supernova



In the next section, we'll take a look at the most spectacular nebula in the Milky Way.